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**Novel Combustion Flame Luminosity Methodology to Track Gun
Propellant Combustion Progress in Closed Vessel and Semi-Closed
Vessel.**

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the degree of PhD in Defence Chemistry
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Abstract

This research project investigated a novel technique aiming to evaluate the performance of gun propellant combustion. The voids between propellant particles cause some difficulties in accurately measuring the performance of powder propellants. Closed vessels and strand burners are methods capable of measuring propellant burn rate, however, cannot consistently control the non-linear progression of gun propellants due to the voids. Combustion models have been employed to solve this problem; however, several models still produce unrealistic predictions, hence the necessity for an experimental technique.

The combustion parameters commonly associated with propellant combustion were recorded and their correlation with the luminosity was investigated. A novel technique was designed intended to contribute to the knowledge obtained during certain combustion processes. The luminosity generated by the combustion flame is associated with the chemistry of the propellants and can be measured by cameras from safe distances. A camera was utilised to record the luminosity generated by the combustion and the data was compared to the pressure and combustion time. Several modes of operation were utilised in the form of closed vessel, vented vessel, and open vessel to study the difference between these modes on the parameter's correlation.

It was observed that the luminosity data was closely correlated to the pressure, especially the peak luminosity to the peak pressure, obtained when the burn rate was at its highest conditions. Despite individual variation between firings, the average luminosity for any propellant loading density generated a reproducible and consistent rise, indicating the correlation hypothesised exists.

Despite making useful observations, the luminosity technique requires improvements to more accurately describe the correlations. The usefulness of this technique does rely on the ability of the propellant to produce a smokeless burn, generally a requirement for several military weapon systems for safety purposes.

Keywords

Energetic Materials

Propellant

Luminosity

Burn Rate

Mass Consumption Rate

Closed Vessel

Vented Vessel

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List of Abbreviations

RDX	Hexogen
TG	Thermogravimetric
DSC	Differential Scanning Calorimetry
NQ	Nitroguanidine
CMDB	Composite Modified Double Base
AP	Ammonium Perchlorate
KP	Potassium Perchlorate
HTPB	Hydroxyl Terminated Polybutadiene
HIC	Hydroborate Iron Compound
NC	Nitrocellulose
CL-20	Hexanitrohexaazaisowurtzitane
STP	Standard Temperature and Pressure
LOVA	Low Vulnerability
CV	Closed Vessel
SCV	Semi-Closed Vessel
VV	Vented Vessel
OV	Open Vessel
AN	Ammonium Nitrate
TNT	Trinitrotoluene
NO	Nitric Oxide
CO	Carbon Dioxide
AlO	Aluminium Oxide
3-D	3 Dimensional
PIC	Plastic Igniter Cord
AUC	Area Under the Curve
MCR	Mass Consumption Rate
N120	Vihtavuori Propellant Classification
R ²	Coefficient of Determination
FPS	Frames per Second
EMTAP	Energetic Material Testing Assessment Policy
C*	Characteristic Exhaust Velocity

1 Introduction

Energetic materials are materials that contain a large concentration of energy stored in their bonds that can be released through combustion. Propellants are a subcategory of energetic materials that combust through the process of deflagration, a rapid chemical reaction progressing as a surface phenomenon towards the unreacted material along the surface at subsonic velocity [1]. Gun propellants represent one classification of propellants. These are often in powder form, but may also be in grains of various shapes, and as their names imply, are used in guns and artillery. A typical grain is shown in Figure 1.



Figure 1: Gun Propellant Example [2]

Generally, research on combustion of gun propellants is conducted inside closed vessels, capable of observing the effect of total or partial confinement required to propel objects. The combustion process of gun propellants generates considerable heat and product gases, which when properly utilised remains partially confined, raising the pressure. The hot product gases remain confined until the pressure inside the barrel rises enough to transform the chemical energy from the combustion into kinetic energy applied to thrust projectiles. The performance of such materials varies depending on the expected requirement. An important factor describing the overall propellant performance is described by the burn rate of propellants, observed during combustion describing the reaction speed.

The chemistry of the combustion reaction will dictate the total energy output and total gaseous quantity. The heat is dependent on the temperature of the product

gases, while the volume of the closed vessel utilised for combustion influences the pressure history.

Time of the combustion process is an important parameter to be considered since it influences the rate at which other parameters rise. Time has a prominent role in the temperature of combustion as longer combustion processes allow longer intervals for heat dissipation into the atmosphere, and instrumentation alike. On the other hand, short combustion processes release all the heat from the products with limited time for dissipation of heat to the surrounding. Although not relevant for the entire combustion process, the ideal gas law does highlight that the pressure is proportional to any temperature change, and thus, the combustion time has a direct effect on pressure.

Vielle's law describes the burn rate equation for a combusting material, in other words, the speed at which the energetic material will combust. The most important parameter in the equation is pressure, which is influenced by the energetic material's chemical and physical properties. As described in the paragraph above, temperature also participates in the pressure build up during combustion based on the speed of the reaction.

Due to the nature of propellants, experimental work can be hazardous even with careful practice throughout, while also being expensive and in some cases difficult to prepare. Hence, combustion modelling has an important impact on current propellant combustion research to generate data without the need of producing, transporting, storing, preparing, and combusting energetic materials. However, gun propellants have characteristics that increase the difficulty in predicting its overall combustion effects through combustion modelling. Most importantly, the porosity of powder propellants has characteristics that make it difficult to combust linearly. To address this difficulty, a novel technique focusing on the measurement of the combustion flame luminosity was developed, where it would not require propellants to burn linearly.

During the deflagration process, the combustion flame generated by the chemical reaction can be visible through the emission of photons caused by the excitation

of electrons that change between electron shells. The flame generated during combustion can only be visible once combustion gases are generated, similar to the pressure and temperature parameters, which can only rise when product gases from the exothermic chemical reaction are released. Incidentally, once the combustion process concludes, no more pressure and temperature rise will be observed since no more combustion gases are being added to the closed vessel system. Similarly, no more luminosity will be visible as the combustion flames run out of fuel and oxidiser.

This research project aims to investigate possible correlations between the flame luminosity generated by deflagration of gun propellants to combustion parameters, including pressure, temperature, and combustion time. This will be achieved by designing a closed vessel capable of combusting gun propellants at controlled environments, allowing the addition of a planetary camera to record the flame luminosity output. Despite the importance of combustion modelling, this project will focus solely on experimental work, and henceforth, no more combustion modelling will be discussed.

This thesis will be further discussed in 4 chapters. The following chapter will focus on the literature review of the relevant literature on topics of relevance. The methodology chapter comes next describing the development of the burning vessel alongside experimental plan devised. The results and discussion chapter will highlight the collected data and discuss what they could mean. Finally, a conclusion will be presented in the last chapter of this thesis to discuss positives and negatives of the research made.

2 Literature Review

The literature review chapter will describe the preceding research on propellant combustion, confinement, accidents, and luminosity to discuss important findings.

2.1 Propellant

Propellants can have different forms and are manufactured in various ways, depending on their required characteristics. Liquid propellants typically provide better performance, however, can be difficult to work. Solid propellants have been extensively used for decades for various applications. Within solid compositions, propellants can have homogenous or heterogeneous physical properties. As their names suggest, propellants with homogenous physical structures have one continuous layer made of the same composition throughout the samples, while heterogeneous propellants have multiple physical layers [3]. These different physical structures are a result of manufacturing techniques based on ingredients characteristics and will have an impact on the propellant combustion process.

Propellant research currently focuses on improving several parameters of combustion properties, including:

- Performance
- Mechanical Properties
- Service Life
- Safety
- Environmental Impact
- Ease of Manufacture
- Cost
- Visibility

These parameters depend on the application objective, since certain propellants applications focus on the increase of energy release, combustion time, or thrust, whilst for others it is desired to combust at low pressures, or even simply to prevent the overheating of the mechanical parts, especially for guns and artillery

if used numerous times. Often, there are trade-offs between certain characteristics. For applications that have desire to increase the performance, the safety characteristic can be affected [4].

As eventually any variation in the propellant preparation or composition will impact at least one of the performance parameters (e.g., pressure, temperature, and time), these are continuously tracked throughout the combustion process.

Since these parameters affect one another, a change in any parameter usually leads to a change in all of them. Due to their importance, an equation was created to describe the burn progress of propellants; it includes all the parameters mentioned above and others in the form of the burn rate. The burn rate relates to the speed which the combustion flame travels through the propellant surface, it is measured in distance over time as it refers to a velocity measurement [5].

Vieille's law [6] has been used as a reference burn rate equation, established by Paul Vieille in 1893 [7].

$$r = aP^n$$

Equation 1: Vieille's Law.

In this equation, “r” refers to the burn rate, “a” is a variable of multiple factors including temperature, “P” is the chamber pressure, and “n” is the pressure coefficient index.

Vieille's law has been accepted to describe a wide range of propellant compositions [8]. Nevertheless, it may not be applicable to all propellant compositions since they may differ in surface characteristics, especially gun propellants that comprise of powder compositions rather than a homogenous physical structure. The porosity present in powdered compositions increases the surface area and drastically changes the combustion progression when compared to propellants with homogenous layer. As a result, Vieille's law may not be best suited for gun propellants, and a new technique may be required to track their combustion progress.

2.1.1 Chemical composition

Changing the chemical compositions or the addition of novel chemical compounds can be used to improve the combustion chemistry during reaction. The integration of oxidisers and metal fuels can significantly impact the combustion during deflagration of homogeneous propellants as can be seen in with the work of Elbasuney et al [9], who studied how adding ammonium perchlorate (AP) or potassium perchlorate (KP) to double-base propellants affected the burn rate and characteristic exhaust velocity (C^*), an important parameter typically used within rocket propellant research that considers propellant characteristics, however, without considering the rocket nozzle characteristics [10]. While KP favoured an increased in the burn rate by 22%, AP enhanced the characteristic exhaust velocity by 5.3%. Further investigation replaced small quantities of AP by aluminium metal as a source of fuel, which resulted in benefiting both burn rate and characteristic exhaust velocity. Liang et al [11] investigated the addition of Boron and oxidised boron compounds to HTPB and NH_4ClO_4 to evaluate their effect on the total energy released during combustion. The data suggests that the various compositions improved at least one of several parameters, indicating that it would depend on the propellant requirement to select the most appropriate boron oxidiser composition. Wu et al [12] measured the combustion performance when including various metal oxides to a composite modified double base propellant (CMDB). The data suggests that for low pressure environments the reference CMDB without any metal additives contained the highest burn rate; however, once the pressure reached 15 MPa, all combinations of metal additives overtook the burn rate measured for the reference propellant. The authors propose that this effect results from the low temperature, limiting the heat released from the metals. Therefore, the heat feedback to the unburnt propellant surface decreases, yielding a lower burn rate. The presence of copper tungsten oxide (CuWO_4) as a catalyst was investigated by Jain et al [13] to monitor the thermal decomposition of AP-based propellants. Despite diminishing the caloric value of total energy present in the sample, a significant increase in the burn rate and pressure exponents were observed.

Naya and Kohga [14] conducted experiments to investigate the importance of RDX content and its particle size on RDX-based propellants. An increase was observed in the propellant performance when increasing the RDX content due to the increase in combustion pressure. When decreasing the particle size, it was possible to notice a rise in burn rate, attributed to the increase in active surface area. Cao et al [15] investigated the effects of nitroguanidine (NQ) on thermal behaviour and burning characteristics of a specific classification of propellants specialised as a gas-generating agent for fire-suppressant applications. Through thermogravimetric (TG) and differential scanning calorimetry (DSC), the performance was determined with various heating rates. The NQ addition resulted in a reduction in combustion temperature and flame height, while increasing the burn rate and gas output, indicating an increase in efficiency.

2.1.2 Propellant Grain

The propellant design's shape has an important impact on the overall combustion performance since it is one factor contributing to the amount of energetic material being combusted.

This concept is referred to as propellant grain, where different grain shapes and sizes are selected based on desired output. The propellant grain knowledge includes information on grain configuration, grain dimension, and surfaces containing inhibitors [16], finally capable of measuring the burn-back pattern, and thus calculating the thrust applied to the object intended to be propelled.

Propellant grain applies to both gun and rocket propelling industries. Figure 2 shows a range of different grain designs.

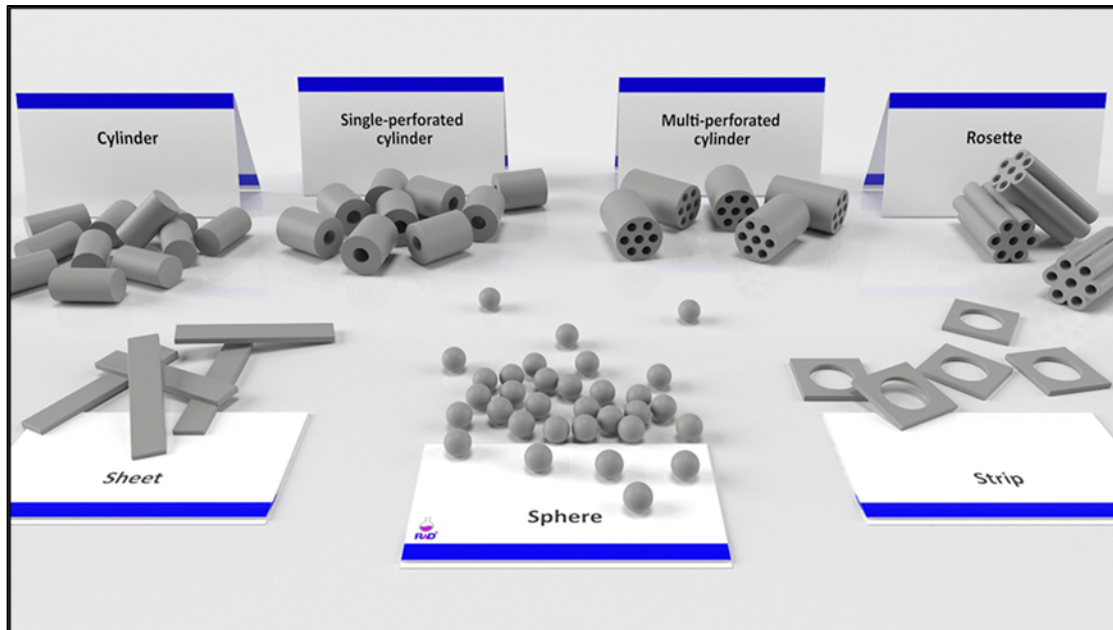


Figure 2: Typical Grain Designs [17]

Hartfield et al [18] demonstrates analytical methods used to calculate the burn area and port area of various grain shape designs, including star, long spoke wagon wheel, “dogbone”, dendrite, and truncated star.

An increasing interest has been given to the combination of homogeneous and heterogeneous propellants, called the Composite Modified Double Base propellant (CMDB), where chemicals normally used in composite propellants are mixed with a double base propellant. The physical structure of this approach mostly resembles a heterogeneous one, while the physicochemical properties contain a mixture of homogeneous and heterogeneous properties [19].

Continuous investigations on energetic materials allows the scientific community to further investigate desired properties such as thermal expansion by Kuznetsov et al [20] and improve existing techniques, such as Michalski J. and Leciejewski Z. [21] who investigated propellant ignition inside closed vessel with a capillary plasma generator to ignite the propellant sample. Bao et al [22] researched the

possibility to control the ignition process by consistently extinguishing the combustion front and re-igniting when desired on HAN-based propellants.

2.2 Performance Parameters

Combustion of energetic materials generate product gases at elevated temperatures. The product gases occupying a fixed volume apply pressure to the surrounding instrument, while the heat provided by the exothermic reaction cause these gaseous products to be released at elevated temperatures. Hence, temperature and pressure are relevant parameters to evaluate the performance of combustion. The temperature parameter also influences the pressure parameter by causing materials to expand at higher temperatures, which ultimately further raises the pressure recorded if all else remains constant.

The Propellant Section above discussed Vieille's law includes pressure and temperature to calculate the burn rate, or speed of the reaction. The pressure parameter is more directly involved in the equation, whilst temperature is present within the "a" parameter. This relationship indicates that pressure and temperature influence the combustion time, another impactful parameter that can be measured throughout combustion.

Any mechanical or chemical property variation can lead to differences observed in pressure and temperature recorded. Morrow and Petersen [23] investigated the effect particle size has on propellant burn rates to further understand the importance of varying mechanical properties. Particle sizes between 20 and 354 micrometres of Ammonium Perchlorate (AP) were used. The obtained data demonstrated an increase in burn rate when decreasing the particle size. This highlights the effect mainly comes from increasing the total surface area of combustion. Since it can be unlikely to obtain propellants of uniform particle size throughout the entire composition, the authors also studied combustions where 80% of a particle size was selected to confirm the consistency. A similar trend was observed where 80% of 23 and 46 micrometres AP particles measured greatly increased burn rates compared to larger particle size compositions of 138 and 200 micrometres. Conversely, Ritter et al [24] found that higher particle size yielded higher burn rate for two small calibre ball propellants. The reasoning

surrounded the use of a deterrent, which slowed the combustion speed, hence the larger particle size would only differ by having more available energy.

The propellant loading density at the start of the combustion process can also influence the performance parameters, as loading density refers to the loaded propellant density with reference to the available volume inside a burning chamber. If the burning chamber's volume remains constant, the propellant mass is the only parameter that influences the loading density. Mehta et al [25] investigated the effects of increasing the propellant loading density from 0.2 to 0.3 g/cc for a gun propellant. The pressure observed during the combustion was the highest at the maximum loading density utilised, which led to calculating the fastest burn rate. With a faster combustion, less time was required to completely combust all propellant sample, hence, the combustion time, denoted as the rise time, was lowest at the highest loading density. The increase in propellant mass not only increase the total energy available for reaction, but also increase the total surface area available for combustion processes to stem from and disperse, hence the increase in combustion performance parameters was observed.

Modification of the chemical composition will also impact the combustion process since a different combustion mechanism takes places, regardless of the scale of the modification. Pang et al [26] researched the changes in the reaction mechanism by adding hydroborate iron compound (HIC) in a composite propellant composition. HIC deemed as a promising alternative as a combustion catalyst, hence partially replacing the existing component with this function, which for this particular propellant composition was powdered aluminium. HIC was present in the composition with up to 5% in mass and the data was compared to a reference composition where no HIC was present. The combustion data observed an increase in burn rate when increasing the HIC composition for all compositions, thus, the largest increase in burn rate was observed when 5% of HIC was added to the composition. The flame brightness observed appeared to be higher in luminosity at higher pressures when HIC was present, which can be attributed to the increase in burn rate recorded, since more propellant was being combusted, leading to a higher release of photons by the continuous combustion.

Courty et al [27] investigated how the addition of RDX, nitrocellulose (NC), and graphene would affect the ignition properties of insensitive gun propellant. Insensitive propellants refer to propellant compositions that are harder to initiate combustion, indicating a higher level of safety present, especially when transporting, handling, and storing. Nevertheless, certain energetic material compositions can become too insensitive, and thus becoming practically unusable. The authors utilised a laser to ignite the propellant composition, where graphene works as a good ignition composition, which was reflected in the results gathered, highlighting that the composition containing graphite produced the highest ignition characteristics compared to the addition of the RDX and NC. The increase in ignition properties can lead to faster combustion and more uniform flame development, hence, potentially increasing the burn rate.

Divekar et al [28] conducted combustion experiments where a variation of triple base propellant composition substituted nitroguanidine (NQ) with Hexanitrohexaazaisowurtzitane (CL-20) to enhance the overall combustion properties. An increase in the modified propellant force-constant values was observed with increased CL-20 concentration, ranging from 2-6% rise, a similar rise seen pressure of 1-6%, while a 500 Kelvin flame temperature difference was measured at the most.

The effect that pressure and temperature have on the burn rate has been established by researchers above. Therefore, it must be acknowledged that if the starting pressure and temperature were not at standard laboratory conditions, such as standard temperature and pressure (STP) at 0°C and 1 atmospheric pressure, the combustion of propellant would develop differently, hence modifying the burn rate. This is an important consideration since the variation between winter and summer in some countries contains a large variation in temperature recorded, hence the performance of certain propellants might differ depending on the conditions present. Curdaneli et al [29] tested the effect initial temperature and pressure had on the burn rate of solid propellants. Temperatures and pressures representing the highest and lowest possible conditions for certain propellants to be utilised ranged from -35°C to 60°C and 60 and 120 bar. The

results obtained suggest that lower starting conditions yield lower burn rates, which confirms the discoveries made earlier in this section indicating that any modification made that led to an increase in pressure or temperature was reflected in an increase in the burn rate. Yaman et al [5] conducted a similar study where several starting pressures were selected to exemplify the possible conditions that can be achieved if high levels of confinement are achieved.

Boukadi et al [30] conducted a study that investigated the effect of firing temperature on the properties of gun propellants. This research highlights the importance in understanding the possible locations where gun propellants can get ignited. Igniting a gun propellant in extremely cold locations nearing -40°C should not have much different effect to the ignition in the warmer conditions of $+50^{\circ}\text{C}$. Nevertheless, the chemical and physical properties could have affected results in extreme conditions. According to Vieille's law, higher parameter conditions in pressure and temperature translate to higher burn rate, hence, higher firing conditions investigated by the authors, which showed higher combustion rates compared to lower firing temperatures. The firing temperature influenced the speed of the combustion, and hence, the combustion time, which in turn reduced the maximum pressure measured. The pressure observed in gun chambers directly translates to the propelled bullet velocity, which was also influenced by the initial firing temperature, demonstrating as much as 17% increase in projectile velocity while firing conditions increased from -54°C to $+71^{\circ}\text{C}$.

Leciejewski and Surma [31] investigated how varying the ignition system while maintaining the propellant sample fixed affected the overall combustion parameters. Various quantities of black powder inside a plastic bag were compared with each other as well as a test where the black powder was loose. It was identified that recurring increase in black powder quantity inside the plastic bag continuously decreased the combustion time. The data highlighted a small increase in the peak pressure observed, demonstrating that faster combustions will lead to higher parameter conditions inside the closed vessel. Since the same propellant was ignited, there was no difference in total gaseous products' volume

once all the propellant sample was ignited. However, when the combustion occurs faster, there is more heat dispersed inside the closed vessel, which can be a contributing factor to pressure increase due to thermal expansion. When comparing the data collected from closed vessel to a micro closed vessel, Leciejewski and Surma observed an increase in burn rate in the micro closed vessel combustion. Overall, this demonstrated that the burn rate coefficients of propellants are connected to the ignition method selected during closed vessel tests.

2.3 Confinement

Confinement in the context of energetic materials refers to trapping combustion products inside a sealed vessel. When combustion occurs in confined spaces, the hot gases generated by combustion accumulate inside the vessel increasing both pressure and temperature. According to Vieille's law, the elevated conditions will lead to further increases in the burn rate, indicating that more propellant will combust per unit time, generating even more hot gases. Therefore, confinement creates a positive feedback loop with increasing burn rates, pressures, and temperatures, until the energetic compositions fully combust or the confining location ruptures.

There are two confinement classifications: partial and total confinement. As their names suggest, the product gases will either be trapped without the possibility of escaping or can be released to the surroundings through an aperture of a known location and size. Combustion under confinement is conducted in closed vessels, and the data is presented in the form of pressure, temperature, and time history data [32]. It consists of burning a known amount of propellant in a closed combustion chamber of known volume [33] to record pressure-history data to further calculate other performance parameters, such as force constant, dynamic vivacity, and burn rate. The dynamic vivacity describes the propellant grain' surface area evolution throughout the combustion [34], and the force constant is a parameter describing the energy aspects of a propellant. [35].

2.3.1 Total Confinement

Research on combustion occurring in total confinement through closed vessels produce relevant data, especially for gun propellant research. Despite additional forces being present during the firing of gun propellants inside weapons, closed vessel experimental data is the first step to collecting interior ballistic data [19].

Tirak et al [36] combusted artificially degraded double-base propellants with a stabiliser to investigate the impact of the degraded propellant on the performance parameters. Nitrate esters (e.g., nitrocellulose), which are an essential component in certain classifications of propellants, undergo decomposition if stored for prolonged periods of time. Once the slow decomposition process begins, its performance parameters may be affected by the change in chemical composition. Visible changes were observed in the propellant powder, while the stabiliser concentration reduced from a starting 1.3% to below 1% once a few days of accelerated aging were underway. An increase in dynamic vivacity and maximum pressure was observed for aged propellants; this was estimated by the increased burning surface area due to the increased presence of microscale pores resulting from the reaction of the stabiliser with nitrate esters.

Liciejewski Z [37] utilised a closed vessel testing technique to combust single-base propellants of varying loading densities and combustible layer sizes. When drastically increasing the combustible layer size, the time required for the combustion to reach an exponential pressure rise increased, while also diminishing the pressure rise rate. Mehta et al [33] also investigated the effect of loading densities on the performance parameters, which led to an increase in maximum pressure recorded, while decreasing the rise time required to achieve the maximum pressure point.

Michalski & Leciejewski [21] explored an alternative ignition technique inside a closed vessel by applying a capillary plasma generator to low vulnerability (LOVA) propellants. The velocity of cloud propagation by the plasma demonstrated a faster propagation compared to the conventional black powder, indicating the possibility of a more homogeneous ignition.

Cooper & Oliver [38] utilised a hybrid closed bomb strand burner experiment to start investigating the deflagration characteristics and data of titanium subhydride potassium perchlorate. The hybrid vessel utilised could register both the burn rate and pressure rise, while describing their combined effect. The burn rate recorded was measured with break wires between each pellet that would break within 1-2 ms once the voltage was recorded as a result of the flame progression, proving accurate time measurements for known and fixed distances. This method would not be feasible for gun propellants due to the unsteady burn rate progression through the sample. The burn rate recorded was continuously rising due to the increase in pressure inside the vessel resulted by the partial deflagration, until all energetic material sample was combusted. This is attributed to the shift in heat transfer mechanism during the combustion process from conduction initially to a convective burning regime when enough energetic materials combusted rises the pressure sufficiently to accelerate the burn rate beyond the atmospheric pressure burn rate.

Ghosh et al [39] investigates the combustion properties of triple base gun propellants in a closed vessel of 700 cubic centimetres. The combustion time measured for each propellant firing was equated to the time where the pressure inside the combustion vessel rose, indicating that pressure was only possible to rise when propellant was deflagrating. The manufacturing method selected was by solvent method, where a propellant dough was pressed into a strand, rather than the usual powder format of gun propellants.

2.3.2 Partial Confinement

Closed vessels (CV) can be utilised for partial confinement in combustion processes by having an aperture or a vent, allowing gaseous products to flow out the vessel, changing the burning chamber designation to a semi-closed vessel (SCV) or a vented vessel (VV). The decreased volume of gaseous products inside the vessel will lead to a decrease in pressure recorded. The temperature-history data follows the same trend since the product gases leaving the vessel contain most of the heat; this is so as the heat has not had enough time to be dissipated into the vessel and product gases still inside the burning vessel.

Research led by Parate et al [40] investigated the combustion of a propellant inside a burning chamber as both closed and semi-closed vessels, by adding a vent of 5mm in diameter. Since pressure naturally equilibrates, the addition of a vent would cause the combustion products to escape outwards once the pressure inside the burning vessel was higher than atmospheric pressure. Hence, the combustion increases the pressure and temperature, but at a lower rate compared to the same experiment in closed vessel format. Vieille's law explains that the burn rate of propellants directly depends on the pressure measured, which is directly and indirectly influenced by the temperature of the system. Therefore, a decrease in burn rate is observed for combustions occurring in semi-closed vessel conditions. This can be seen in Figure 3, a graphical representation of the pressure-history data collected during the combustion research by Parate et al [40]. When the 5mm diameter vent was implemented, the initial rate of pressure rise was slightly slower than the same observed for closed vessel. This led to a longer combustion time needed to reach the maximum pressure observed during combustion, which meant that more heat was dissipated to the atmosphere and a lower maximum pressure and temperature were recorded.

Research on semi-closed vessel combustion of propellant has limited literature available, however, other energetic materials benefit greatly from this mode of operation. The scientific behaviour and reasoning of detonations of explosives differ completely from propellant deflagration and the trends observed from semi-closed vessel combustion in literature can still provide confidence of its importance.

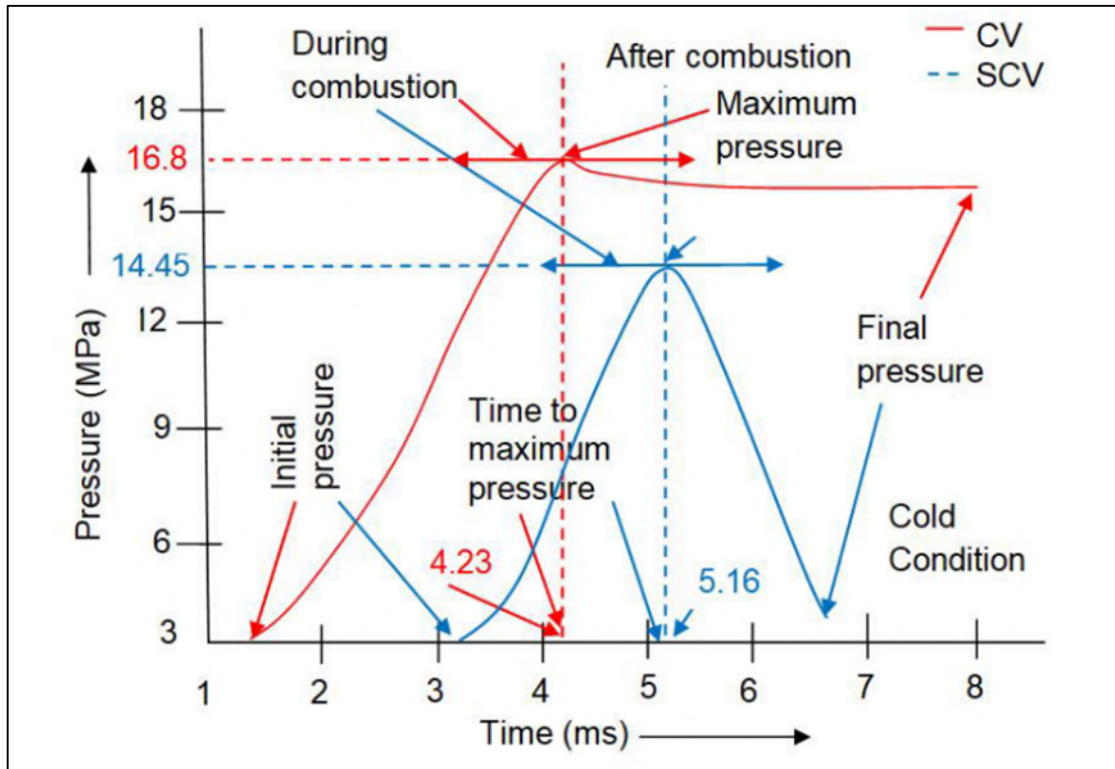


Figure 3: Closed and Semi-Closed Vessel Combustion Data collected by Parate et al [40].

Ahn et al [41] studied the effect of smoke dynamics on buildings under confined and unconfined conditions. The selected parameters to be investigated were temperature, pressure, and velocity, the same relevant parameters present in propellant combustion under confined locations. At the highest level of confinement, the largest increase in temperature, flame velocity, and pressure differential were observed, confirming that the pattern observed by Parate [40] remains true for non-propellant combustion products. Once confinement decreased, the performance parameters decreased in intensity.

2.4 Safety Importance

The high energy content present within energetic materials raises the importance of safety, whether transporting, handling, storing, or processing them. Undesired initiation of these materials can cause devastating damage depending on the quantity of material, sensitivity, and distance to the blast [42]. In 2012, in Brazzaville, Republic of the Congo, explosions were initiated at arms dump near

a densely populated area. Several small blasts were felt for several hours, claiming the lives of 300 victims as well as injuring at least 2500 more [43]. In March 2021, four explosions took place in a barracks in Bata, Equatorial Guinea, fatally wounding 100 people with 600 other injuries [44].

Innovative ideas have been developed attempting to increase safety inside laboratories, with special attention to chemical dedicated research laboratories, attempting to address all possible aspects related to what can cause accidents during regular experiments, from human error to chemical spillage to high temperature variation throughout the year [45]. Accidents and undesired ignitions can be mitigated by good working conditions and understanding the dangers present, however, cannot be avoided altogether.

A munitions expert accidentally initiated a chain of explosives when attempting to dismantle explosive storage in Gërdec, Albania in March 2008. The chain reaction led to two catastrophic explosions, 33 s apart [46].

Energetic materials are not the only compositions that can lead to detonations and deflagration; this was the case in Manisa, Turkey, in a coal mine now known as the Soma mine disaster [47]. Coal contains several elements capable of oxidizing and initiating exothermic reactions, such as carbon, hydrogen, sulphur, and nitrogen. Several reasons have been hypothesised as to the cause of the accident, nevertheless, most of them acknowledge that a spark from a motor must have ignited combustible products in the air to initiate a fire, which further increase the temperature and led to an uncontrollable combustion, finally exploding. There were 301 fatalities recorded out of the 787 workers inside the mine when the first of two explosions recorded.

More recently on a large scale, on August 4th, 2020, an explosion in a warehouse in a port in Beirut, Lebanon, was caused by the undesired initiation of approximately 2,750 tonnes of Ammonium Nitrate (AN) [48]. Stennett et al [49] used available tools and data to predict the TNT-equivalent of the AN with estimations from shock arrival time and distance from blast, which predicted that only 42% of the total AN available detonated during the blast, while the remainder

was unignited, propelled outward by the blast, or burned before the detonation occurred.

Another major accident at a smaller, yet considerable, magnitude occurred on August 12, 2015, at the port of Tianjin, China. A storage station housing several energetic materials compositions initiated at around 23:30 local time, followed by smaller blasts that lasted for a few more hours. The overall undesired combustion claimed the lives of 173 workers and injured 700 more. The combustion included 700 tons of sodium cyanide, 800 tons of ammonium nitrate, and 500 tons of potassium nitrate, however, no cyanide was detected in the victims and injured blood samples [50].

On May 13th, 2000, in Enschede, Netherlands, a depot of S.E. Fireworks went through a series of explosions, claiming the lives of 22 people, while injuring hundreds more. [51]. The casualties could have been higher had this disaster occurred on a weekday, as no employees were present since it was a Saturday. [52]. Once one of the smaller storage containers caught on fire, and eventually exploded, the fire grew out of control to start ignition in other storage containers. The second explosion was estimated to have an equivalent to 800 kg TNT, which blew several doors and windows, allowing the flame to further expand into unreacted pyrotechnic compositions. This would eventually trigger a third, final explosion with an equivalent of 4 to 5 tonnes of TNT.

Although the combustion products cause more alarming damage to personnel or civilians, these are not the only potential hazards threatening lives. Some energetic materials contain carcinogenic compounds or additives that can slowly generate deadly chemicals, exemplified by Frys et al, describing that conventional stabilisers can form substances with toxic and carcinogenic effects [53].

Confining combustion can be generated by intentional or unintentional factors, such as the result of poor storage or planning conditions, resulting in accidents. Intentional confinement uses imply for both the propulsion of rockets and bullets, by attempting to maximise the propulsion force used to measure the interior ballistics performance, in thrust [54]. By intentionally confining propellants to

combust inside a location of known volume, the resulting process raises the performance parameters, especially the pressure and temperature. Relating to Vielle's law, an increase in these parameters would yield an increase in the propellant burn rate, and increasing the thrust applied to the projectile, which in rocket and weapon systems, might be a necessary action.

2.5 Luminosity

The visible combustion flame observed from deflagration is the result of electromagnetic radiation with wavelengths inside the range of the visible light spectrum to the human eye [55]. Electrons get excited due to the increased temperature caused by the exothermic reaction; once excited, the electron releases its energy as it cannot sustain the increased movement for prolonged periods of time. The energy released comes in the emission of a photon [56]. Photons released within the visible light spectrum can be recorded and summed by applications like ImageJ [57], where the overall luminosity can be efficiently measured. For slow burning materials, the flame demonstrates the location where the exothermic chemical reaction occurs, releasing combustion products, while heating up the neighbouring unburnt propellant.

Most of the electromagnetic radiation emitted falls within the visible spectrum region, however, there will be a small portion of radiation emitted in the infra-red or ultraviolet spectrums. Photons emitted with wavelengths in both these regions cannot be captured by some cameras, hence, some luminosity could be lost [58].

The intensity of the combustion flame depends on the gas temperature of the combustion products released, where higher temperatures yield brighter flames and thus, higher luminosity. Therefore, energetic materials that contain high energy content, or that have higher burning rates, normally produce brighter flames due to the higher number of photons being generated per unit time. The luminosity generated can only be observed when propellants deflagrate, hence, there exists a connection between propellant combustion and total light generated, like other parameters (e.g., pressure and temperature) that can only be measured during deflagration. Due to this relationship, measuring the luminosity could become an alternative method to measure the combustion time

since it is linked to the length of time of an active flame. As a result, certain questions arise, such as: Is the luminosity generated during the deflagration of a propellant a consistent component? If so, can it become a new parameter used to help describe the burn rate? To answer these questions, several propellant combustion tests need to be recorded, so that a correlation can be made between the luminosity data and other performance parameters.

There are certain difficulties associated with measuring luminosity of propellant combustion. Several propellants produce smoke as a by-product of their combustion, limiting the light being captured by the camera, and diminishing the effectiveness of this technique, making smokeless propellants provide more accurate results. There has been an incentive towards continuous research on smokeless propellants because certain applications of propellants, especially gun propellants and artillery weapon systems. When engaging in warfare, the utilisation of smokeless propellants can prevent enemies from tracking down the location a weapon was ignited from [59], while also increasing the efficiency of the guiding system and visibility of the battlefield.

Measuring the luminosity requires the knowledge of the initial luminosity before and after deflagration. Light generated by the sun can vary between seasons, or even a cloud can block part of the light, so a dark location allows for a controllable initial luminosity. Utilising a closed vessel to combust propellant could prove to be an effective method to measure the luminosity since the light inside the closed vessel will be fixed and the luminosity observed by the camera will only be generated by the chemical reaction.

Gilabert et al [60] used a combination of 3 colour cameras to reconstruct the luminosity distribution of a combustion flame generated by combustion of gas and coal. The authors highlight the importance of the physical parameters that are observed during the flame luminosity recordings, including the size, brightness, and uniformity among others. The 3 cameras were placed to measure 180° of the combustion to more accurately calculate the total luminosity emitted during the combustion.

Industrial furnaces started shifting from liquid to gaseous fuels due to environmental pollution [61]. A significant reduction in flame luminosity as well as furnace efficiency resulted due to the shift of fuel type. Javadi and Moghiman investigated the effect of inlet natural gas temperature on the flame luminosity, boiler efficiency, and NO emission. It was identified that raising the initial temperature from room temperature to 240°C has no impact on the flame luminosity, however, further increasing the inlet fuel temperature beyond 240°C considerably increased the luminosity recorded. The NO emission increase when the fuel initial temperature increases up to 240°C alongside the increase in flame temperature, followed by a decrease once the initial temperature was further increased.

Although flame luminosity has attracted interest from several researchers in various fields capable of generating combustion flames, only some relate to propellants and their generated luminosity. Some research has studied the combustion flame through spectroscopy, where flame luminosity makes up one of the various interactions between matter and electromagnetic radiation.

Gill et al [62] combusted solid rocket propellant in an attempt to define the thermal-chemical-physical environment near a burning fragment. Spectroscopy was utilised to record the temperature of the flame components in soot, droplets, and gas. The gas and particulate temperatures were measured throughout the combustion demonstrating higher temperatures for the gases compared to the particulate. Ruesch et al [63] utilised spectroscopy to measure the temperature of CO and AlO to obtain information regarding the temperature evolution throughout combustion to feed combustion models. By varying the particle size of the aluminium, it was recorded that the smallest particle size generated the highest temperature with the least amount of variation regarding measurement location. Smaller particle size aluminium increases the surface area to volume ratio, increasing the burn rate of the propellant and the temperature by the highest factor.

3 Methodology

The literature review described in detail the ins and outs of some topics faced in the energetic materials research industry. Regarding combustion modelling, there is a general lack of confidence when describing the combustion of gun propellants. Generally, for deflagration process, even advanced modelling techniques predicting combustion do not accurately describe the outcome due to the large number of variables present in combustion. This could be explained by the higher degree of difficulty present in the chemical reactions present [64]. Modelling some physical and chemical effects, such as surface behaviour cannot be accurately modelled, hence must be approximated, or contain a constant that can describe certain parameters for within specific parameter ranges. Depending on the level of detail desired on the analysis, computation modelling can become a time intensive task.

Therefore, an experimental approach was selected to further understand propellant combustion reactions. To tackle this challenge, a novel technique was designed to capture the luminosity generated by the combustion to track the combustion progress. The luminosity measurement accompanied by the performance parameters collected can confirm certain aspects of the combustion process, such as the speed of the reaction by observing the time where light was observed.

The combustion process occurs when the energetic material reacts with oxygen and consumes the total available quantity of material or until the oxygen run out. For combustion to occur, it requires 3 components to be present simultaneously, commonly described in the fire triangle:

- Fuel
- Oxygen
- Heat

Energetic materials typically contain both the fuel and oxygen components as part of its chemical composition. Hence, the only remaining component required is the heat source, which for this scenario refers to a method of initiating the

chemical reaction between the oxygen and fuel. For some energetic substances, the heat required to ignite the substances initiating method can be a flame, spark, friction, or heat.

Properties referring to combustion parameters can be useful in determining the total luminosity that can be generated. The heat of combustion describes the heat generated when combusting 1-gram of any combustible substance, if the propellant mass to be combusted is known, the total heat generated during the combustion process can be calculated. Knowledge on these properties indicate that the overall luminosity to be released should be of similar magnitude if the combustion time remains consistent.

3.1 Relevant Parameters

Vielle's law describes the burn rate equation for a combusting material. The most prominent parameter of the equation refers to the pressure build up nearby the combustion. Therefore, defining the pressure measurement as a requirement. The temperature has an indirect effect on the equation, since it makes up one of the terms that influences the parameter "a". Temperature has also a direct effect on the pressure build up, especially if the combustion process occurs inside a building or a vessel. The heat will be released into the existing gases, and the walls surrounding the building. Gases expand when heated, hence, gases at high temperature occupy more space than gases at low temperature [65]. Since the volume inside the building or vessel is fixed, the resulting effect lies on a further increase in pressure due to thermal expansion. Temperature becomes the second required parameter to be studied during the combustion since it has a direct and an indirect effect on pressure. Measurement of the combustion time can be a useful method to confirm the predicted burn rate for energetic substances that burn linearly.

Lastly, the luminosity generated by the combustion will be captured with a camera. Not only will the luminosity be useful to evaluate the intensity of the combustion but can also be used as a method to measure the combustion time, since the flame will only visible while the combustion process remains active.

3.2 Data Collection Techniques and Instrumentation

In order to record data on the relevant parameters discussed above, certain techniques and instrumentations were required to be connected to the instrument.



Figure 4: Pressure Sensor (left) and Oscilloscope (right).

The pressure was recorded through the use of a pressure transmitter of various pressure limits based on the expected peak pressures to be exhibited in order to measure the data more accurately. The limiting pressure of the chosen gauges were 1, 10, 40, and 100 barG to investigate a large range of peak pressures, with a data acquisition rate sample of 1000 per second. The pressure gauges were connected to a Tektronix DPO 2004B Digital Phosphor Oscilloscope. These are shown in Figure 4. The pressure data was observed as voltage readings from the oscilloscope. A trigger unit was connected to one of the oscilloscope channels to start collection of pressure readings once a voltage has been received by the oscilloscope.



Figure 5: Pico Logger TC-08 capable of recording up to 8 channels of temperature data (left) and Temperature sensor type K (right).

The temperature measurement was made by a RS PRO Type K Thermocouple 100mm length, 1mm diameter, connected to a Pico Logger TC-08 unit. These are represented in Figure 5. The Pico logger was connected to a laptop to record and store the temperature data. The Pico Logger unit has 8 thermocouple inputs, allowing the opportunity to investigate the temperature at various locations or distances. Data was collected every 100ms for each thermocouple.

Combustion time measurement was recorded with break wires, which are intended to break apart once any flame comes into contact with the wire. The wire was connected to a break wire detector unit, which constantly checks whether the wire was broken at a fast rate. By placing the break wires at the start and end of the propellant tray, it was thought possible to record the time required for the flame to travel the known distance. A soldering wire was utilised as the break wire with its low melting point and ease of heating, allowing the wire to snap shortly after the flame came into contact. The break wire data sampling was at 200M Hz. The solder wire utilised had a diameter size of 1mm. Solder wires with thinner diameters would break apart faster, and thus provide a more accurate description of the combustion time location. Nevertheless, it would take on average the same amount of time for a flame to break any break wire set up, hence, the difference between break wire time recorded would truly indicate the combustion time.



Figure 6: Planetary Camera (Left) and Soldering wire (Right)

Unfortunately, the break wire instrumentation did not function properly, and was only fixed and in working conditions once all the firings had been completed. The resistor selected for this instrument was not suitable and blew on the first attempt, however, had it been selected appropriately, this technique would have yielded results. It is possible this technique would have provided accurate results, or at least results that could be used to compare to the combustion time recorded with the pressure and luminosity data.

A planetary camera ZWO ASI 120 MC-S was selected to capture the luminosity generated during the combustion via a glass window. The camera was connected to a laptop capable of running ImageJ, a java-based image processing program, which analysed the luminosity captured by the camera. The camera was set to record the maximum number of frames, which was capped at 30 frames per second, or 33 ms per frame. In some cases, however, bright conditions required changes to be made to record less frames per second. The camera utilised can be seen in Figure 6 along with the soldering wire as part of the break wire technique.

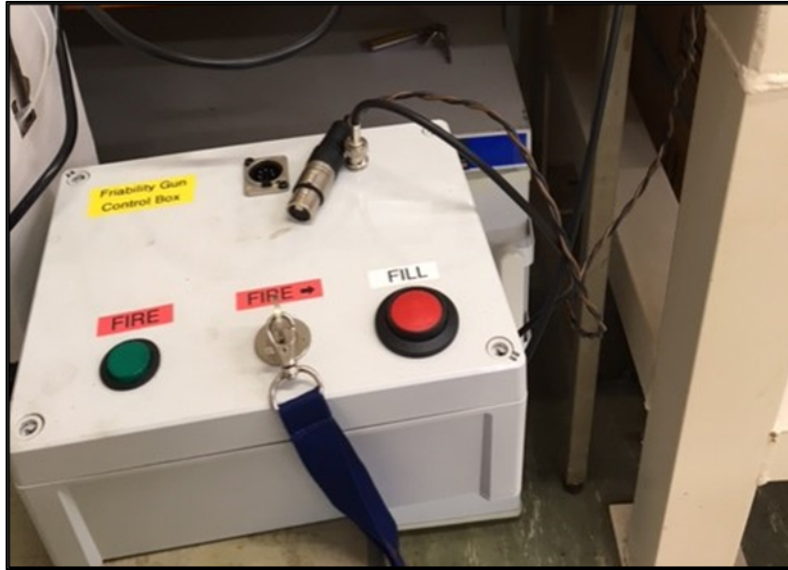


Figure 7: Ignition Box with the key and circuit connection.

An ignition box was assembled to initiate the propellant sample once the experimental setup process was complete. Several safety mechanisms were included to prevent an undesired ignition, especially when setting up the experiment, or when loading the experiment with explosive. The ignition box was connected to the oscilloscope used to record the pressure, where a voltage was sent to both the oscilloscope and the ignition system at the same time, indicating that time 0 on the Oscilloscope would represent the time when the combustion process had started. The ignition box is illustrated in Figure 7.

3.3 Instrument Design Requirements

Based on the relevant parameters and the methodologies associated with measuring their data, the instrument required to account for all requirements can start to take shape. Each parameter and condition imposed by the combustion demand a requirement from the burning vessel to be designed:

3.3.1 Pressure Requirement

The necessity of a pressure gauge installed in the instrument requires a port capable of attaching a pressure gauge without leaking the vessel. Since a pressure gauge was required to evaluate the overall stress being applied to the burning vessel wall, the burning vessel must be capable of withstanding high

pressures to study several loading densities of gun propellants. In order to prevent gases escaping before desired, the burning vessel had to be capable of operating under closed vessel conditions. Once the combustion was completed and the pressure data had been recorded, a ventilation valve was required to safely expel the gases outside the instrument in a safe orientation. Considering the damaging nature of the combustion products, the ventilation valve released the product gases outside the building to prevent any inhalation.

3.3.2 Temperature

Temperature measurement occurred through type K temperature sensors, which are long and thin steel rods. Several temperature sensors were required to measure the temperature at different distances from the centre of the vessel, where the combustion was taking place. Therefore, a port capable of including several type K temperature sensors was included in the instrument design.

3.3.3 Combustion Time

The combustion time was measured through two different techniques, which entailed various requirements. The methods used to calculate the combustion time were through the flame luminosity camera data, and the pressure rise data. The flame luminosity requirement will be discussed below during the requirements of luminosity parameter measurements. The pressure rise data had already been acknowledged, where it will be possible to have an estimation of the combustion time based on the time required for the pressure to reach its peak condition.

3.3.4 Flame Luminosity

Measuring the flame luminosity from the combustion required only a camera that has access to the inside of the instrument, a glass window was placed at the lid of the instrument. It must be addressed that the addition of a glass window diminished the pressure limit that can be withstood inside the closed vessel, since steel has superior mechanical properties to glass.

3.3.5 Ignition System

Igniting the propellant train from outside the vessel required a mechanism to send a voltage through the port that was previously utilised for both the temperature sensors, and break wire methodology. The connection was made via tinned copper wires; hence, 1mm diameter holes were required to send the signal through.

3.3.6 Personnel Protection

Due to the nature of energetic substances and their potential effect if not treated carefully, there was a safe operating environment to prevent injuries, or undesired initiation from damaging any personnel or other instrumentation. Although this does not classify as an instrument design requirement, the location the instrument was installed would limit the accessibility to the instrument, especially when loaded with energetic materials.

3.3.7 Non-Parameter Requirements

Designing the instrument accounted for the parameters requirement to be capable of measuring all desired properties during the combustion, while also accounting for the appropriate design characteristics. If a rectangular design was selected, the existence of walls would create the possibility of wave superposition with the possibility of positive and negative interference [66]. The lack of walls and edges in a cylindrical shape for the burning vessel would reduce this difficulty.

The base diameter had to account for the addition of supporting elements, such as terminal blocks, metal plates, as well as the designed part to hold the propellant together. It was required to carefully work inside the vessel to connect the entire process, hence a diameter of 23 cm was chosen for the base. The height of the instrument was chosen based on the diameter of the vessel. Depending on the propellant behaviour, researchers work with loading densities normally ranging between 0.02 to 0.2 g/cm³. The propellant mass to be combusted was selected to rise from 1 gram until 30 grams to evaluate the pressure rise.

3.4 Burning Vessel Safety Considerations

Safety is an important parameter to be taken into consideration on everyday tasks, however, needs further attention for activities involving energetic materials. Considering the volume available inside the burning vessel instrument and the propellant mass expected to be combusted inside, it was possible to predict a range of working pressures expected to be observed. To mitigate any damage to personnel and the burning vessel, the instrument was designed to have thick walls to maximise the internal pressure allowed.

To prevent unnecessary damage, the instrument's strength was tested by slowly increasing the propellant mass tested from 1 gram until 50 grams to evaluate the total effect on the burning vessel. Even when the pressure inside reached 90 bars with the highest propellant mass tested, the burning vessel behaved as designed, indicating the successful design. As a further means to mitigate the instrument damage, the limiting propellant mass decided for this research project's experiment was 30 grams.

It was previously discussed that accidental initiations have led to disasters and catastrophes; however, minor injuries have also occurred. To prevent an accidental ignition of the propellant inside the burning vessel, several factors were included. The ignition inside the vessel can only occur when the ignition box was connected to a plug, turned on, was connected to a trigger unit, had the voltage trigger turned on, had a key attached, and finally, the key was rotated at a 90° angle to start the combustion. Failure in any of these steps would prevent the ignition from occurring, and thus protecting the instrument and personnel. Before and between firings, the ignition unit box key would hang on a key chain safely away from the ignition box to guarantee no unwanted ignition would occur.

3.5 Burning Vessel Safety Considerations

Designing the burning vessel had to be carried out in an effective manner because it could take weeks to maybe a few months to be completed by the workshops, hence it was desired to identify any possible future failures during the design stages to prevent the necessity of a secondary vessel from being

developed. The first instrument design can be seen below in Figure 8 with the simple design of a cylindrical shape. The ports seen in the instrument design drawing were included to hold the pressure gauge where a larger section outside was used to thread the gauge in place, while having only a small aperture for the sensor to measure the pressure inside the vessel. There were 4 pressure gauge ports included in the design at the same height.

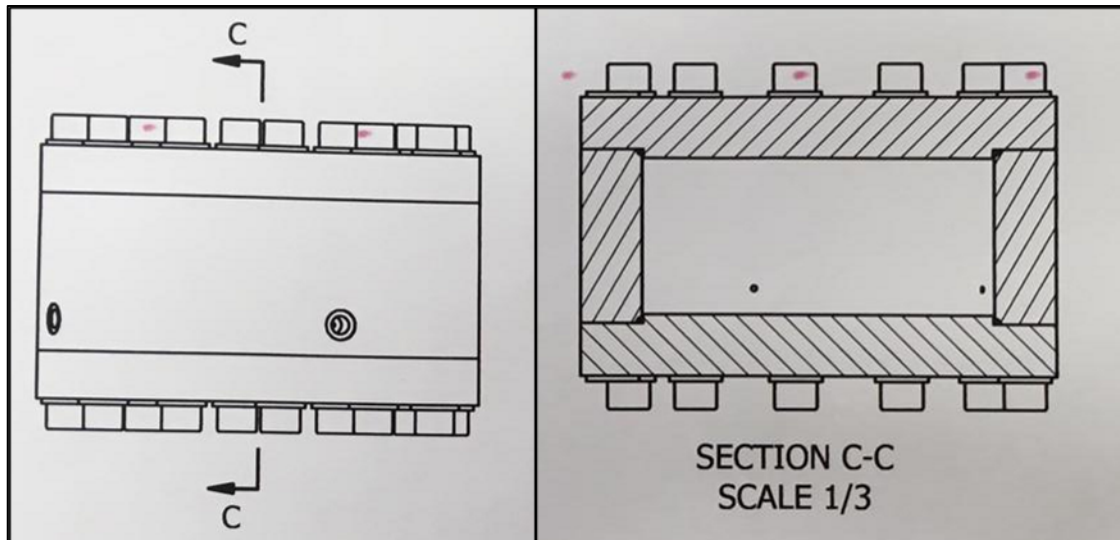


Figure 8: Burning Vessel Preliminary Design (Left) and Burning Vessel Thick Walls (Right)

The burning vessel was designed to have thick walls to withstand high combustion conditions, demonstrated in as the right picture in Figure 8. The 4 pressure ports had smaller apertures on the inside to reduce the overall area, which leads to a smaller force being applied to blank nuts.

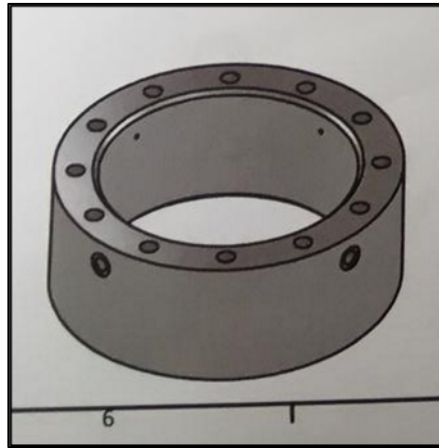


Figure 9: Burning Vessel Main Body Drawing 1

The burning vessel body was originally made to have 16 bolts connected to the lid and to the base, however, since all bolts connected to the lid would be required to be drilled inside and removed for every firing, a lot of time could be lost just on the set up. Once 8 of the 16 bolts that were supposed to be attached from the lid to the body were removed, the burning vessel was ready to be constructed by the workshops. This can be visualised in Figure 9, while Figure 10 shows the 3D illustration of the instrument design on the left image and the designed vessel on the right image.

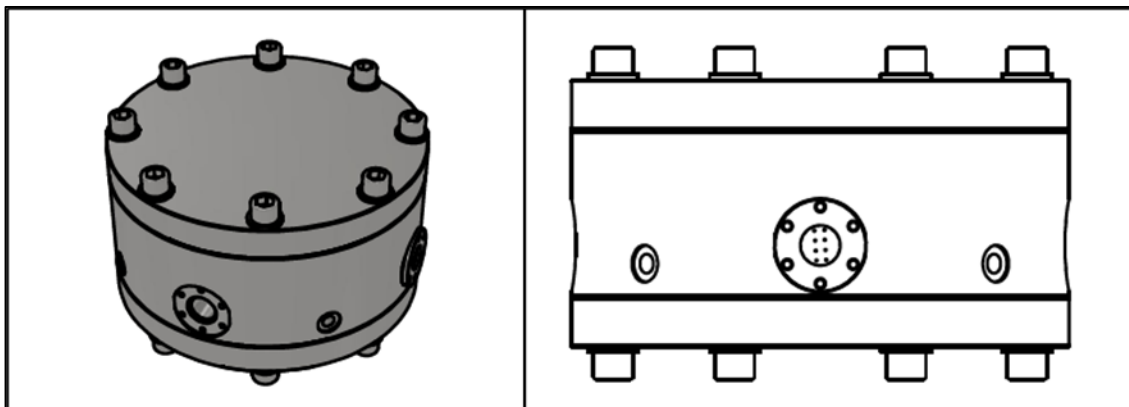


Figure 10: Burning Vessel 3D Design Final (Left) and Overall Instrument design

With a pressure port in all sides, it was also possible to change the pressure gauge location without compromising the entire process. Once the pressure

gauge port was selected, the remaining 3 empty ports would be blocked with a blank nut to prevent the gases from escaping.

The larger port was designed to connect the outside instruments and techniques to inside the designed vessel to accommodate for the temperature sensor, break wires, and ignition system. Two parts were included in the design, where a thin plate with 2, 4, or 8 holes of 1.0 cm in diameter could fit the vessel, while being covered with another plate that would attach the thin plate to the instrument by bolting it together. The 1.0 cm holes in the thin plates were chosen to be small to limit the pressure limit to be imposed at this weaker part of the instrument due to the presence of holes.



Figure 11: Instrument Lid with Glass Window

The instrument lid was designed to have a glass window to record the combustion process with a planetary camera, seen in Figure 11. Figure 12 shows the glass window installed within the instrument lid. The glass window was made of float

glass, allowing it to withstand enough pressure, with a thickness of 18 mm and 5 cm in diameter.



Figure 12: Final Instrument Set Up

The final instrument was made up of a steel alloy EN24T and can withstand an overpressure of 120 bar before beginning to force leaks through ports. Since a thick layer of steel was required in all directions, it was expected for the assembled instrument to have a considerable weight, totalling nearly 50 kg. Even when separating the bottom plate, body, upper plate, and lid, each individual part still weights a minimum of 10 kg, which can be a tiresome process since the lid must be removed between firings.

3.6 Propellant Tray

The propellant composition was placed in the centre of the instrument, inside a 3-D printed plastic tray of various sizes, depending on the propellant mass to be tested. The propellant tray design was conducted on Fusion 360, a computer-aided design, manufacture, and engineering application. A rectangular shape was selected to study the evolution of the flame. Despite having discussed that powder propellants contain higher degrees of randomness because of the voids between propellant particles, investigating the combustion progress could still yield relevant results. The increase in propellant mass combusted would require the increase in propellant trays, which was fixed at a ratio of 10:1:1 in length-diameter-width.

The design of the propellant tray started as a single unit with the propellant tray opened at the top to allow the combustion products to flow upwards. A small circular hole was connecting the gun propellant to the ignition system. The diameter of the hole matched the diameter of the plastic igniter cord (PIC) to prevent the small particle sized propellant from falling through the hole. The PIC would be attached to an electric matchhead with a tape, while still inside the propellant tray. The circuit connection of the electric matchhead was connected to the terminal block inside the instrument vessel. Figure 13 shows the propellant tray design.

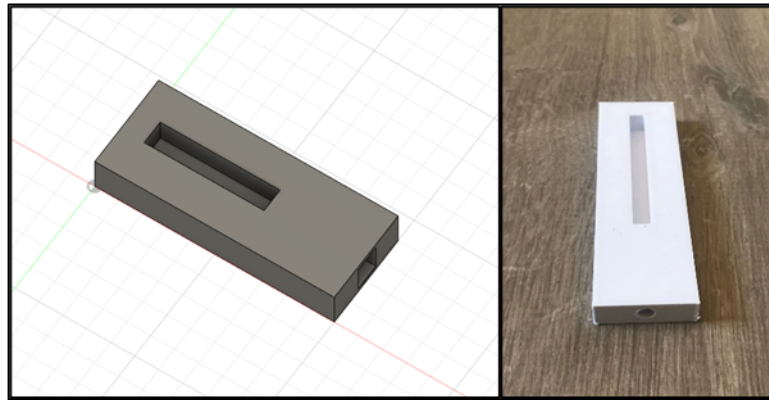


Figure 13: Propellant Tray in one piece.

The first propellant tray design shown above was effective, however, did not have enough room for the combustion products to escape from the side opening, hence, some of the combustion gases were passing through the unreacted propellant sample. Also, the assembly section proved to be slightly complicated to include the PIC through its intended section without damaging the end, hence, a new propellant tray design was planned.

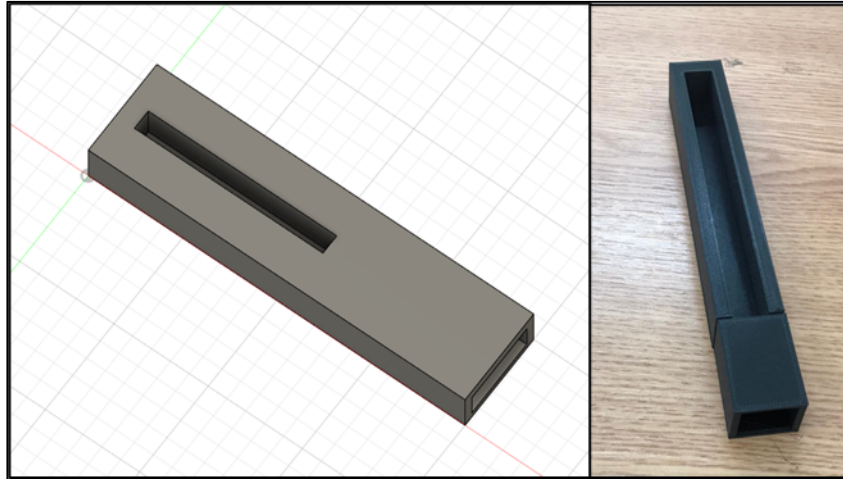


Figure 14: Design of Propellant tray improvement (left) and printed 3D part (right).

The design shown in Figure 14 shows a significant improvement in the combustion gases exhaust through the side opening, which was significantly increased in size. It was thought at that time that the increase inside opening would also facilitate the installation of the ignition system through the PIC hole because of the increased manoeuvrability available. Nevertheless, the set up was still not smooth and could slightly damage the edge of the PIC going through the hole because of its tight fit. To specifically target this limitation, the propellant tray was divided into two parts, the section with the tray where the propellant would be placed, and the ignition system housing. These parts were given a hook mechanism to fit together once the ignition system was securely in place.

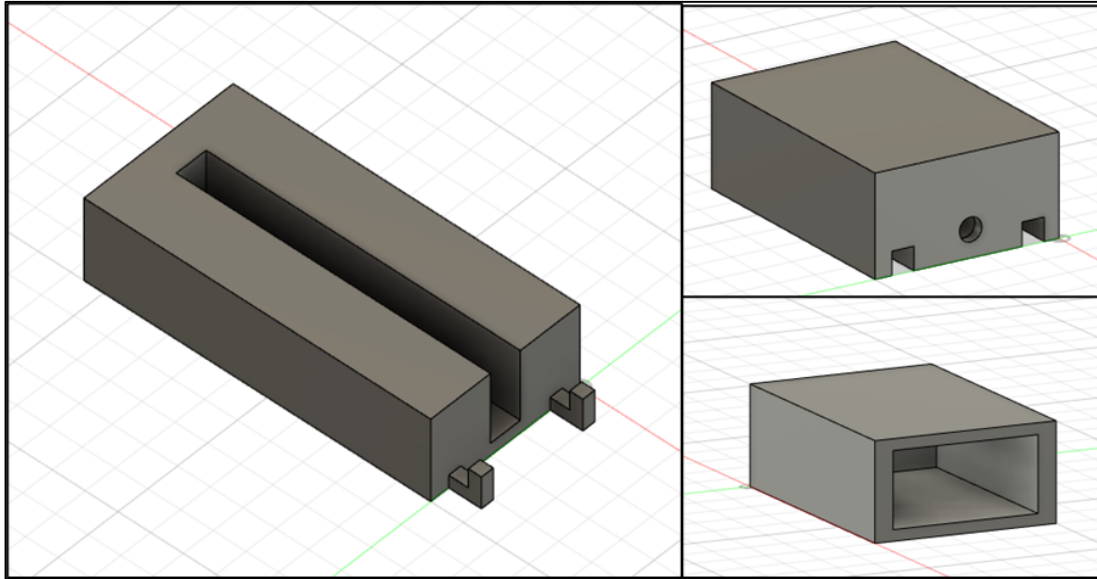


Figure 15: Drawing of separate parts.

By separating the propellant tray into two parts, the ignition system installation was easier, allowing the PIC to be safely connected without being slightly damaged in the process, raising the confidence that it would ignite the propellant sample inside the tray. The design can be seen in Figure 15, with the printed 3D propellant trays shown in Figure 16. Once the ignition system was installed in the smaller tray part, it would connect to the remaining propellant tray design part via the hooks.

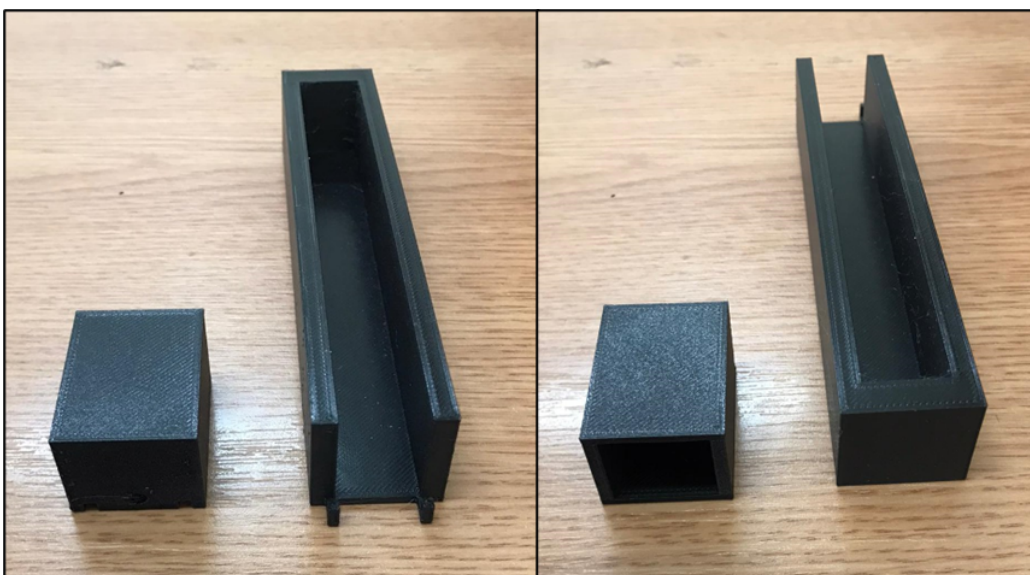


Figure 16: Propellant Trays Separate Parts

To extract more information from the combustion process, a break wire methodology was intended to measure the combustion flame progress. To accomplish this requirement, tiny circular holes were made perpendicular to the propellant sample capable of fitting wires. The variation in design is shown below in Figure 17.

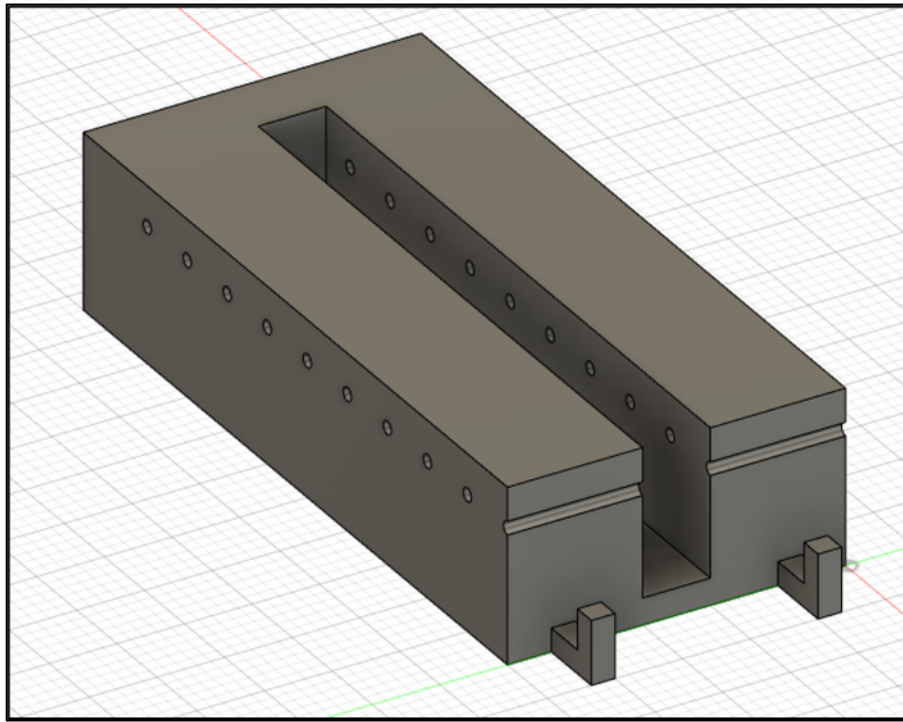


Figure 17: Propellant tray modification to install break wire technique.

The circular holes were placed at the top of the propellant tray because the combustion flame flows upwards, hence, the flame would need to pass through the break wire to break the circuit. The first break wire location was placed directly above the PIC to capture the initial combustion time.

When testing the above propellant tray design, it was identified that the combustion flame agglomerated together, instead of simply combusting above the entire tray. This effect led to some break wire connections to remain unbroken throughout the combustion process, hence, not correctly capturing the location and time the combustion flame had reached a specific checkpoint. The solution

relied on the location of the break wire holes, which were switched to the base of the propellant tray, near the first layer of propellant sample, shown in Figure 18.

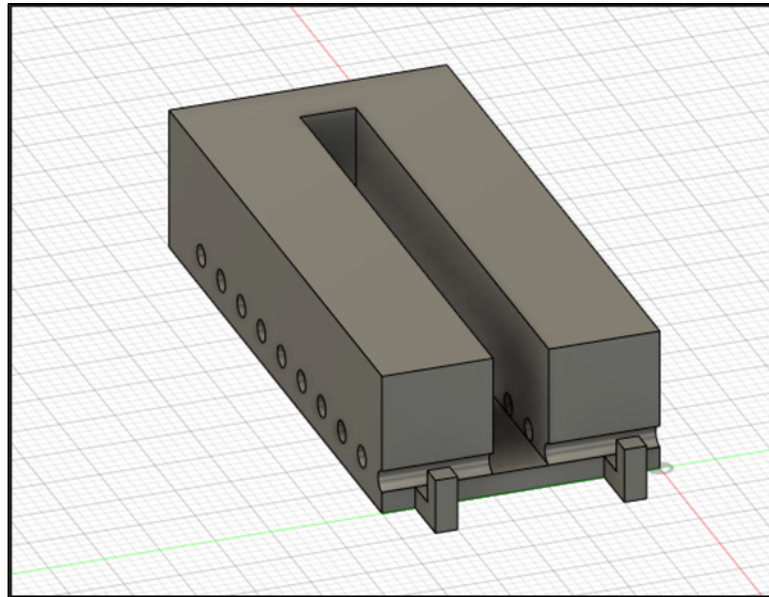


Figure 18: Break wire fitting holes move to base of the propellant tray.

3.7 Material Selection

The gun propellant selection required certain characteristics, including safe handling properties, consistent combustion process, smokeless properties, to name a few. A commercially available gun propellant would meet several requirements because of the fact that it can be sold to the public. The safe handling properties will naturally be a requirement imposed to the propellant manufacturer if the material intends to be sold to civilians. It has been established that gun propellants cannot perform as consistent combustion to solid propellants due to the presence of voids between the grains, however, if particle size varies slightly, the combustion should behave similarly when enclosed in the same location. Since the project had a limited time, propellants that were designed specifically for certain missions would require longer to be made, hence, some precious time could be lost. The decision of selecting Vihtavuori gun propellants followed the above critical thinking in identifying what material would best fit the desired and available tools.



Figure 19: Vihtavuori N120 Gun Propellant

The propellant series that start with the number 1 indicate they are single base propellant, and therefore mainly composed of Nitrocellulose (NC), while propellants starting with the number 5 are double-base propellants. The second part of the numbering system describes the relative particle size within the same series, where increments are in the form of multiples of 10. A propellant with a larger numbering system indicates it contains larger particle sized propellant particles. The chosen propellant classification for this project was the N120, therefore it was a single base propellant with a relatively small particle size, having only one propellant of the same chemical composition with smaller particle size, the N110 series. It is possible to visualise the propellant selected in Figure 19. This propellant was selected because of its vast availability at the time of purchase while having a low particle size and being of low energy content, compared to other gun propellants available within the Vihtavuori propellants. The propellant has a bulk density of 860 g/l, and an energy content of 3700 J/g.

3.8 Data Processing

This Section will focus on demonstrating how the collected data was processed for all relevant parameters in pressure, temperature, time, and luminosity. All instruments were calibrated to confirm the data obtained was representative of

the expected result, with the exception of the luminosity data where no previous data had been gathered. To confirm the technique was recording changes in the data, various propellant masses were tested, and the total luminosity was gathered as a guideline of how the luminosity was changed.

3.8.1 Pressure

The pressure transmitter selected for this instrument works through the use of a diaphragm, where any overpressure present inside the vessel will apply some force to the diaphragm. Any change in pressure were recorded by the oscilloscope in the form of voltage signals, which can be translated back to pressure traces. A connection was made between the ignition box and the oscilloscope to measure the time where combustion was active. Once the ignition box was activated, not only the ignition system would begin the combustion, but also the oscilloscope would receive a trigger signal, initiating the pressure measurement.

Below (Figure 20), a graph including the pressure trace obtained during the combustion of 1 gram of the Vihtavuori propellant was used to demonstrate the processing techniques used for the pressure data.

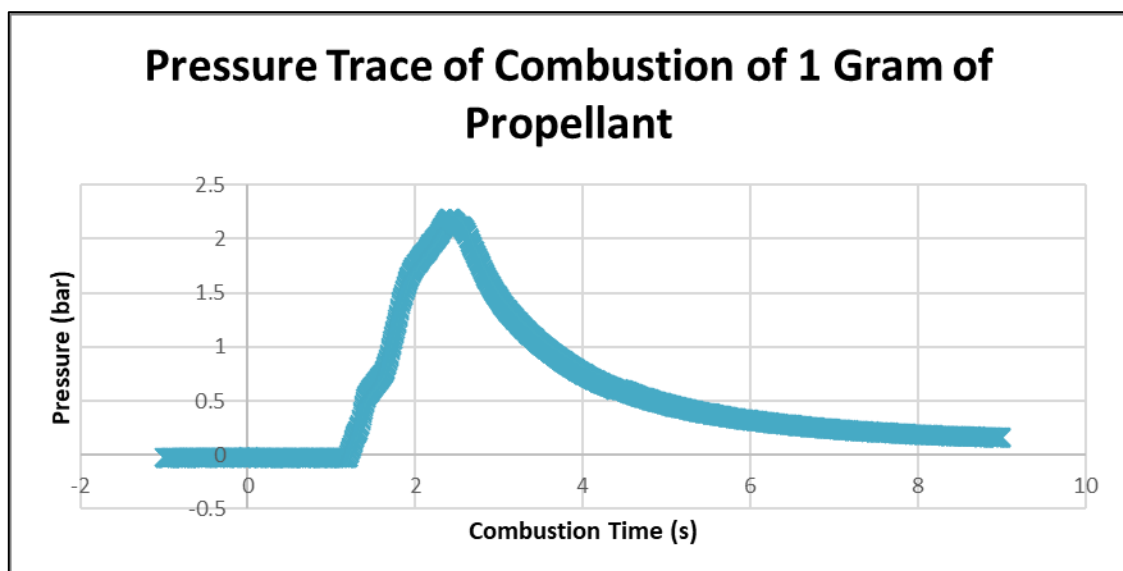


Figure 20: Pressure Trace of Combustion of 1 gram of propellant.

The propellant ignition releases product gases at high temperature, raising the pressure and temperature inside the vessel. The pressure could only keep rising while the propellant combustion occurs, and so will start to decay when the unburnt propellant has been depleted. Therefore, the combustion time can be estimated to the time when combustion begins, until the peak pressure achieved, signalling the end of combustion. In the example above, the pressure started rising after 1.20 seconds since the beginning of the pressure recording, and reached its peak pressure at 2.42 seconds, estimating the combustion process actually lasted 1.22 seconds.

The peak pressure observed can be assimilated to stress applied to the walls of the instrument, hence, the increase in pressure will intensify the force at which the pressure inside applies to the instrument. When combusting 1 gram of propellant inside the vessel with all the ports closed and the lid attached, the peak pressure observed was of 2.19 bar overpressure.

3.8.2 Temperature

The temperature sensor was installed through one of the side port plates, where 7 sensors were connected to the Pico logger to measure the temperature in various locations inside the propellant burner instrumentation.

The temperature sensors were placed at a fixed distance between each other, focusing on the same propellant tray section during the combustion. Due to the presence of the flame, the temperature sensors could not be placed directly above the propellant tray because the flame intensity might cause irreversible damage, and new sensors would need to be installed between every firing. Instead, channel 1 was placed a few centimetres away from the tray, and the remaining temperature sensors were a fixed distance of 2.4 cm away from each other.

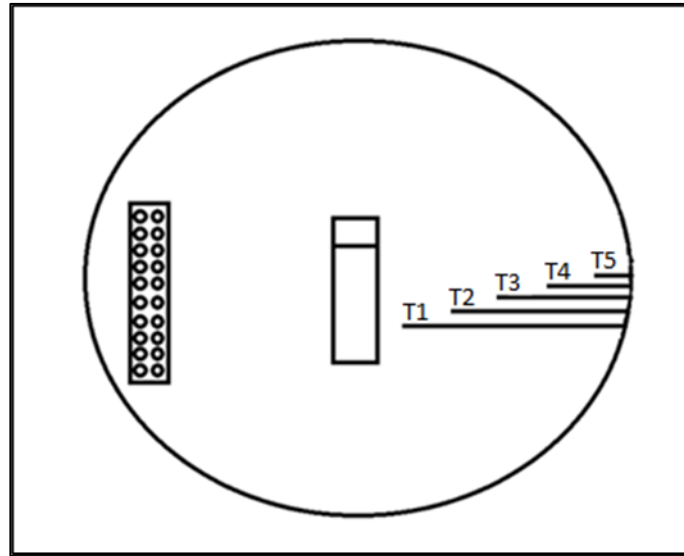


Figure 21: Representation of 5 Temperature Sensors Inside Burning Vessel.

Figure 21 represents how the 5 temperature sensors inside the instrument align with the propellant tray. There were 2 other temperature sensors present in the system, but these would be placed outside to measure the increase in temperature of the instrument vessel. The propellant tray sizes kept increasing with increase in propellant mass due to the fixed length-diameter ratio, so their location would be maintained at a fixed distance away from the closest temperature sensor to observe the temperature drop caused by the increase in distance from the active flame. The sample rate selected to collect data from the temperature sensors was the lowest available, at 100 milliseconds, to obtain the most data points as possible.

It is estimated that the temperatures observed closest to the combustion flame will provide the highest temperature peak at channel 1 with a diminishing effect as the distance between the flame and the temperature sensor increases from channels 2 through 5.

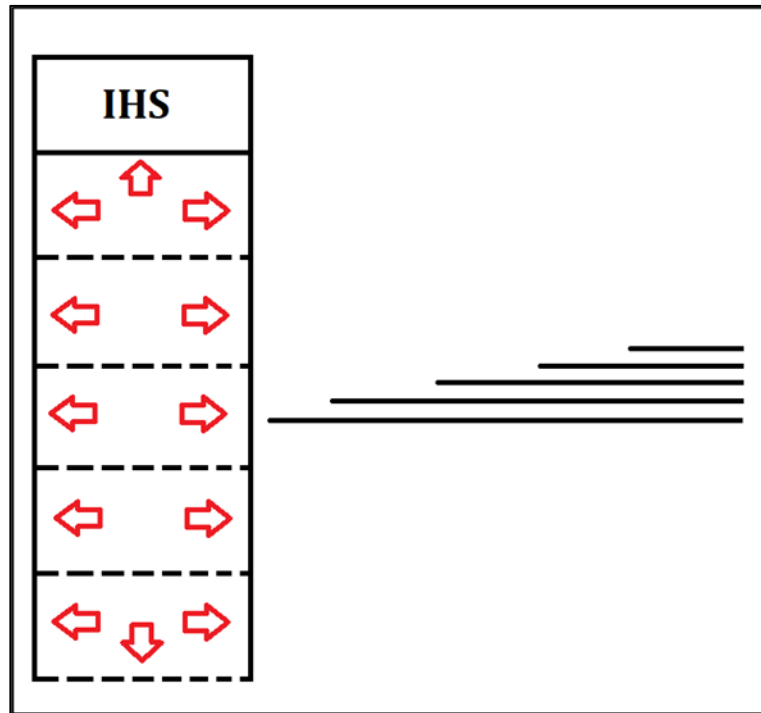


Figure 22: Temperature Dissipation diagram.

Figure 22, the ignition housing system (IHS) demonstrates the ignition system location and what direction the burn would take. If we consider the local combustion occurring in edges of the propellant tray, the heat generated from the reaction can disperse in the 3 directions available away from the centre of the combustion process, whereas from the inside section of the propellant tray have only got 2 available directions for the heat to dissipate to, hence the rate of cooling in this section should be smaller, and hence, their expected temperature is slightly higher.

3.8.3 Luminosity

Light generated by the combustion was captured by a planetary camera placed on top of the glass window at the instrument lid and was processed using imageJ. The luminosity data was provided in values between 0 and 255 since it uses an 8-bit setting, equivalent to 2 to the power of 8 available levels. In order to block the ambient light, a 3D printed part capable of holding the camera in a fixed location while guaranteeing that the only light observed through the camera lens was from the combustion, seen in Figure 23. The lower end of the luminosity data

indicate that low light was visible, while data reaching closer to 255 meant that there was too much light for that specific exposure time.

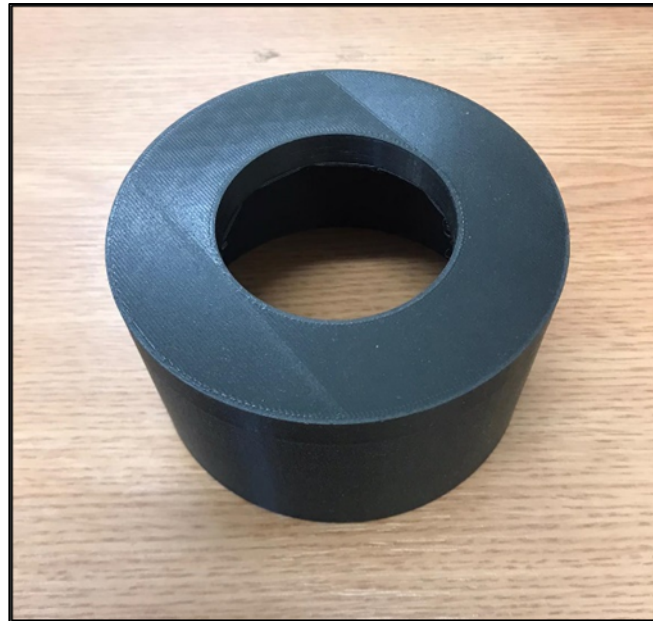


Figure 23: Camera Holder capable of blocking out outdoor light contribution.

This luminosity observed increases as the mass of propellant increases, and rather quickly would reach the saturation of several frames, thus limiting the information gathered for higher combustion masses. To prevent any data saturation, the exposure time would need to be changed with increasing propellant mass. This saturation would require a normalisation technique, where it would account for all the changes in exposure time to be able to compare luminosity data in the same experimental plane. To normalise the data, the average peak luminosity would be divided by the exposure time set for that specific propellant mass.

$$\text{Normalised Luminosity} = \frac{\text{Average Peak Luminosity}}{\text{Exposure Rate}}$$

Equation 2: Normalised Luminosity Calculation.



Figure 24: AstroSolar Film Layer

Despite being capable of capturing the data at low exposure times with low masses, any further increase in propellant mass would require an even further decrease in exposure time, however, the camera was already working at one its lowest capable exposure times. Therefore, it was decided to include an AstroSolar photo film to decrease the overall light absorbed by the camera. The addition of the AstroSolar film allowed for slightly higher exposure times to be used, guaranteeing that data for all desired propellant masses would be collected. The AstroSolar photo film shown in Figure 24 comprised of an optical density of 3.8, a log-scale factor related to the multiplier of photons absorbed by the photo film. With a known multiplier, it can be possible to calculate the exact number of photons absorbed by the camera. The luminosity generated would only be visible when the combustion was active, therefore, it would be possible to have another approximation of the combustion time, based on the period where luminosity was visible. Figure 25 shows an example of combusting 1 gram of propellant with an exposure time of 10 ms.

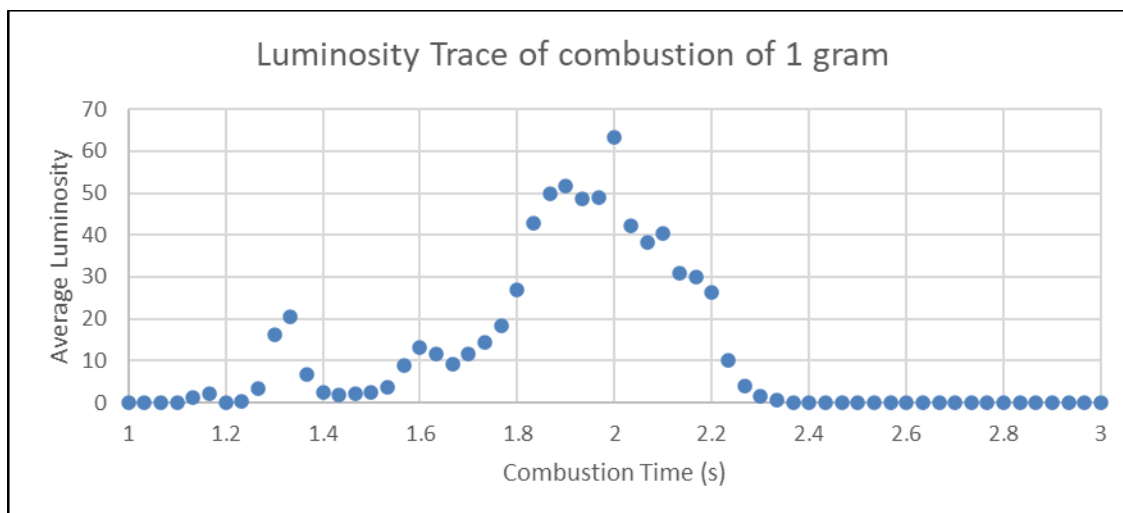


Figure 25: Luminosity Data collected during combustion of 1 gram of propellant.

The luminosity trace seen in Figure 25 was obtained during the combustion of 1 gram of propellant. A smaller peak can be observed at close to 1.3 s after the combustion started, followed by a larger transmittance. From the recorded video, it can be understood that the initial bright flash is a result of the ignition system. Once the firing key is activated, the electric matchhead receives a jolt of voltage which ignites the PIC, which burns and produces a small quantity of light, since it is surrounded by the ignition system. It was noted that for smaller masses, of up to 5 grams, the ignition system produces a significant flash to be observed during the luminosity trace, however, as we use higher quantities of propellant, the exposure time set at the camera was low enough for the light generated by the ignition system to become indistinguishable from the ambient light.

The peak luminosity data can be comparable to the peak pressure data obtained as they represent the section during combustion with the highest propellant consumption rate, which causes the highest pressure data as well as producing the brightest light. These peak conditions are useful to describe the highest stress being applied to the instrument.

3.8.4 Area under the curve & Combustion time

The area under the curve (AUC) parameter was the second metric used to trace the luminosity data, however, during the entire combustion process, thus considering the total combustion time.

The total area under the curve was measured throughout the firings to study its consistency between firings. It is hypothesised that the total AUC would present similar values for combustion of the same mass of energetic substance. The working theory is that the total energy stored within the propellant was fixed, hence, the pressure and temperature reached after all the material combusted should have similar magnitudes, therefore the speed of reaction, or burn rate, would be within a certain range from each other, and thus the total light generated should be consistent. The AUC can be calculated by measuring the total luminosity observed during a combustion, by summing the luminosity observed for each frame.

$$AUC = \int_{Frame(0)}^{Frame(n)} \frac{Luminosity(n) - Luminosity(n - 1)}{Time(n) - Time(n - 1)}$$

Equation 3: Area Under the Curve.

There is, however, one factor that needs to be taken into consideration during the combustion of gun propellants. Since there is void space between propellant particles, the flame produced when one particle is ignited can travel a random distance away, igniting an unknown number of particles ahead. This could cause the burn rate to have a large variance, as in the fastest scenario, the flame keeps moving forward, igniting a higher quantity of propellant particles, thus causing the combustion to complete in less time.

Similar to the maximum luminosity data, normalisation is required to be able to compare the results.

$$normalised\ AUC = \frac{AUC}{Exposure\ Time}$$

Equation 4: Normalised Area Under the Curve.

If the time of combustion is taken into consideration, then we could calculate the total intensity “of the light observed throughout the entire combustion process.

$$Intensity = \frac{\text{normalised AUC}}{\text{combustion time}}$$

Equation 5: Intensity.

But how exactly do we decide what the combustion time is based on the luminosity? Alternative methods had to be identified to measure the combustion time to replace the break wire methodology, which resulted in inconsistent ignition of wires at randomised times due to the nature of the gun propellant combustion.

There are a few possible methods including the combustion flame luminosity, such as the total time needed for the luminosity to return to its minimal value, the time taken to reach the maximum luminosity observed, or perhaps the time where the luminosity was above a certain arbitrary value.

The first and second methods can immediately be ruled out because the total time needed for luminosity to return to its lowest value includes time for the ignition system to burn and then ignite the propellant. It must also be addressed that time zero on the luminosity curve data does not translate to time zero when the firing mechanism is initiated. The camera recording is set to record a specified time, and is initiated before firing the experiment, to make sure that the entire combustion process is recorded.

The last method has an interesting approach, where a certain arbitrary value is selected and used to separate what kind of luminosity is accepted as combustion. Although it seems like this method can easily be used to manipulate the data collected to make it seem more feasible, this will not be possible as the arbitrary value will be selected only once, for the first experiment. The arbitrary value would also be scaled with the exposure time, to make sure that the same luminosity defined as combustion would be consistent with all propellant loading densities tested. The arbitrary value used for 2 grams of propellant would be calculated using Equation 6:

$$\frac{\text{Arbitrary Value (2 grams)}}{\text{Exposure Rate (2 grams)}} = \frac{\text{Arbitrary Value (1 gram)}}{\text{Exposure Rate (1 Gram)}}$$

$$\begin{aligned} &\text{Arbitrary value (2 grams)} \\ &= \frac{\text{Exposure Rate (2 grams)} * \text{Arbitrary Value (1 gram)}}{\text{exposure rate (1 gram)}} \end{aligned}$$

Equation 6: Arbitrary Value Calculation.

Since the luminosity data will be available in the range of 0 all the way to 255, where 0 represent the lack of any light, while 255 is recorded when too much light is available. The arbitrary value selected would need to be close to 0 because the luminosity will only be observed when combustion is present. The data collected from firing 1 gram of propellant was useful to decide that the arbitrary value would start at 10 to account for the light generated at the ignition system.

By taking Figure 25 as an example, the luminosity first reaches the arbitrary value of 10 at a time of 1.3 s, however, after observing the recorded combustion, this initial luminosity curve is associated with the ignition system, which should not be included in the combustion time. Therefore, the recorded combustion should be used to determine the starting point for each firing. Below are the screenshots taken of individual frames during the ignition system in Figure 26, which is followed by a few frames where no light is observed, where then the combustion is first observed in Figure 27.



Figure 26: Ignition System Flashing Before Propellant combustion

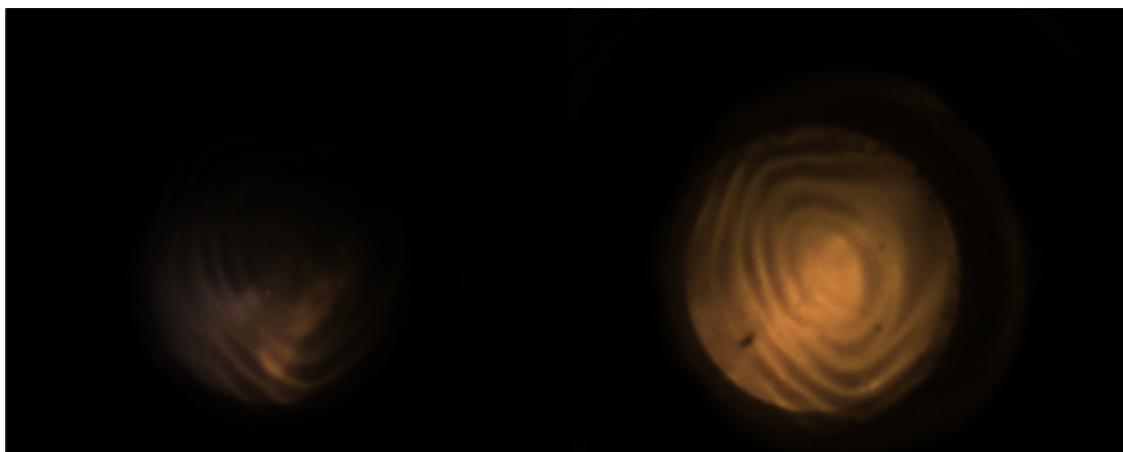


Figure 27: Combustion observed from recording

Figure 28 contains the same luminosity data seen in Figure 27 with the addition of a red line to exemplify the concept of the arbitrary value, which stands as the threshold of luminosity required to consider that combustion was underway. As long as the luminosity was maintained above 10, the combustion was assumed to be active. Once the luminosity data dropped below 10, it would indicate that there would be no more flame present, and hence, no more reaction occurring, therefore marking the end of the combustion time.

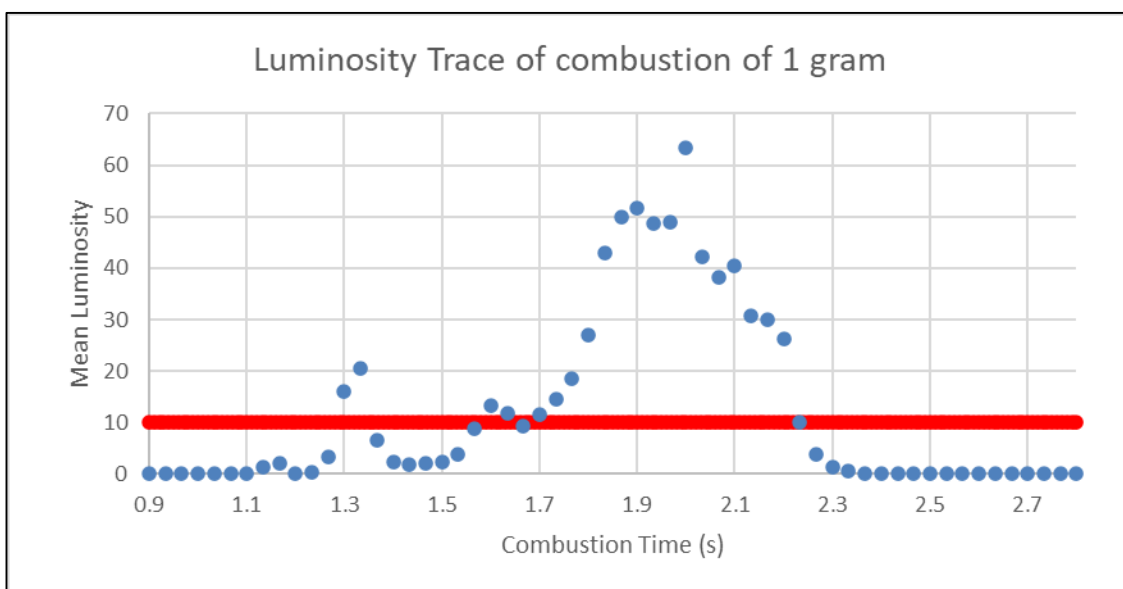


Figure 28: Luminosity data demonstrating the arbitrary value analysis.

In this firing, the combustion was believed to have started 1.6 s after starting the recording and finished after 2.23 seconds, accounting for a total of 0.63 s of combustion reaction, the equivalent of 20 active frames.

3.8.5 Mass Consumption Rate

Vieille's law describes important parameters affecting the linear burn rate of combustion, which can be used efficiently to describe solid propellants. Gun propellants on the other hand, do not combust in a linear fashion, therefore, a larger variance must be accepted for burn rate data describing gun propellant combustion.

Information of the burn rate data of specific propellants can be used to calculate parameters related to the maximum conditions to be achieved. By knowing the active burn area and the burn rate, a volumetric burn rate can be calculated by Equation 7:

$$\text{Burn Rate} * \text{Burning Area} = \text{Volumetric Burn Rate}$$

Equation 7: Burn Rate.

The volumetric burn rate with units of volume per unit time describes the volume of propellant being combusted. When combined with the propellant density, the total mass consumption rate can be calculated.

$$\text{Volumetric burn Rate} * \text{Density} = \text{Mass consumption Rate}$$

Equation 8: Volumetric Burn Rate.

By knowing the chemical reactions taking place and being able to accurately predict the number of gases produced per mole will provide information on the gas generation rate.

$$\text{Mass consumption rate} * \text{Molar ratio} = \text{Gas generation rate}$$

Equation 9: Mass Consumption Rate.

Also, information on the energy release during reaction will allow the estimation of the heat released into the environment.

$$\text{Mass consumption rate} * \text{Heat released (per gram)} = \text{Heat released (total)}$$

Equation 10: Heat Released.

Equations 9 and 10 calculate the total volume of gases being generated per unit time and the heat released, respectively. Both parameters can be compared to the recorded pressure and temperatures to measure the amount of heat being lost to the environment.

For gun propellants, however, the voids between the propellant particles allow the flame to travel an unknown distance, igniting more particles simultaneously, which in turn accelerates the quantity of material burning. This increase in active burning particles does not follow a linear pattern, hence, the term linear burn rate does not appropriately describe the rate at which gun propellant deflagrates. A more appropriate description would be the mass consumption rate, aiming to track the quantity of mass that was ignited at any given time.

A few methods were used to best describe the mass consumption rate, including the utilization of solder and the measurement of luminosity during the combustion. By measuring the total AUC data within an experiment, it was assumed that the luminosity data measured was equivalent to the total initial mass of propellant consumed. This assumption originated from the understanding that light would only be generated during combustion; once the combustion process was complete, no more light would be captured, hence, no more mass of propellant was consumed. If accurate, it would bypass the need to identify the traditional linear burn rate of gun propellants.

This method will utilise the normalised AUC, because all values are present within the same spectrum as the different exposure times used were accounted for during the normalisation process. By using the data collected for 1 gram as an example, Table 1 contains the normalised AUC data collected.

Test	Normalised AUC
1	489
2	605
3	480
4	612
5	967

Table 1: Luminosity Data collected for 1 gram.

The first test generated a total of 489 of normalised AUC summed by the average luminosity measured throughout the combustion time. The assumption above estimates that once half of the luminosity during each test was observed, it would indicate that half of the mass of propellant has already ignited. The parameter used to track the propellant consumption measured in grams was calculated by dividing the normalised AUC by the total normalised AUC value during the active combustion.

$$\text{Propellant consumption (\%)} = \frac{\text{Normalised AUC (frame)}}{\text{Normalised AUC (Active combustion)}}$$

Equation 11: Propellant Consumption.

From the luminosity data collected, the previous frame where the average luminosity is above the arbitrary value marks the starting point, where the normalised AUC value starts at 0. The first frame where the summed normalised AUC value reaches the next mass consumption increment will be used as the time. Once all the time frame points have been identified for all increments, the mass consumption rate will be calculated for each repetition for all masses. Data on two mass consumption rates can be retrieved, one measuring the mass consumption rate observed between each frame, the segmented mass

consumption rate, and one accounting for the overall mass consumption rate since the first active frame.

The segmented mass consumption rate was developed to track the propellant mass consumption rate throughout the entire combustion process, by calculating the mass consumed between each active frame during combustion.

$$\begin{aligned} & \text{Segmented mass consumption rate } \left(\frac{g}{s}\right) \\ &= \frac{\text{Propellant combustion (frame } X) - \text{Propellant combustion (frame } X - 1)}{\text{Combustion time (frame } X) - \text{combustion time (frame } X - 1)} \end{aligned}$$

Equation 12: Segmented Mass Consumption Rate.

The overall mass consumption rate would account for the total mass consumed only.

$$\text{Overall Mass consumption Rate} = \frac{\text{Total mass consumed}}{\text{Total combustion time}}$$

Equation 13: Overall Mass Consumption Rate.

In Figure 28, the total AUC luminosity during combustion was 14,668, which when divided by the exposure time of 30 ms, we obtain the normalised AUC total of 489. As previously mentioned, the combustion time defined for this test run was 0.63 s, which equates to 21 frames by accounting for the 30 frames per second achieved by the camera.

It must be noted that one assumption made so far was that the combustion would only be considered to have started after an arbitrary average luminosity value was reached. If the entire luminosity data set was observed for this experiment, there were some frames that did not reach the arbitrary value selected, however, showed an average luminosity higher than 0, hence, combustion could have had already started. It was not easy to separate the luminosity generated by the ignition system, hence, for lower masses, it might produce more uncertainty. As the experiments incorporate higher propellant masses, the ignition system produced less luminosity due to the decrease in exposure time, hence, it became easier to distinguish the source of light.

3.9 Experimental Plan

The burning vessel was designed to work in multiple modes of operation, where the ports and side plates were attached as an objective to modify the overall system. This would be done to investigate the possible effects on the relevant parameters by using the established techniques and methodologies.

3.9.1 Closed Vessel Series (CV)

The first mode of operation studied was the closed vessel mode, where all the ports and side plates that were not being utilised by instrumentation were blocked to prevent any combustion product gases from escaping the vessel. The instrument lid was attached once the propellant was secured in place and connected to a terminal block. Lastly, the ventilation valve was closed during the combustion, and only opened once the combustion was deemed complete and all parameter data were collected. Figure 29 shows the vessel with all side ports blocked to conduct closed vessel testing.



Figure 29: Final Instrument Set Up

The closed vessel mode of operation was the ideal experimental series to investigate the luminosity technique designed, since it ensures that the combustion products and combustion flame are trapped inside the instrument

and would allow the recording of the entire combustion process. It was important to record the luminosity data when all the combustion was accounted in a single location to measure the total amount of light generated for all propellant masses investigated.

Data gathered from this experimental series focused on describing the worst-case scenario when combusting a propellant, since the hot gases generated during the combustion were trapped inside the vessel, and so increasing the pressure and temperature. The pressure recorded inside the instrument was assimilated to the stress being exerted on the walls of the vessel. Despite standard warehouse storage facilities never achieving pressures beyond a few bars, the decision to investigate extreme pressure scenarios was focused on investigating if a correlation between luminosity and pressure could be observed for a large range of operating pressures.

3.9.2 Vented Vessel Series (VV)

The ventilation valve present during the closed vessel series had a different role during the closed vessel mode of operation, a focus towards safely releasing the trapped gases inside the vessel once the combustion was concluded. However, by purposely opening the ventilation valve while the combustion occurs, combustion products including the hot gases and combustion flame are free to flow outside the instrument. Data obtained during the closed vessel series work as a benchmark of the maximum stress achievable during combustion, while the addition of vents of various sizes allows investigation of the effect of vent diameter on all measurable parameters. Several works have shown the reduction in pressure inside instrument by the addition of a ventilation method, including the previously discussed work of Parate [40], while this Section focuses on the effect of luminosity data reduction due to gaseous and flame reduction. Figure 30 demonstrates the vented vessel set up, which differs ever so slightly from the closed vessel setup, where the difference observed comes from the lack of a blanking plug on one of the larger ports, allowing the hot gases to escape the burning vessel.

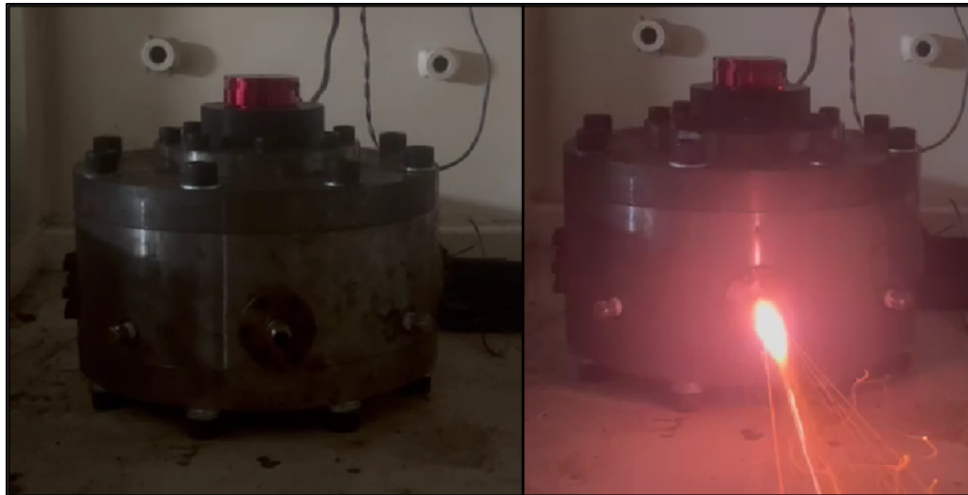


Figure 30: Vented Vessel Setup (Left), set up during firing (Right)

To investigate the ventilation effect thoroughly, two vent valves were tested, one of 0.1 cm in diameter, which connected the pressure port to a pipe transporting the gases outside the building safely out of the laboratory, and a 1.0 cm diameter valve attached to one unused side plate.

3.9.3 Supporting Experimental Series

The novelty aspect of the luminosity data being used to investigate combustion contains several uncertainties and questions, some of which can be investigated to provide valuable additional information.

Variable Exposure Time

The exposure time selected for each experiment had an important influence in the length of time that the camera aperture was opened to record the luminosity during combustion. To quantify the impact the exposure time had on the total luminosity collected, a single propellant mass was selected to be combusted inside the propellant burner instrument at 3 different exposure times.

Bulk and Separate

Combustion of a fixed loading density was studied when separate in several equal piles of propellant or put together as a single bulk inside one propellant

tray. This idea was designed to provide critical information describing that, if possible, to separate total propellant mass being combusted into smaller piles, the overall performance parameters would diminish.

Safety Distance

While the pressure and temperature influence the overall stress, it is the flame that combusts the unignited propellant particles. Investigating the minimum safety distance to prevent the flame from igniting other propellant trays would increase the confidence when storing energetic materials. The lower the propellant mass combusted, the smaller the flame will be, hence, splitting the total propellant mass in several trays or parts will diminish the overall stress to the instrument walls if a delay can be achieved between separate tray combustion times.

Separate Trays & Large Vent

On separate occasions, both methodologies fundamentally decrease the stress accumulated by diminishing the pressure and temperature peaks during combustion. The separate trays can lower the MCR, hence, a lower gas generation rate is observed, while the large vent allows the gases to vent outside if left opened during combustion. By combining both these mitigation strategies, it might be possible to reduce the pressure and luminosity even further, deeming an even safer storage condition.

Open Vessel

To test whether the luminosity was constant during combustion, a short series was conducted while having no lid and no top plate attached, a new mode of operation. The open vessel series will investigate the total luminosity generated without the interference of a lid, which could have prevented some luminosity from being captured by the camera because of the blind pots. The removal of a lid causes the sunlight to interfere in the overall luminosity measured, however, it was possible to identify how much luminosity was generated by the combustion alone by subtracting the final luminosity from the luminosity immediately before

the combustion had begun. Since the combustion process would last a maximum of 20 s, there was only a small window of opportunity to observe large luminosity variation caused by the environment. An image demonstrating the open vessel testing methodology is represented in Figure 31.



Figure 31: Open Vessel Setup

4 Results and Discussion

4.1 Closed Vessel Series

In order for the series to qualify as a closed vessel series, all unused ports and connections were blocked. Leaks would easily be detected as there should be no release of gases until the ventilation valve is opened once all the data has been collected. The lid with a glass window would be utilised to allow the recording of each firing. An AstroSolar film was attached to the camera to prevent any light saturation during the combustion process as described in Chapter 3, subsection 3.6.3. The tray used to hold the propellant would be placed underneath the glass window to guarantee that most of the light produced would be collected by the recording. The data to be collected from each firing includes the luminosity, pressure, and temperature.

4.1.1 Pressure

Pressure represents the force being applied to a specified area:

$$Pressure = \frac{Force}{Area}$$

Equation 14: Pressure Calculation.

Retracing back to the ideal gas law:

$$P * V = n * R * T$$

In this equation, “P”, “V”, “n”, “R”, and “T” represent pressure, volume, number of moles, universal gas constant, and temperature, respectively.

Equation 15: Ideal Gas Law.

The pressure exerted by a gas depends on 3 of these factors, namely the volume, number of moles, and temperature. This relationship can be seen within the context of the propellant burner instrumentation, where the volume available inside the vessel is fixed and known, the number of moles can be calculated by information on total propellant loading density present during an experiment and the chemical reactions associated with the propellant combustion mechanisms,

and lastly, the temperature can be measured. Hence, the pressure could be predicted if the ideal gas law was known to work for all gases and situations, sadly, it does not work accurately for all gases or situations since no truly ideal gas exist.

It is understood that as soon as the ignition system initiates the first propellant layer, combustion begins, where gases at high temperatures will be generated from the chemical reaction. These gases will spread around the vessel as much as possible, while the temperature will be continuously distributed to cooler bodies, whether it be the air present before the combustion started at ambient conditions, or the instrument body, or even the propellant particles yet to be combusted. The combustion will continue generating gases and heat until all the propellant has been combusted.

It must be noted that during combustion, the temperature inside the vessel will be pushed into the two directions: the zeroth law of thermodynamics will cause the high temperature from the gases being generated to equilibrate with lowered temperature bodies inside the vessel, whereas the continuous combustion and generation of hot gases will keep pumping heat into the system, further heating the temperature inside the vessel.

Temperature has an important role in the pressure measurements as noted by Vieille's law, but also due to the effects of heat expansion. Thermal expansion is a term used to explain that materials at higher temperatures will have larger volumes than the same quantity of the same material at lower temperature [20]. It is a small difference per degree Celsius, however, when propellant combustion generates gases at 2000 Celsius or higher, then the heat expansion has a much larger impact. Therefore, when measuring the pressure inside the vessel, it is important to also be aware of the temperature of the gases to understand the relationship between them.

Pressure Data

During the combustion experiments conducted with 1 gram of N120 Vihtavuori propellant, several parameters were measured, including the pressure behaviour

during the entire combustion process. For each mass of propellant selected, 5 repetitions were carried out to increase confidence in the data collected. A total of 14 masses tested, where masses 1 through 10 were all tested, followed by 5 grams increases until 30 grams of propellant was reached. The data was plotted to observe the pressure inside the burning vessel compared to the time of combustion.

The first pressure data set provided below includes the relationships obtained during the combustion of 1 gram of propellant to illustrate how the data was processed and discuss the important points to be observed from the plot.

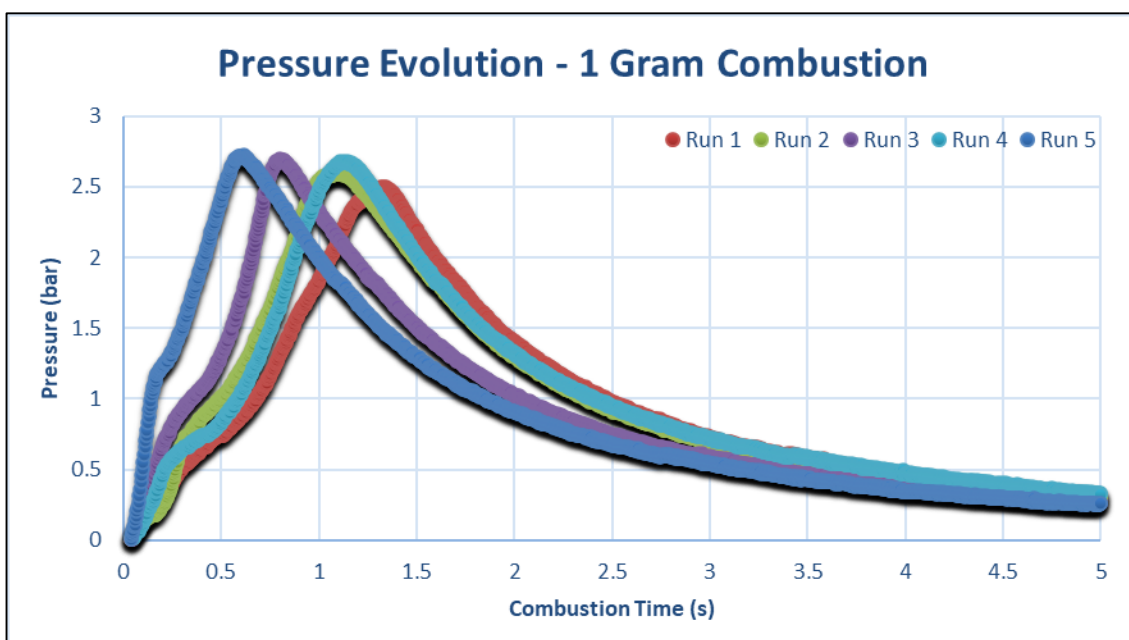


Figure 32: Pressure data evolution during combustion of 1 gram of propellant under closed vessel mode.

From Figure 32, it can be observed that all 5 pressure traces produce a similar behaviour, where a sharp rise is observed until a peak pressure was reached, followed by a smoother reduction over a few seconds. There are two factors raising the pressure inside the vessel, whereas there is only one attempting to negate the pressure rise. During combustion, a large number of moles of combustion product gases are released. For energetic materials, the chemical reaction states that one mole of substrate normally generate several moles of product gases [67], drastically raising the pressure inside the burning vessel.

Also, combustion is a highly exothermic reaction, resulting in the release of a large amounts of energy, which as discussed before, has an effect on expansion of materials, especially in gases. Therefore, the large increase in gaseous products and temperature drive the pressure inside the vessel to rise for as long as the combustion occurs.

The zeroth law of thermodynamics is the only factor present during the closed vessel mode operations to diminish the pressure inside the vessel while the ventilation valve remains close, by causing the high temperature of the gases present to heat up the surrounding cooler air, which was present before the combustion began, and the instrument itself. It must be remembered that the temperature travelling through the instrument will move slowly from the inner section to the outer section because conduction is the slowest heat transfer process, therefore, this process will take considerably longer than it did to heat up.

The combustion of N120 Vihtavuori propellant produces a fast reaction, which facilitates the rapid rise in pressure as the combustion process occurs quickly, releasing a high quantity of gases and energy, while also providing less time to allow the temperature dissipation to reduce the temperature inside. Slower burning propellants would allow more time for the temperature to be released, thus, reducing the peak pressure achieved if all other parameters remained constant.

Time zero on the plot indicates the moment the operator turned the ignition box key on, to initiate the ignition system, which ignited the propellant, hence, the time taken to reach the peak pressure from the beginning of the reaction can be assumed as the combustion time. Although it has produced a large variation, where the peak pressure was observed after 0.614 s after ignition for experiment 5, it took 1.34 s to reach the same condition during the combustion of experiment 1. It shows some inconsistency with the time taken to burn all propellant, however, it must be remembered that this time includes the time required for the ignition system to complete, where the plastic igniter cord would produce a small flame during combustion, which would ignite the propellant. Several processes

were made to limit the variability between each repetition, however, there could have been certain limitations.

A positive result seen from the plot was that the peak pressures observed during the combustion were similar to each other, despite the larger disparity in combustion time observed. The pressure peaks varied between 2.5 and 2.72 bar of overpressure. This trend shows that the rate at which the temperature decreases by means of temperature dissipation has a slow effect for 1 gram, because lower temperatures and pressures were reached. Although it was expected that the peak pressures had similar values, it still indicates that it is possible to predict the pressure peak, and its behaviour to some extent, if the experiment has been done before.

Since the peak pressure data produced consistent data throughout the repetitions of the same masses, the average value of each mass was collected to produce an overall plot for all masses tested, which is shown below.

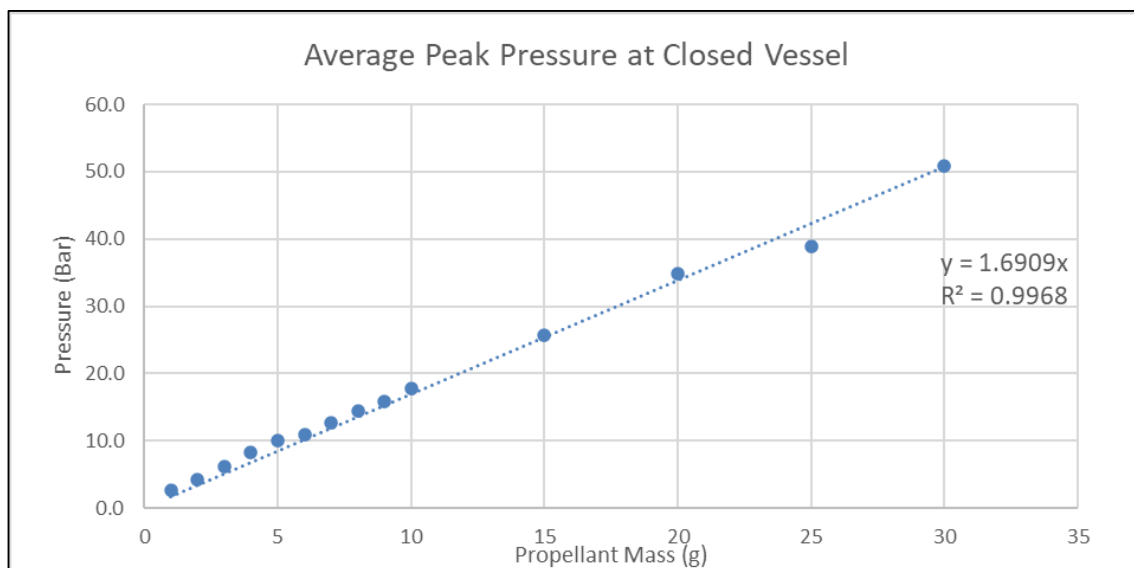


Figure 33: Average Peak Pressure measured during closed vessel combustions.

A linear relationship clearly describes the peak pressure rise with an increase in propellant loading density combusted. Despite experiments where the combustion of 25 grams demonstrates the highest variation from the overall relationship, the change was not far enough to lose its high accuracy.

This variation could be attributed to increase in tray density, where the flame had to travel further to increase all propellant sample. However, if that was consistently the case, the 30-gram firing experiments wouldn't align with the relationship in figure 33.

The plot calculates a relationship confidence of 99.68% (R^2), or the data collected for these masses, which only represent small scale experiments. The relationship confidence is a statistical measure that indicates how much the independent variables explain the variation of the dependent variable, where values closer to 1 represent a perfect fit and values closer to 0 demonstrate no confidence in the relationship.

4.1.2 Temperature

The temperature data collected would contain the 7 curves, one for each temperature sensor. Not all sensors were placed inside the burning vessel, where 2 of the 7 sensors were attached to the burning vessel metalwork to detect changes in the temperature resulted from the conduction. Figure 34 demonstrates how the temperature sensors were installed relative to the propellant tray.

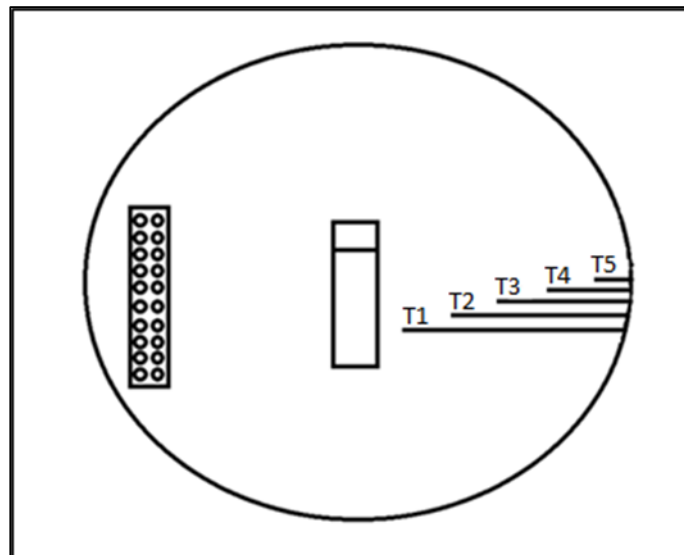


Figure 34: Representation of 5 Temperature Sensors Inside Burning Vessel.

The closest temperature sensor is represented by channel 1, while the furthest temperature sensor inside the burning vessel is marked by channel 5. During the combustion process, it is expected that the temperature shows higher values in the earlier channels due to them being placed closer to the combustion flame.

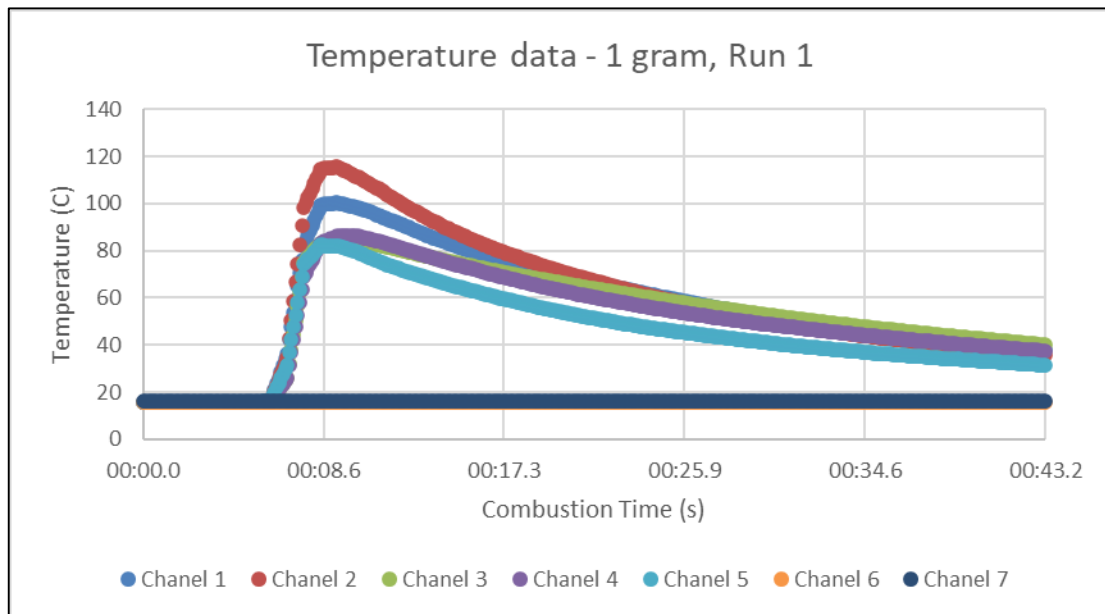


Figure 35: Temperature data collected during the firing of 1 gram of propellant, run 1.

Figure 35 above describes the temperature behaviour throughout and after the firing. The firing effects on temperature are seen from the sudden rise from stable temperature, until a peak temperature has been achieved, followed by a slow reduction caused by conduction through the vessel walls. Curiously, channel 2 observed a higher temperature peak than channel 1, despite being slightly further away from the combustion flame. The remaining temperature peaks decreased in a more predictable pattern, with channel 5 being the lowest value obtained from the temperature sensors placed inside the burning vessel.

It can be seen that there seems to be a large uncertainty within the readings of the same distance to the flame. The temperature recorded in channel 1 varied between 100.3° and 186.3°C, which indicates a large variation between firings. As the distance from the temperature sensors increases from the propellant tray,

the data variability diminishes, as can be seen to be much smaller in channels 4 and 5.

	Temperature (°C)		
Channel	Average	Maximum	Minimum
1	156.4	186.3	100.3
2	158.9	194.8	115.7
3	117.8	159.0	84.6
4	88.9	100.6	79.9
5	80.7	83.4	75.3
6	16.8	17.6	16.0
7	17.3	18.1	16.4

Table 2: Temperature Peaks during 1-gram firings at closed vessel mode

Figure 36 contains the average temperature peaks measured for the combustion of up to 10 grams of propellant. Despite the chaotic quantity of symbols present, the trend observed for all loading density appears constant, where the highest temperature peak is observed in channel 1, and the lowest in channel 5. No data was recorded from channel 4, although it seemed to be working at the time, however, it was later discovered that the sensor was not reading correctly as the data did not make sense. Unfortunately, data from 8 grams onwards from channel 4 had to be removed.

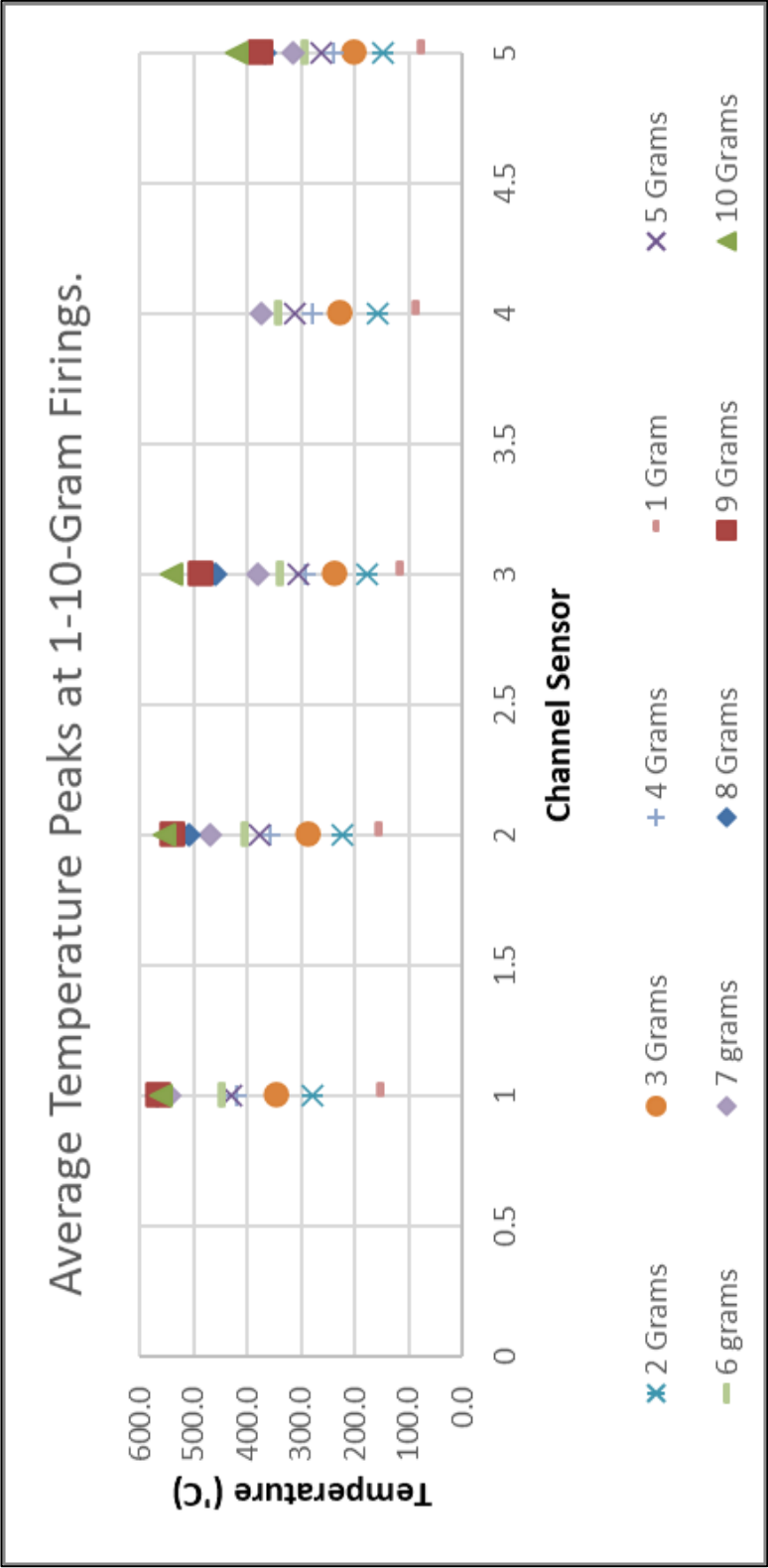


Figure 36: Average Peak Temperatures for masses 1–10-gram data

It was seen that for 1 gram combustion, the temperature data collected showed that channel 2 had a higher average temperature peak than channel 1, which was not expected. This pattern seemed to have been an anomaly, since for the other 9 propellant masses shown in Figure 36, channel 1 produced the highest average temperature peaks, followed by channel 2 throughout 5 in a descending order.

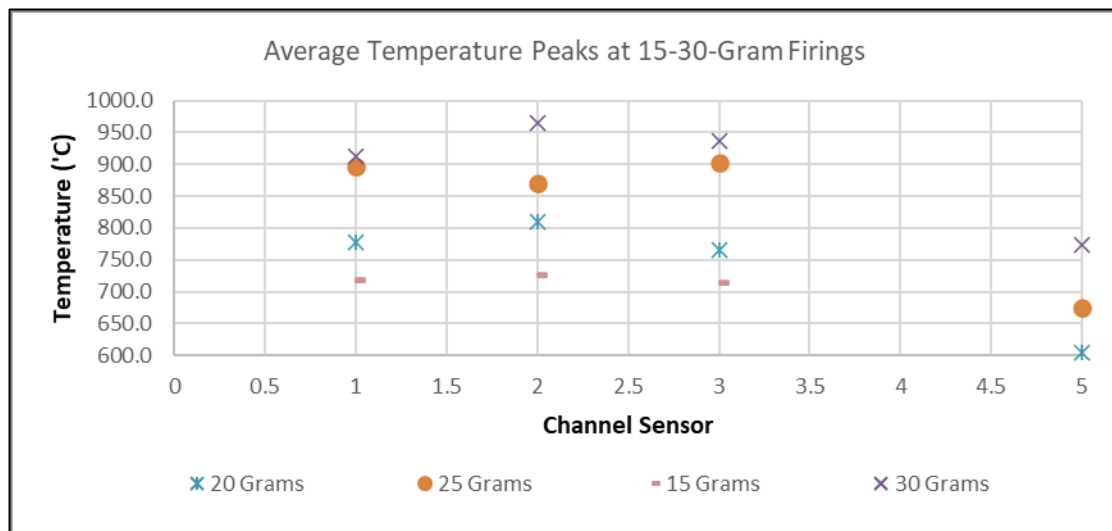


Figure 37: Average Peak Temperatures for masses 15–30-gram data.

When further increase in the propellant masses being combusted, a slightly different pattern was observed. Figure 37 shows that similar to the 1-gram experiment, the average peak temperature measured in channel 1 was not the highest for any of the loading densities tested. Channel 2 had the highest temperatures in these remaining 4 propellant masses tested, except for experiments conducted at 25 grams, where channel 3 measured the highest temperatures. It is believed that the flame generation eventually overwhelms the size of the vessel, hence the flame surrounds the entire vessel, heating up all channel sensors simultaneously, and potentially observing higher temperatures further away from the centre of the vessel where the experiments were being carried out.

It can be argued that for smaller masses, the gases being generated and movement inside the vessel was still resembling a laminar flow, whereas 15 gram experiments and higher generated enough temperatures and pressures that

changed the flow behaviour to a more turbulent flow, which would explain the fact that channels 2 and 3 had the highest average temperatures for larger masses.

Observations of Temperature Measurement

The ability to measure temperature throughout a combustion process aids the understanding of the conditions being generated, however, it must be remembered that there are some limitations to it. Heat transfer through conduction occurs at a much slower rate than convection and radiation, which limits the ability to measure more accurately the conditions present [68]. The hot gases had to heat up the steel rod making up most of the temperature sensor, however, what actually reads the temperature is inside the steel rod, therefore, the steel rod has to heat up to the temperature of the gases to conduct heat inside to the sensor. Given that the combustion reaction occurs so quickly, it does not provide enough time for the temperature to accurately equilibrate inside the temperature sensor.

When preparing the experiment and setting up the temperature reading properties, the instrument could provide 100 ms as the fastest sampling rate. Considering that the combustion processes occurred between 0.45 and 0.80 s during the closed vessel series, there would be a maximum of 8 temperature data points provided for the longest experiments, and between 4 and 5 for the fastest. It would have been desired to obtain more data during the combustion processes to track the temperature evolution over the combustion process, similar to what was observed in the pressure and luminosity data, however, it was not possible with this instrument.

Unfortunately, during temperature data processing, it was understood that the temperature instrument was in fact collecting data every 800 ms, instead of the 100 ms data sampling selected. Therefore, experiments where the combustion time was low, either one or no temperature data were collected whilst combustion was active.

Had the temperature data points been actually measured at a sampling rate of 100 ms or faster, the relationships observed would have most likely resemble the

pressure and luminosity data until the temperature peak was reached, at which point the temperature decay would be similar to the slow process observed in Figures 36 and 37.

An interesting difference can be observed between Figures 36 and 37, where the highest temperatures observed for Figure 36 was always in channel 1 and slowly decreased until reaching the lowest temperatures at channel 5, while in Figure 37, channel 1 did not contain the highest temperature for any of the 4 firings.

An accurate temperature measurement allows for a more accurate understanding of all the parameters measured during the combustion process. The combustion temperature has an important role in determining the pressure inside the vessel due to the gaseous expansion being influenced by the temperature of the gases and considering a large volume of gases are being generated, especially at the higher masses of propellant combustion.

4.1.3 Combustion Time Measured by Peak Pressure

It was previously discussed that one method that could be used to measure the combustion time was driven by the time required to reach the peak pressure during combustion. The working theory focuses on the fact that the pressure will only rise while propellant deflagrates, hence, once the peak pressure has been reached, the combustion time can be calculated.

Similar to the peak pressure data, an averaged value was measured of the time required for each mass to reach the peak pressure. It was easily noted that the variation of time within each repetition was much larger, hence, just including a single data point in the hope of summarizing results that are very far apart is not the best way to project the data. Instead, all experimental results were included in Figure 38, all repeated experiments contained several data points per experimental mass combusted.

In Figure 38, each propellant mass was presented in a single colour to shift the focus to the contrast to the red data representing the averaged value obtained. It can be observed that for smaller masses, a larger variation is seen between the same repeated experiments. For 1 gram, the time taken to reach the peak

pressure ranged between 0.61 and 1.34 s, whereas the experiment with the least variation was 20 grams, with a range of 0.38 and 0.47 s. Due to this large variation in individual data points, the average value may not truly represent the total combustion time during the firing, however, can work as an indicator.

The average value can be used to observe the overall pattern detected when increasing the propellant mass. The average combustion time diminished with increasing the propellant mass, however, not at a steady rate. This can be described by a logarithmic relationship, where the data suggests that at lower masses, the combustion time difference has larger impacts, while at larger masses, the changes observed in time were much smaller.

Data does not work for all cases, as the average combustion time measured for 20 gram combustion was lower than the 30 gram experiments average. There are some possible explanations to this observation, however, it was not possible to conclude whether that was an anomaly, or the actual behaviour of this relationship. It is possible that the combustion could be rising further, since more propellant mass was being added and the propellant tray was getting longer, hence, it would require more time to ignite and burn the entire mass present. Nevertheless, everything up to this point indicates that when more mass of propellant is present, the pressures and temperatures reached are higher, increasing the burn rate of the propellant ignited, which accelerates the combustion process, and thus decreasing the combustion time.

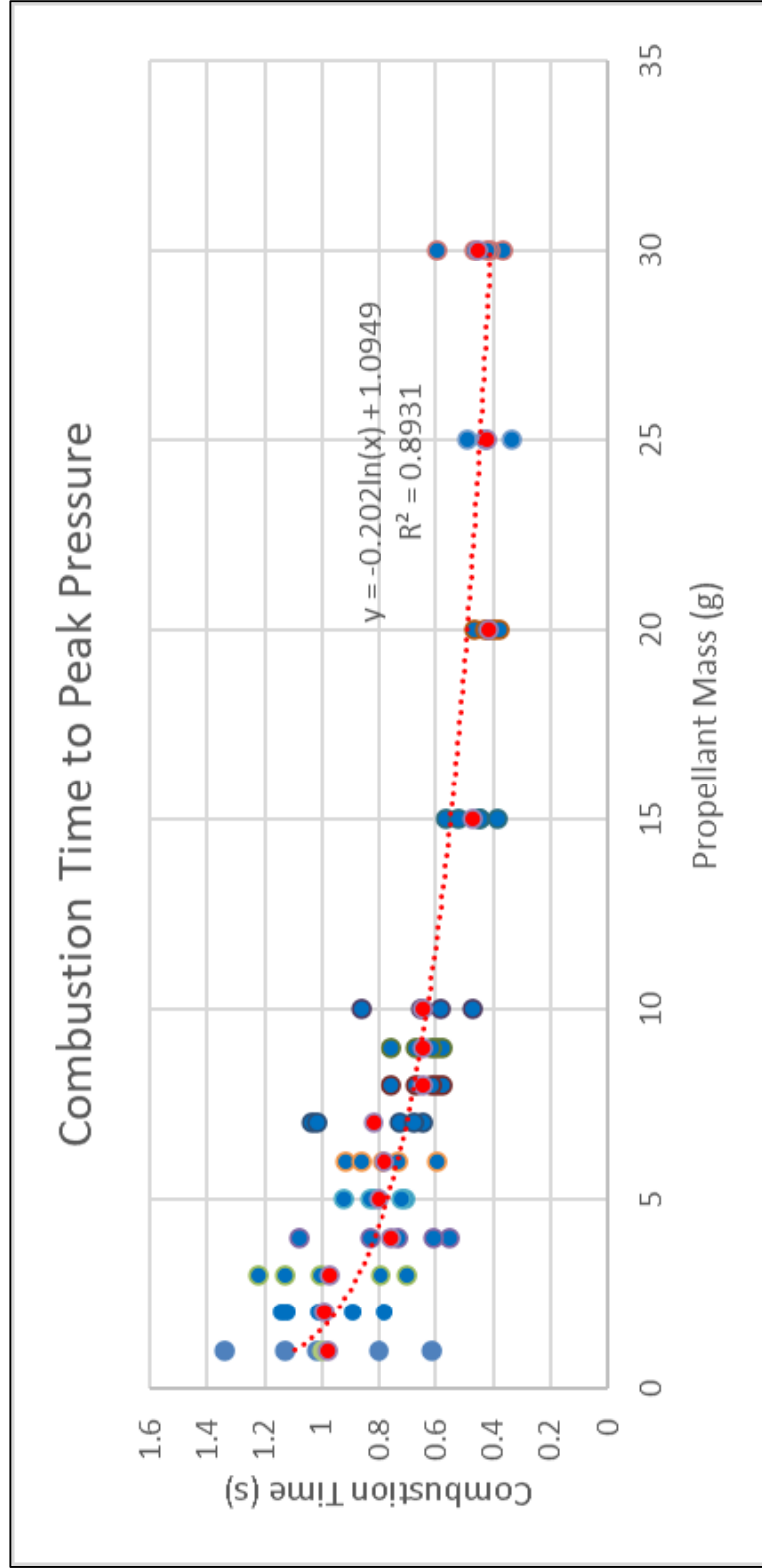


Figure 38: Combustion time measured by time taken to reach peak pressure

4.1.4 Rested Pressure

The concept of rested pressure refers to a measurement where combustion of a propellant would occur inside the instrument at closed vessel mode and be left unchanged, until the temperature inside the vessel returns to ambient conditions, while the gases remain trapped inside. This pressure measurement indicates the effect that temperature has on pressure. Therefore, there will be two pressures measurements to be collected from each experiment, the pressure data during the combustion, where gases are hot and heat expansion has an important role, and the rested pressure where the gases have cooled to standard temperature conditions and heat expansion has no effect on the pressure.

Rested pressure can only be measured during experiments conducted at closed vessel mode because the gases will be trapped inside the vessel. At vented vessel mode, where a ventilation valve was left opened, allowing gases to escape, the heat will also be leaving through the vent valve, hence, ambient pressure will be measured when the temperature inside the burning vessel returns to standard conditions.

Rested Pressure Data

This measurement provides information on the impact that temperature and combustion gases have separately on the peak pressure achieved. The graph in Figure 39 contains the data collected for 1 gram combustion to demonstrate the variability within the same propellant mass.

It can be observed that the pressure was constant throughout the reading, which was conducted once the temperature inside the vessel was lowered to 20°C. The measurement was taken for a few seconds only to obtain a clear average value for each experiment run.

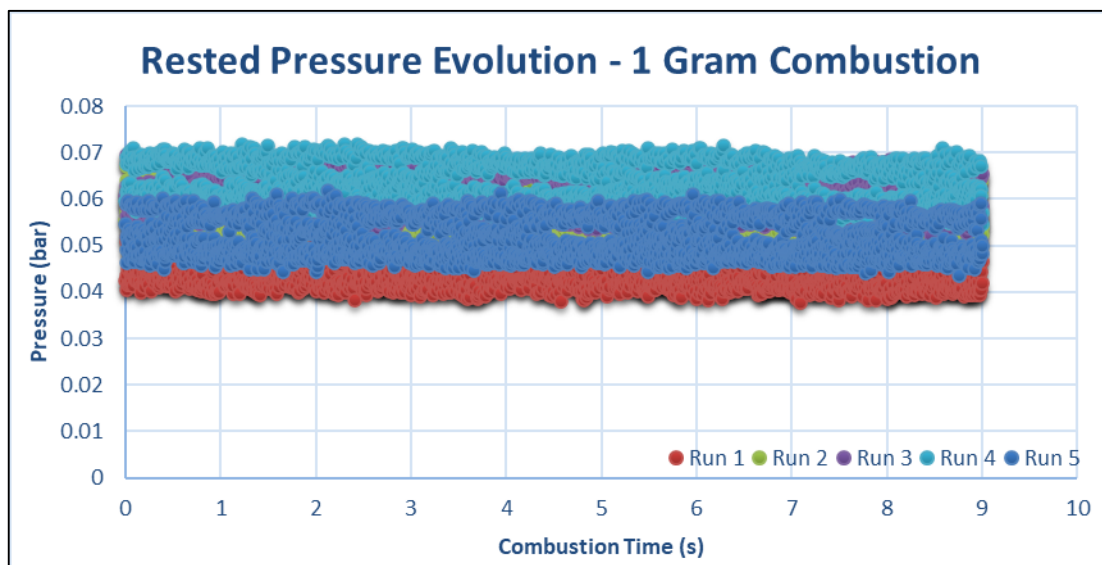


Figure 39: Rested Pressure data collected during 1 gram combustion of N120 Vihtavuori Propellant.

It was expected that the overpressures retained at cooler temperatures would have little variation because the same propellant mass was combusted, hence the same moles of gases would be produced. The combustion time for each experiment was similar, indicating that the peak pressure reached for each experiment was similar for all samples. The same vessel was used throughout all firings; hence, the temperature being absorbed by the instrument would occur in a similar speed, therefore, the pressure inside was expected to be similar once the temperature inside the vessel would reach 20°C for each experiment run.

Figure 40 contains the data of the average rested overpressures for each mass tested once the temperature inside the vessel returned to ambient. The data shows a slightly polynomial rise but could be interpreted as a linear rise in overpressure, which was associated to the difference in moles of gaseous products generate during the chemical reaction.

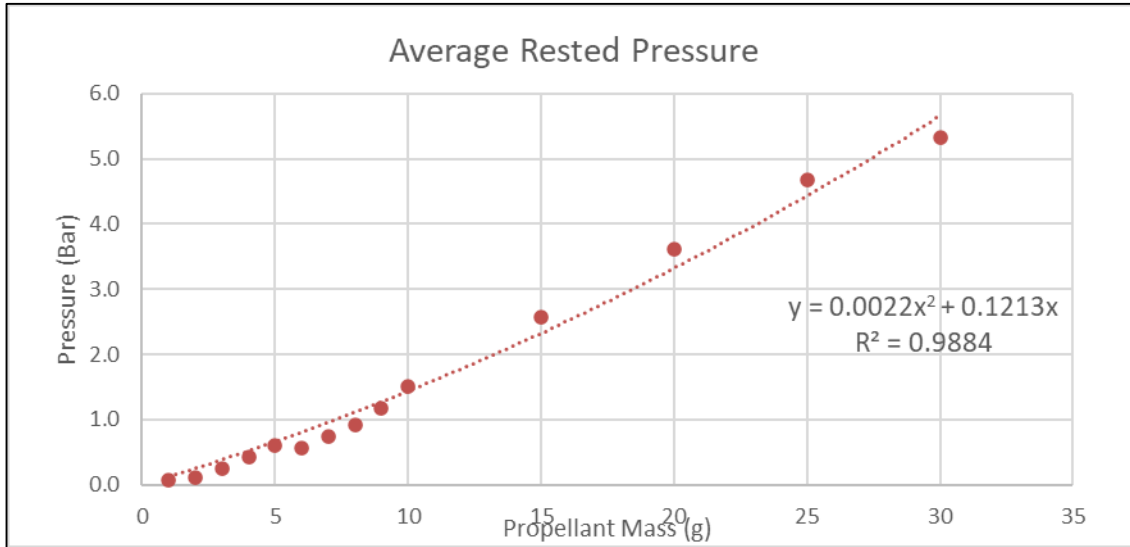


Figure 40: Average Rested Peak pressure during the combustion.

If we refer back to the ideal gas law, where:

$$P * V = n * R * T$$

Equation 16: Ideal Gas Law.

It can be argued that the difference between the average peak pressures and the average rested pressures for each mass tested was solely caused by the temperature of the gases inside the vessel. During the combustion process, the temperatures reached were of values greater than 1000°C for some masses, hence, the temperature impact on the peak pressure would be considerable. By including the relationships observed for these two pressure measurements together, it will be possible to visibly see the impact that temperature has on the peak pressure.

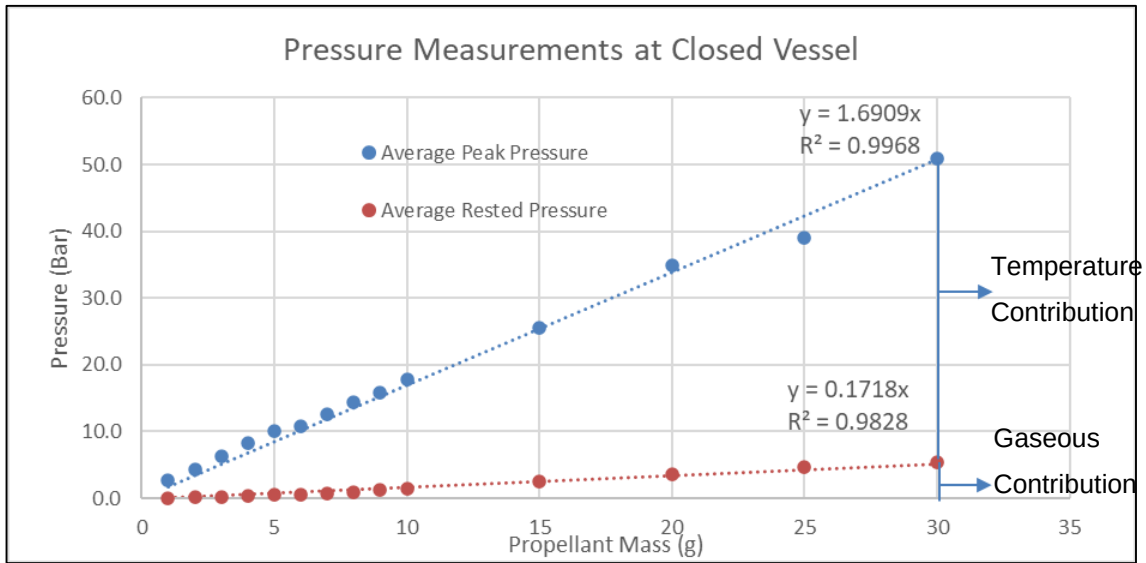


Figure 41: Both pressure measurements conducted at closed vessel mode.

It has been clearly shown in Figure 41 that the temperature contribution has a larger contribution to the peak pressure achieved during all firings. Remembering that the temperature has two effects causing the pressure to rise:

1. Gases at higher temperatures will move keep moving at faster speeds, bumping into the walls at higher rates.
2. Heat expansion forces gases to occupy more space inside the vessel, increasing the number of collisions of gases within themselves and the walls of the instrument.

Since both behaviours shown above follow a linear pattern to a high level of confidence, the temperature contribution can easily be calculated as the difference between the pressures measured. As mentioned, the gaseous contribution was equivalent to the rested pressure, where that is the overpressure generated solely by the production of gases, whereas the remaining overpressure was an effect caused by the elevated temperatures achieved by the exothermic reaction.

Mass (g)	Peak Pressure (bar)	Gaseous (bar/%)		Temperature (bar/%)	
		Pressure	Percentage	Pressure	Percentage
1	2.638	0.066	2.5%	2.572	97.5%
2	4.265	0.109	2.6%	4.155	97.4%
3	6.244	0.242	3.9%	6.002	96.1%
4	8.356	0.421	5.0%	7.935	95.0%
5	10.001	0.594	5.9%	9.408	94.1%
6	10.853	0.570	5.3%	10.282	94.7%
7	12.673	0.736	5.8%	11.937	94.2%
8	14.353	0.926	6.5%	13.427	93.5%
9	15.871	1.184	7.5%	14.688	92.5%
10	17.833	1.513	8.5%	16.320	91.5%
15	25.627	2.564	10.0%	23.063	90.0%
20	34.883	3.623	10.4%	31.260	89.6%
25	38.982	4.689	12.0%	34.293	88.0%
30	50.891	5.328	10.5%	45.563	89.5%

Table 3: Gaseous and Temperature contributions during closed vessel series.

Table 3 was included to demonstrate the rise in both pressure contributions in pressure and percentage formats. Although the temperature contribution had a linear rise behaviour with increase in propellant mass, its effect was slightly less prominent at higher masses, starting at 97.5% contribution during the ignition of 1 gram of propellant, and reaching the lowest contribution of 88.0% at the 25-gram experiments. This effect can be visualised in Figure 42.

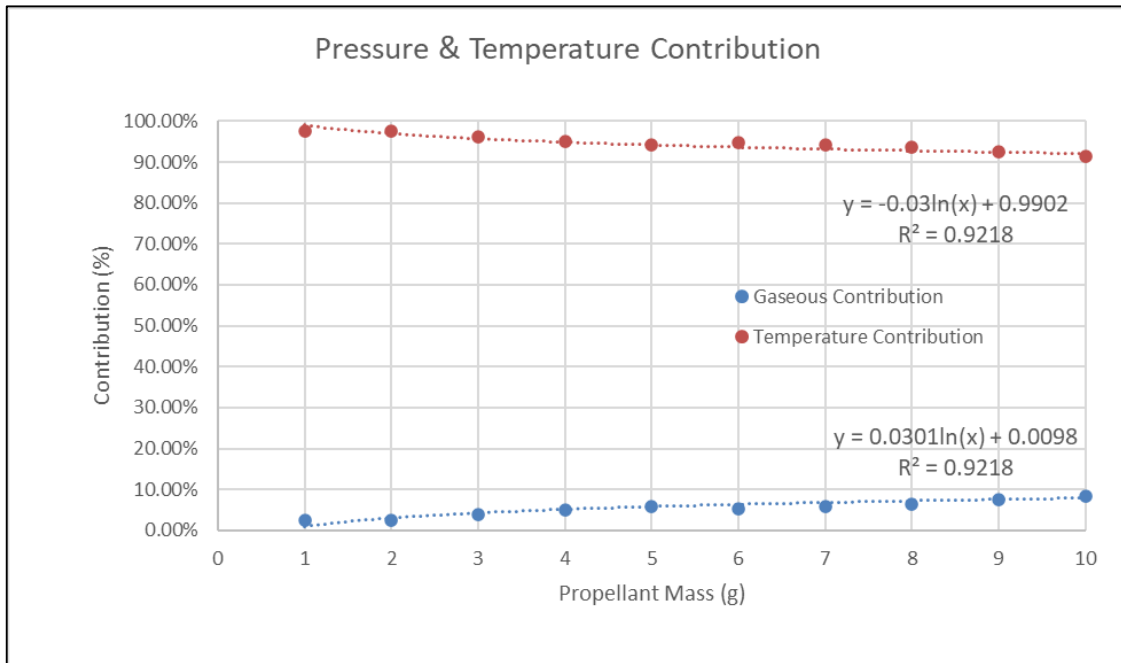


Figure 42: Gaseous and temperature contributions demonstrated percentage values for the closed vessel series.

Increasing the propellant loading density to be combusted will raise the number of moles of product gases by a known factor because the chemistry of the exothermic reaction is constant. Although the amount of heat released will vary according to the total mass released, at higher masses, higher temperatures will be reached, however, due to the zeroth law of thermodynamics demanding temperature equilibrium, higher temperatures inside the instrument will create a higher difference to the vessel temperature, which increases the rate of equilibrium, therefore, more energy will be lost from the gases.

The above was observed from the temperature data collected during the closed vessel series. Despite the data not being accurate enough to identify relationships

and be used in an attempt to further understand the combustion reaction, it can confidently show that the combustion of higher propellant masses released more energy to the system, however, the temperature rise observed did not rise in a similar fashion.

4.1.5 Average Peak Luminosity

After a few experimental series, an exposure time of 30 ms was selected for the combustion of 1 gram. If the exposure time selected was too high, the luminosity average data obtained would be too high, potentially reaching the saturation point; similarly, if the exposure time value was too low, not much light would be observed, hence, the luminosity average would be too low, and it would be difficult to identify an arbitrary value to dictate whether combustion was active. Whenever the propellant loading density was increased, the overall luminosity to be observed would be higher, hence, the exposure time would need to be reduced to maintain the luminosity data within an acceptable range. The planetary camera utilised was capable of recording videos at a rate of 30 frames per second (fps), hence, having an exposure time of less than 33.3 ms fitted the camera settings perfectly, as it allowed for all the recordings to collect 30 fps throughout all firings, since the exposure time would decrease with increasing mass, and the initial exposure time for 1 gram combustion was at 30 ms.

The overall luminosity was measured by the term “intensity” to account for both changes occurring to the combustion, the peak luminosity average, and the combustion time. Equation 17 was utilised to calculate the intensity values seen in Table 4.

$$Intensity = \frac{normalised\ AUC}{combustion\ time}$$

Equation 17: Intensity.

Table 4 shows the luminosity data collected:

Mass	Exposure (ms)	Peak Luminosity Average	Intensity
1	30.00	75.8	2.5
2	20.00	90.4	4.5
3	12.00	90.0	7.5
4	8.00	128.0	16.0
5	4.00	87.2	21.8
6	2.50	59.1	23.6
7	1.75	56.5	32.3
8	1.25	58.9	47.1
9	1.00	48.3	48.3
10	1.00	47.5	47.5
15	0.60	60.9	101.5
20	0.50	71.1	142.1
25	0.35	51.5	147.1
30	0.3	55.3	184.4

Table 4: Luminosity Data collected from Closed Vessel Series.

The increase in propellant mass combusted would generate more light from the flame, hence, the exposure time would be reduced to maintain the luminosity average values to remain within 0 and 255, without nearing both extremes. The normalised luminosity would increase with increasing mass since the luminosity average was kept between 45-130, while the exposure time would drop at higher propellant masses. The exposure time for the first 5 grams was previously selected while testing the planetary camera. From the linear correlation obtained from these 5 experimental masses, it was possible to predict the most appropriate exposure time for the experimental masses with no previous knowledge by

observing the trend obtained for the normalised luminosity up to that point and extrapolate the expected exposure time. Since the average luminosity was aimed to be maintained between 40-100, the exposure time could then be predicted.

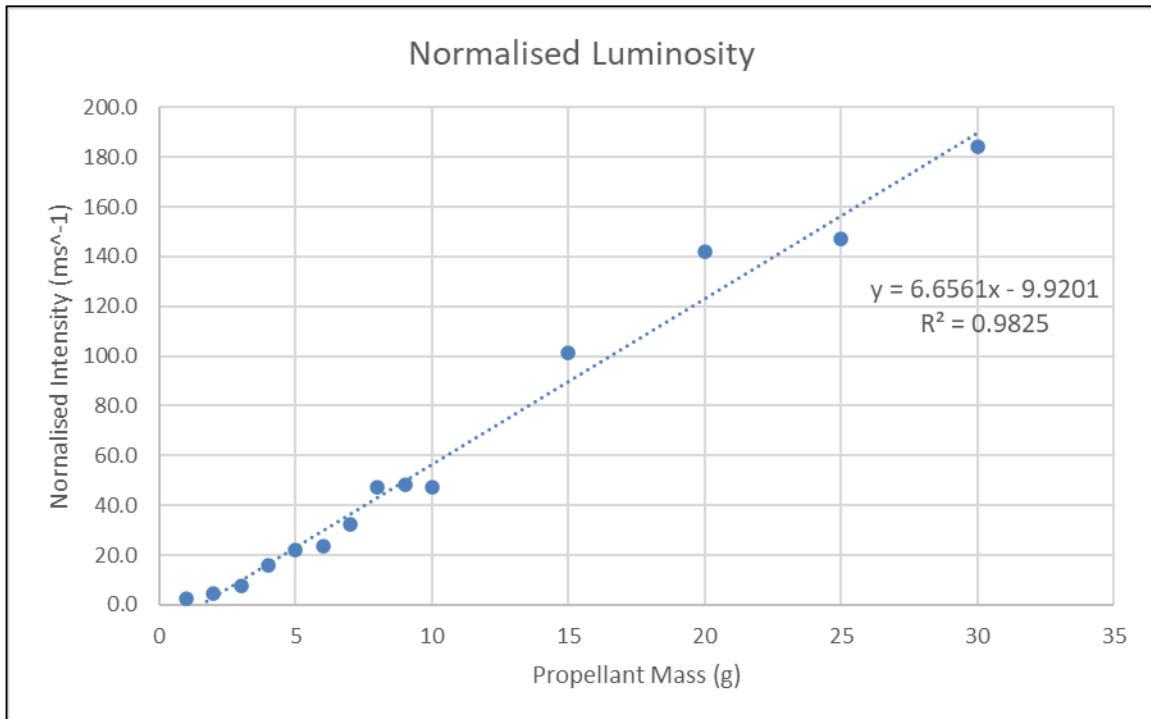


Figure 43: Normalised Luminosity data for Closed Vessel Series

Figure 43 demonstrates the relationship of the intensity data from Table 4 to the propellant loading density increase. A linear rise describes the equation indicating a strong correlation between the patterns. Both the normalised luminosity and pressure rise data produced linear relationships to increasing propellant mass, which indicates a possible connection between these parameters.

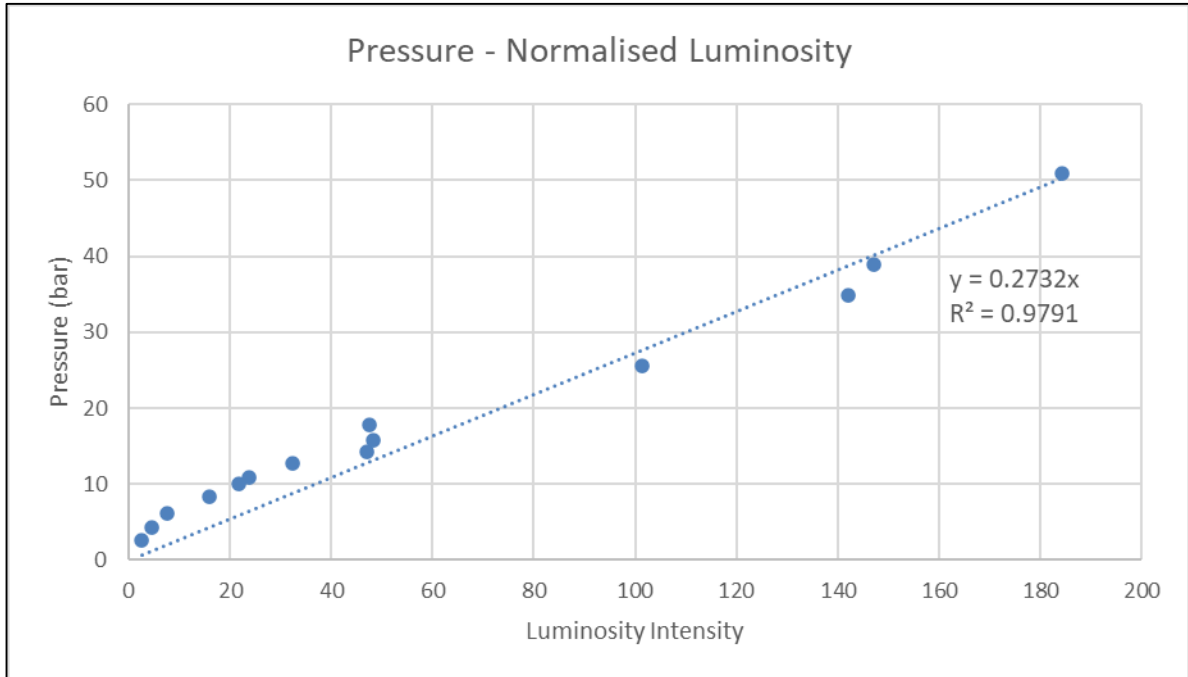


Figure 44: Pressure - Normalised Luminosity Closed Vessel series.

The linear relationship seen in Figure 44 describes how increasing the pressure inside the burning vessel caused by an increase in propellant loading density also increases the luminosity intensity by a similar factor. This behaviour increases the confidence in the connection between pressure and luminosity, especially at closed vessel conditions.

4.1.6 Area Under the Curve (AUC) & Combustion Time

Table 5 shows the data collected from the luminosity measurements. The AUC sum was expected to vary from experiment to experiment and would not behave necessarily in any pattern because there were two parameters acting in opposite directions. The increase in mass would generate more light, leading to higher AUC values, however, the reduction in exposure time to prevent any saturation from the recording values would reduce the total observed light. Therefore, the normalised AUC term was designed to describe the total luminosity generated during combustion whilst accounting for the combustion time, as exemplified in Equation 18:

$$\text{Normalised AUC} = \frac{AUC}{\text{Combustion Time}}$$

Equation 18: Normalised Area Under the Curve.

Mass (g)	Exposure Time (ms)	Area Under Curve	Normalised AUC	Combustion Time (s)	Intensity (ms ⁻¹)
1	30.00	26947	898	0.57	1.59E+06
2	20.00	32664	1633	0.78	2.09E+06
3	12.00	30259	2522	0.70	3.60E+06
4	8.00	29744	3718	0.66	5.63E+06
5	4.00	20124	5031	0.65	7.70E+06
6	2.50	14485	5794	0.73	7.90E+06
7	1.75	11522	6584	0.70	9.41E+06
8	1.25	10322	8257	0.61	1.35E+07
9	1.00	8331	8331	0.67	1.25E+07
10	1.00	8219	8219	0.60	1.37E+07
15	0.60	6571	10952	0.45	2.42E+07
20	0.50	7295	14590	0.46	3.17E+07
25	0.35	5815	16614	0.47	3.56E+07
30	0.30	5301	17671	0.46	3.84E+07

Table 5: AUC, normalised AUC, intensity, and combustion time collected for closed vessel experiments.

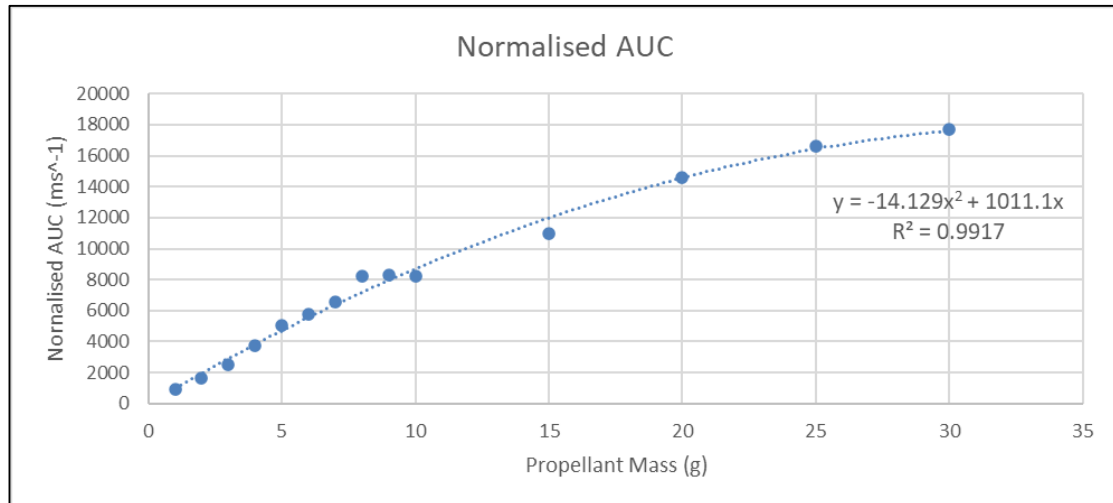


Figure 45: Normalised Area Under the Curve data for the Closed Vessel Series

The normalised AUC data shown in Figure 45 demonstrates a consistent polynomial behaviour with an R^2 of above 0.99. The polynomial relationship observed indicates that further increases in propellant mass combusted will have diminishing effects on the normalised AUC. This could be explained by the fact that as more mass is combusted, the flames inside the vessel occupy more space, reaching areas where the camera might not catch on the recording, hence, losing part of the data. Although the camera was placed directly on top of the glass window lid, the flame could move in a turbulent flow inside, especially as the larger masses tested reached pressures values above 30 bars, hence, producing a turbulent environment. Perhaps, if conditions were possible to guarantee that all the light was to be observed, it could change the relationship above to a linear pattern. The correlation above strengthens the argument that a correlation exists between combustion and the luminosity it emits.

Table 5 also indicated that as the mass increases, the combustion time measured by the use of an arbitrary value was kept almost constant during all the experiments. Once again, there are factors that contribute to the increase and decrease in combustion time, which need to be considered when attempting to identify a correlation. Firstly, the increase in mass means that more propellant was present in the propellant trays, indicating that more time could be necessary to burn the composition entirely. However, the pressure rise observed during the

combustion accelerates the chemical reaction, since Vielle's law state that burn rate is controlled by a few factors, but mainly the pressure.

The design selected for the propellant trays was done to have a fixed length-to-width ratio of 10:1, therefore, an increase in total mass of propellant present meant that longer, wider, and taller trays were used. Therefore, increasing the propellant mass should increase the mass consumption rate. Hence, the pressure rise would be higher, reaching faster burn rates, and thus, potentially requiring less time to combust.

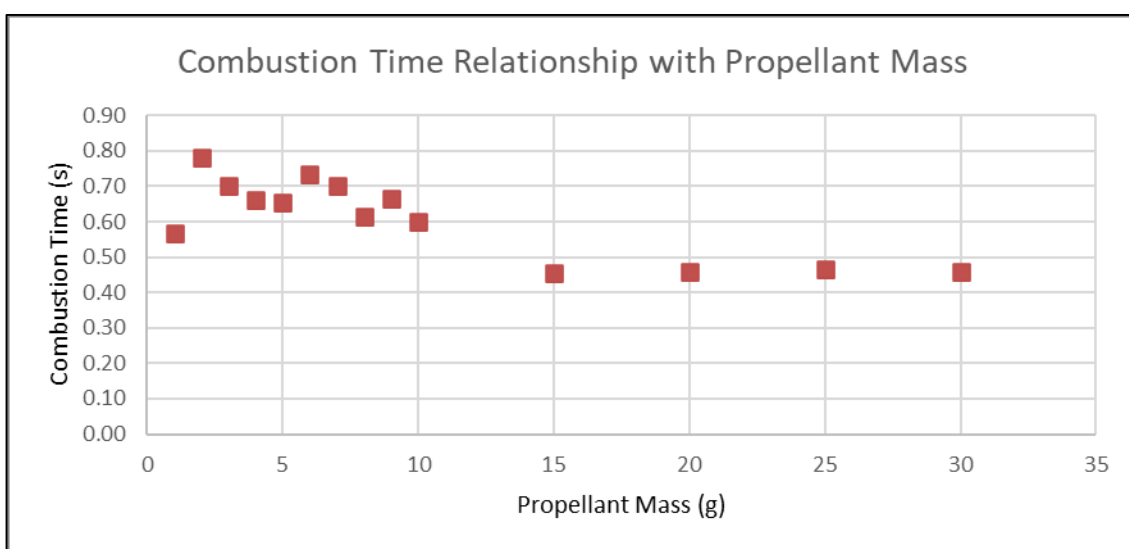


Figure 46: Combustion time measured during combustion inside Closed Vessel.

Figure 46 illustrates that an increase in mass of propellant changed slightly the combustion time. If we exclude the data point of 1 gram of propellant (the first data point starting from the left), the relationship indicates a more clearly in decrease of combustion time with increasing propellant mass, where at masses ranging from 2–10-gram data, the combustion time varied within 0.60 and 0.78 s, leading to a large drop to 0.45 to 0.47 s for masses of 15 grams through 30 grams.

The mode of operation in this series was a closed vessel, hence, there would be no escape option for the gases present. This allowed the burn rate to increase as more material was undergoing combustion. Considering that at larger masses, the propellant trays would be just slightly longer, but more importantly wider and taller, a larger quantity of propellant would be deflagrating after any fixed time

since ignition had started. The porosity between individual particles allowed the flame to move at random directions, which led more material to combust per unit time, hence, at higher masses, the flame would disperse in all directions for longer, increasing the number of active particles that would be generating gases, heat, and luminosity. These would lead to even further particles in a repetitive cycle at accelerating speeds, until all propellant particles were already ignited, at which point, the quantity of gases and heat being generated would drastically increase the pressure, accelerating the reactions even further.

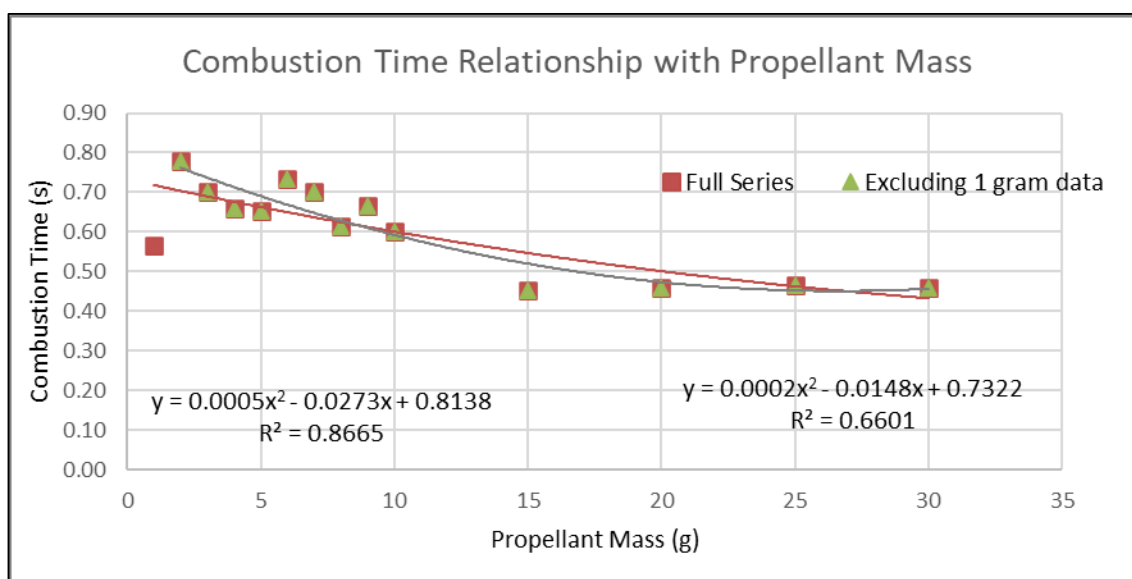


Figure 47: Combustion time measured during combustion inside Closed Vessel excluding data from 1 gram.

By excluding the first data point allows the relationship to describe a smoother correlation, giving more confidence to the data collected. The R^2 of the polynomial relationship increased from 0.66 to 0.87, demonstrating the possibility of an anomaly, seen in Figure 47.

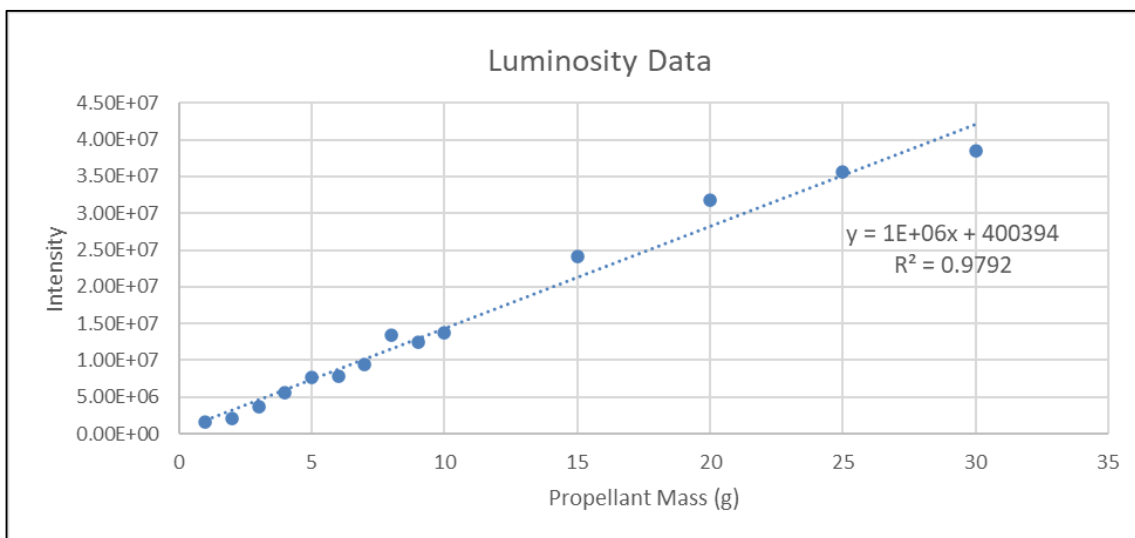


Figure 48: Intensity data for Closed Vessel series.

The overall luminosity intensity data during a combustion can be calculated by dividing the normalised AUC by the combustion time. There were 3 parameters that impact this parameter:

1. The total mass of propellant which will reflect on the total luminosity generated, and thus the total AUC.
2. The Exposure Time, which was reducing with increasing propellant mass to prevent any saturation.
3. Combustion time data, which was reducing with increasing propellant mass combustion due to the increase in burn rate.

Considering all these factors impacting the overall luminosity intensity parameter, the data calculated and shown in Figure 48 describe a linear correlation with a high level of confidence, once again providing evidence that the luminosity measured during combustion can be used to further understand parameters used to describe the combustion process of smokeless substances.

4.1.7 Mass Consumed & Mass Consumption Rate

Figure 49 contains the average mass consumed during the combustion of all experimental masses during the closed vessel series. Although the mass to be consumed is known, the shape of the relationship observed is expected to evolve during combustion, as well as change pattern as more mass is combusted.

Figure 49 shows the increase in mass consumption rate rise as the propellant mass increases. From masses 1–3-gram data, the mass consumed slowly increases as the combustion occurs, while from 4 grams of propellant combustion onwards a slight acceleration in the curve can be seen, followed by a decrease once most of the propellant was deflagrated. Masses of 7-10 gram further highlight the mass consumption acceleration during the combustion. The larger experiments of 15 grams and above continue the trend by reducing the acceleration section and reducing the overall combustion time. It is possible to observe a single rise for each propellant mass tested, caused once the combustion flame spread through the entire propellant tray. Regardless the amount of propellant mass placed inside the tray, the flame will quickly overwhelm the entire experiment and ignite all the propellant and proceed to burn inwards towards the centre of the propellant grain.

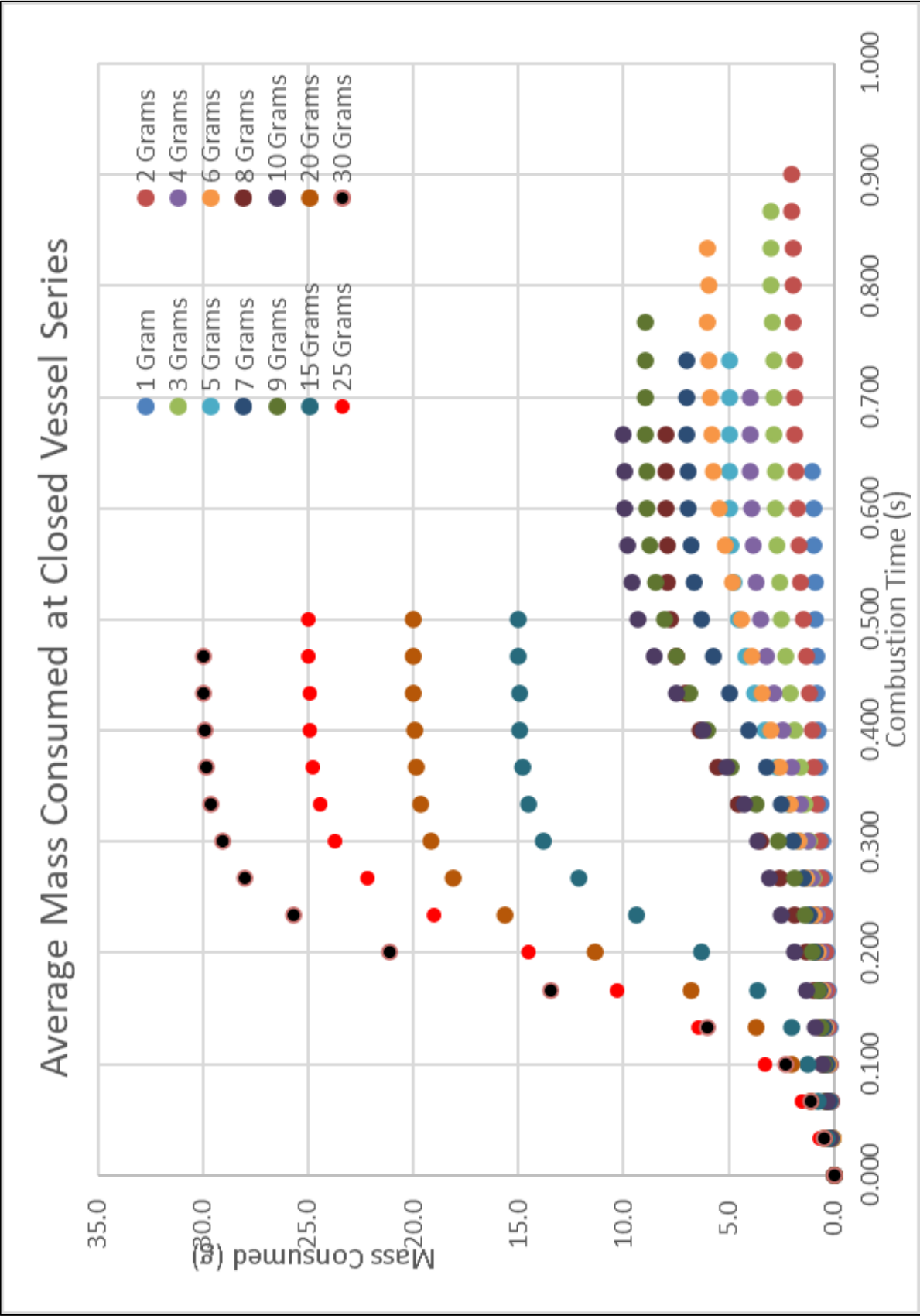


Figure 49: Average Mass Consumed during Closed Vessel Series

Segmented Mass Consumption Rate

The segmented mass consumption rate was measured for all masses and plotted in a graph against the combustion time. It was observed that there was a large area of the graph with few data points, and a small area with several data points overlapping each other, hence, it was decided that the data would be displayed in two graphs, one containing the segmented mass consumption rate of experiments with 1 - 10 grams, and the second graph containing the remaining experimental mass data.

Figure 50 contains data on the segmented mass consumption rate measured throughout the combustion of smaller propellant masses. Although confusing at first, a few trends can be observed. The mass consumption rate grew larger with increasing the total mass of propellant present. This was an expected behaviour to occur because of the diminishing trend described in the combustion time measured for each experiment, seen in Figure 46. Since the combustion time was decreasing with increasing mass, it would indicate that the mass consumption rate would be increasing by two accounts: the increase in mass, and the decrease in combustion time.

It can be observed that for masses up to 3 grams, the increase in the segmented MCR begins as a linear increase, however, as the experiments combusts 4 grams or larger quantities, there seems to be an exponential rise that starts halfway through the combustion process. As the propellant mass increases, the exponential behaviours grow stronger and for a longer period of time.

When increasing the propellant mass, it was expected that the peak in MCR would be observed at earlier frames, which would also explain the shorter combustion time, however, this trend was not observed in Figure 50. The peak MCR data ranged between 0.333 and 0.433 s without any pattern or relationship. Even though there was no relevant change in combustion time when increasing the mass because the propellant tray was longer, it demonstrates that the burn rate and flame speed was increased to allow the entire propellant mass to be ignited almost simultaneously.

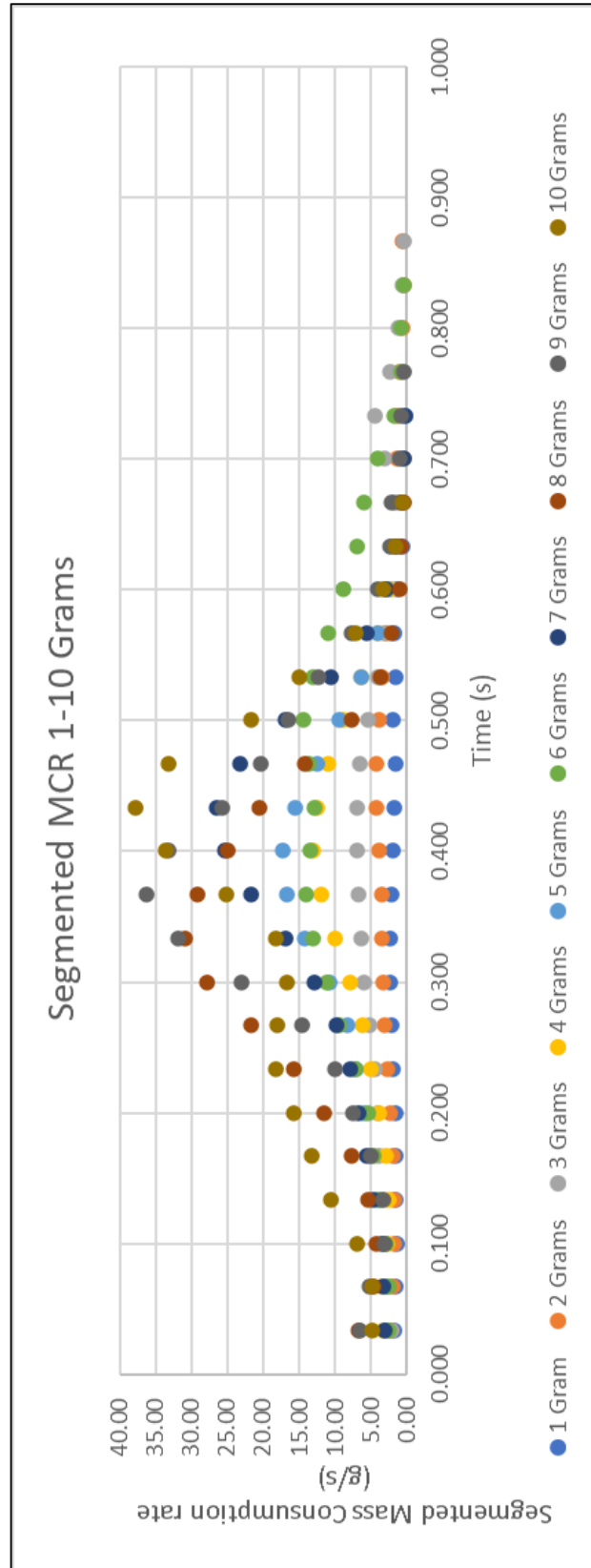


Figure 50: Segmented Mass consumption rate of 1–10-gram data in Closed Vessel mode.

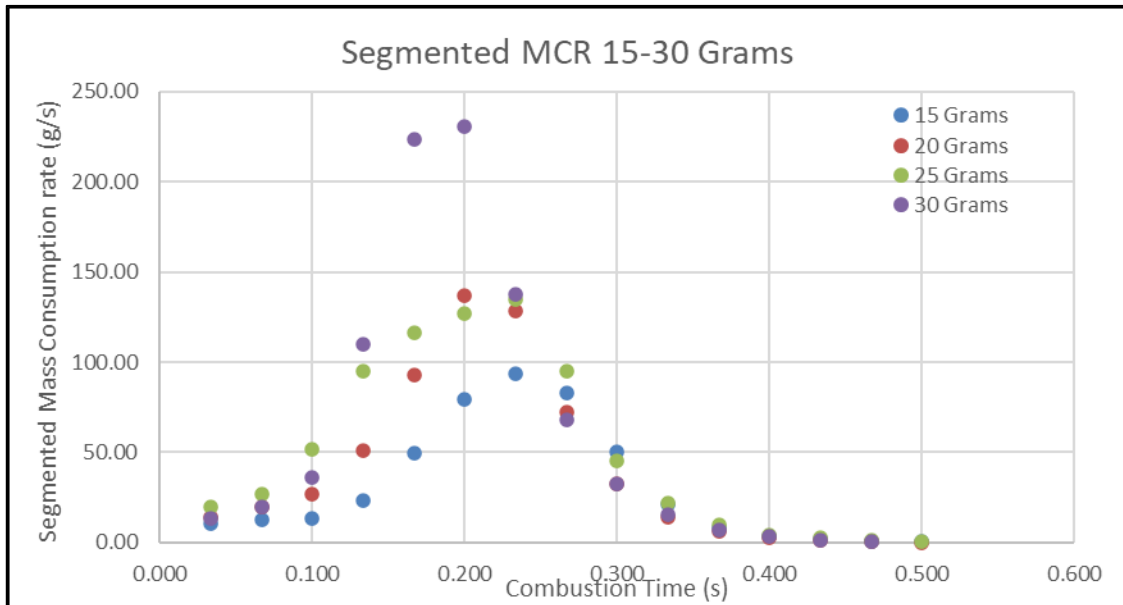


Figure 51: Segmented Mass consumption rate of 15–30-gram data in Closed Vessel mode.

Figure 51 contains the data from the remaining experiments of 15-30 grams of propellant. The data highlights the large increase in segmented mass consumption rate values, where for 10 grams, the maximum MCR measured was 37.79 g/s, whereas the segmented MCR for the relationships above produce much higher values, reaching a peak of 230.44 g/s for the 30-gram experiments.

The peak in MCR data for each mass has shifted now to smaller combustion time values, alternating between 0.200 and 0.233 s once ignition started. This indicates a decrease of at least 50% in time required to reach the peak MCR compared to the experiments of 1–10-gram experiments, indicating an increase in the burn rate throughout the propellant tray. To further comprehend the trend observed, the peak MCR data calculated can be plotted in relation to the mass of propellant, this would inform us of the behaviour of the relationship obtained when increasing the mass consumed and its effect on the peak MCR value.

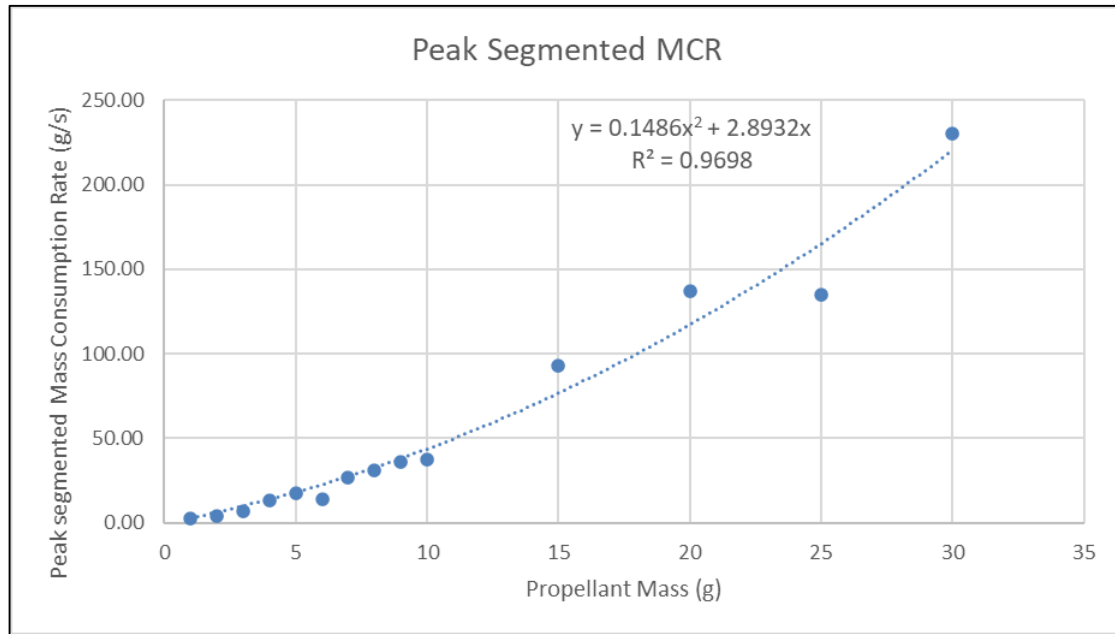


Figure 52: Peak segmented MCR value plotted against its propellant mass.

Figure 52 contains data that highlight how the increase in mass being consumed in a propellant tray of length-diameter-height ratio of 10:1:1 increases the segmented mass consumption rate in a polynomial relationship.

There is an argument that the behaviour of this relationship would change when increasing the mass consumed further. The mass can be continuously increased, as there is no limiting mass, however, the combustion time will not be possible to decrease much further, since we are already reaching its peak value in 0.200-0.233 s, equivalent to 6 and 7 frames respectively. There is a possibility for the peak in segmented MCR to drop slightly, but not significantly. This will occur because there will be a minimum time required for the flame generated during the combustion of the first few particles of propellant to ignite the entire propellant tray, and combust the entire propellant mass, despite the increase in burn rate. At this point, the segmented MCR will continue to rise where the only effect will come by increasing mass consumed.

4.1.8 Luminosity Variation Within Same Propellant Mass

In the previous Section, the average of 5 firings for each mass was utilised to observe the effect of increasing the propellant mass and understanding the

overall relationships that increasing the propellant mass would make possible. However, this Section focuses on differences observed between each firing within the same propellant mass.

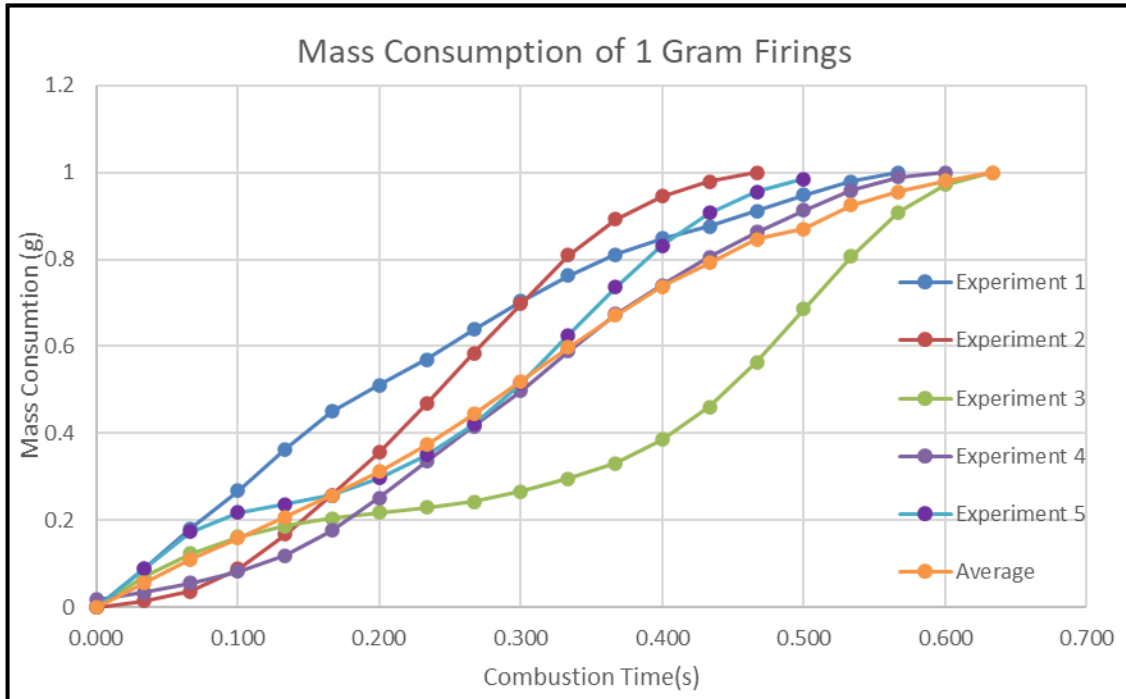


Figure 53: Mass consumption data during 1 gram combustion.

Figure 53 describes the total mass consumed over the course of the combustion process. Although the experiment was identical between the 5 repetitions, the time required to combust the entire 1 gram was different for most tests. Interestingly, all relationships are different enough from each other, demonstrating that no two results were identical. The first experiment produced the steepest behaviour for the first 10 frames, whereas experiment 3 showed an average behaviour in the early section of combustion, decreased its combustion rate for several frames, to then burn half of its mass left in 0.2 s producing the steepest behaviour when deflagrating 1 gram of propellant.

The overall time of combustion measured ranged from 0.467 to 0.633 s, equivalent to a difference of 5 frames. Despite the variation in combustion time, each experiment relationship had a unique behaviour, caused by the uncontrollable flame dispersion due to the presence of pores between propellant particles. For a process that contains an uncontrollable parameter that can cause

the burn rate to fluctuate, the overall time of combustion was considerably consistent, or at least more consistent than it should have been given the variation in behaviour observed.

A factor that can be used to describe this consistency attributes to the burn rate being dependant on the pressure and temperature. Regardless of whether the combustion started fast, or slow, hot gases were generated, increasing the pressure and temperature inside the vessel. According to Vielle's law, the burn rate, although not necessarily linear for powder propellants, would increase, hence, more propellant would be combusted at any point. All this would accelerate the remaining propellant that has not been yet combusted, and thus allow for the overall combustion times to be of similar values. It is important to note that the fact the instrument was in closed vessel mode facilitated the increase in pressure and temperature. If a ventilation valve was opened, the combustion product gases would escape, reducing the pressure and temperature inside the vessel, which would in turn reduce the burn rate of combustion and cause larger discrepancies observed in combustion times.

The segmented mass consumption rate data shown in Figure 54 demonstrate a clear distinction in initial consumption, where experiments 1, 3, and 5 started with higher consumption rates, and experiments 2 and 4 had slower starts. Even with similar starting speeds, however, the rates observed during the middle and end of combustion would continue to burn in randomised speeds due to the uncontrollable nature of the flame travelled through the propellant.

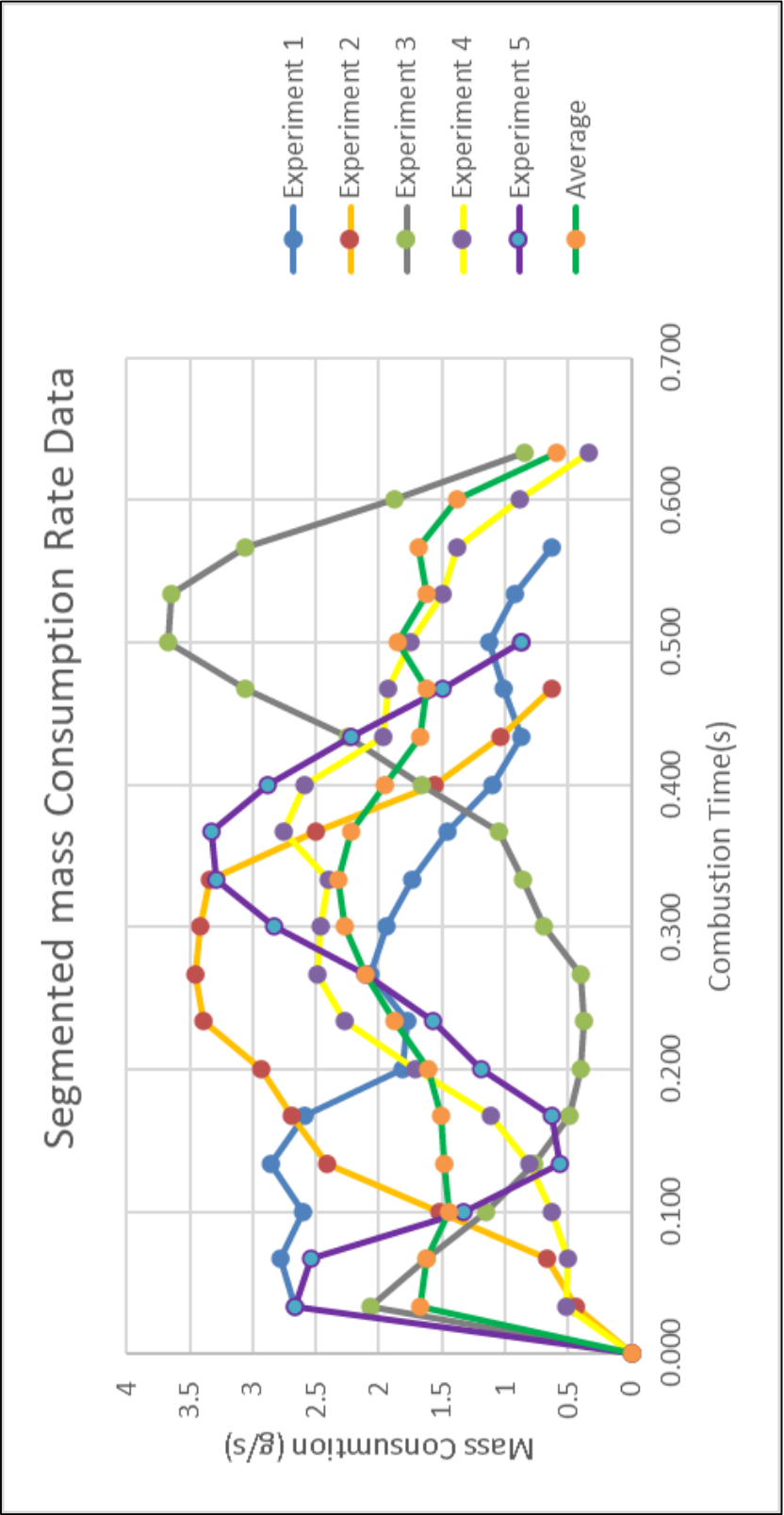


Figure 54: Segmented mass consumption rate data during closed vessel mode.

Experiment 3 was highlighted during the analysis of the mass consumption section, where the lowest mass consumption was observed during most of the combustion. This behaviour was more prominent during the segmented mass consumption rate, where it can be seen to have the lowest mass consumption rate for several frames during the middle section of the combustion, to suddenly reach the highest consumption rate observed for all experiments.

At a first glance, it seems there are little to no similarities between the firings, however, the peak consumption rate observed in each repetition did not vary a great deal from each firing. This indicates that once the flame flows freely, igniting a large quantity of propellant particles, the amount of propellant igniting simultaneously might not differ largely, since the mass consumption rates peak at similar values, ranging from 2.75 to 3.29 g/s. This observation has an important role in defining the peak pressure measured during combustion, because if the highest mass consumption rates of all firings are similar, then similar amounts of hot gases will be released contributing to similar pressure and temperature readings throughout all repetitions, only at different combustion times.

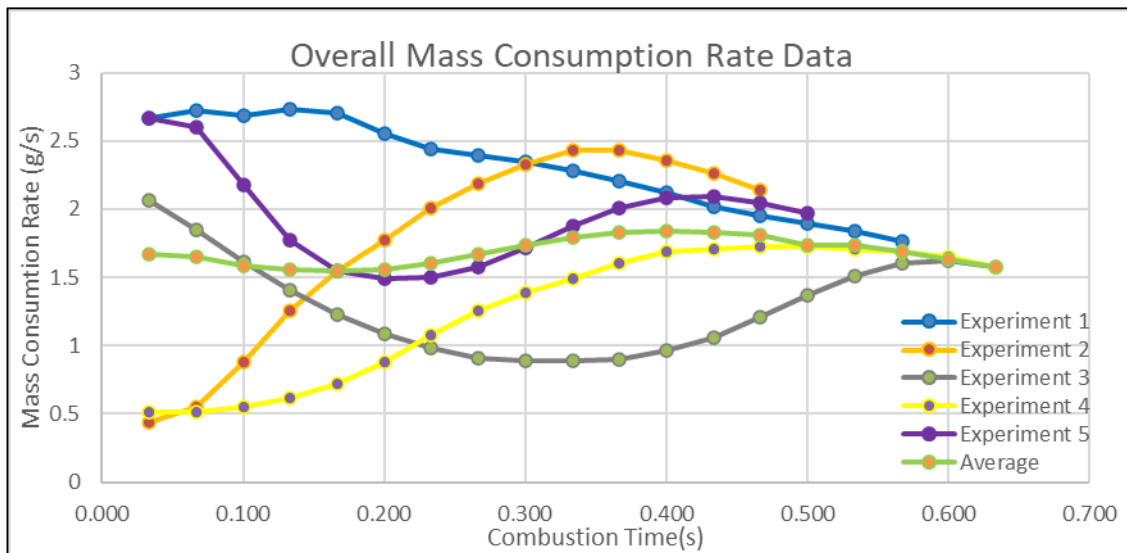


Figure 55: Overall mass consumption rate for 1-gram experiments in closed vessel mode.

The overall mass consumption rate relationships highlight the observation that regardless of speed at the start of the combustion process, the combustion will

adjust itself to reach similar overall mass consumption rates. Since the combustion time and propellant mass consumed was known from the mass consumption graph in Figure 53, the average mass consumption rate was calculated. The combustion time for these 5 repetitions varied between 0.467 to 0.633 s, with a fixed mass of 1 gram consumed. The average consumption rate was measured to be 1.58 to 2.14 g/s.

Figure 55 and the discussion above highlight that some similarities can be observed between the experiments, however, no 2 experiments produce similar behaviours throughout the combustion to confidently predict patterns. The average values measured do not assimilate to any experimental relationship observed for these 5 tests, hence, it must be looked at with a sceptical view. Despite all the observations made in this Section, when observing the average overall luminosity parameters for each propellant mass tested, consistent correlations were observed throughout the closed vessel series.

4.1.9 Closed Vessel Series Observations

The closed vessel series discussed above was conducted to experimentally measure the pressure, temperature, and luminosity generated during the combustion of Vihtavuori N120 powder propellants. The literature review surrounding this propellant was negligible, however, for gun propellant, the pressure observed during the combustion process increases with an increase in propellant mass.

Different to pressure, the luminosity has an instantaneous effect while the propellant particle burns, where light can be seen in the form of a flame. When more particles burn simultaneously, a brighter light is produced, hence, the proposed idea that the luminosity could be used to track the mass of propellant being consumed per frame collected. With information on the mass consumed at specified periods of time in the form of frames, a mass consumption rate could be calculated.

4.2 Vented Vessel Series

A new experimental series was conducted inside the burning vessel, with the only difference being that the ventilation valve was opened throughout the combustion. During the closed vessel series, the ventilation valve was already present, however, kept closed during the combustion to trap the gases inside. The valve would only be opened once the combustion was deemed complete and the gases were to be removed in the safest way possible to clean the inside of the vessel and replace the propellant tray. The exit section of the valve would direct the gases at the back of the building, releasing the gases outside the building to prevent all personnel from inhaling the combustion products.

The ventilation valve addition aims to target the effect that having an outlet location for gases to escape during combustion in overall closed locations, similar to a warehouse storage. The ventilation valve for this experimental series would simulate the effect that windows would have, if left opened or forced opened due to pressure build-up in case of an initiation inside a storage facility. The gas outlet would allow hot gases to escape the vessel while combustion still occurs.

The location of the vent has an important role, since the distance required for the combustion products to travel would dictate the time that the gases were still present inside the vessel. Vents far from the combustion process would allow for longer periods of time before the existing hot gases escape the vessel, which would give the opportunity for the pressure to build up to higher values, thus accelerating the burn rate of the propellant particles under combustion. The vent height will also influence the speed of gases being released. Since the combustion products are lighter than air, these gases tend to accumulate at the top of the location, therefore, having a vent at higher heights would facilitate the escape of such gases as these would naturally flow upwards. In the burning vessel used in this investigation, the valve was attached to one of the pressure ports, which is close to two thirds of the height of the vessel, with the port leading to the ventilation valve.

If a vent location was fixed, the vent size selected would indicate whether it would behave more closely resembling a closed vessel, an opened vessel, or

somewhere in between. Figure 56 shows the range at which vent size dictates the mode of operation.

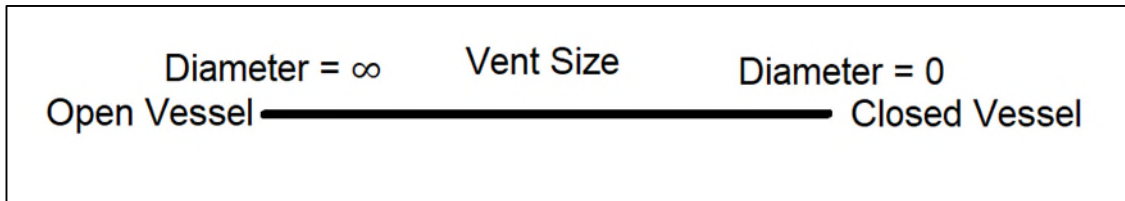


Figure 56: Vent size effect on mode of operation.

Smaller vents more closely resemble a closed vessel, since the quantity of gases capable of escaping the vessel is limited, thus the hot gases will leave the vessel at a slower pace. This will influence the pressure and temperature inside to still reach high values, increasing the propellant burn rate, which would maintain high pressures.

Larger vents would provide better conditions for the hot gases to escape at a faster rate, which would lower the maximum pressure and temperature inside the instrument. In turn, this prevents the burn rate from rising to its maximum conditions, which extends the combustion process to safer working conditions. The temperature and pressures will be reduced compared to closed vessel combustions, thus diminishing the overall impact applied to the structure surrounding the combustion process. Also, at lower temperatures and pressures, the flames generated are smaller, which would also lower the chances of igniting nearby piles of propellants if protected or packaged correctly.

Two valve sizes were selected for the vented vessel series, one 0.1 cm in diameter, and a larger one at 1 cm in diameter, which will be described as small vent and large vent, respectively. It is expected that the small vent will behave more similarly to a closed vessel condition, rather than open vessel mode of operation. The larger vent, however, should behave more towards the open vessel mode. Since the combustion location is at the base of the experiment and the vent height is a close distance away.

Figure 41 located in page 78, demonstrated the importance that temperature has on the peak pressure reached, hence, any gas leaving the vessel through the

ventilation valve will be at high temperatures because it will not have had time to disperse its high energy content as radiation and conduction processes tend to be slow process. This indicates that there are 2 factors contributing to the peak pressure reduction in vented vessel series:

1. Gaseous contribution will diminish because the gases can escape the vessel.
2. Temperature contribution diminishes since the gases escaping contain high quantities of energy. The smaller quantities of gases present inside the vessel will have less overall energy; hence the expansion of such gases will not be as prominent as observed during the closed vessel series.

In terms of luminosity generated during combustion, it can also be expected to diminish for similar masses when compared to the closed vessel data due to the lower pressures and temperatures reached, it is expected that the burn rate will drop, therefore less propellant will deflagrate between each observable frame, and therefore, less luminosity will be generated from the combustion. This domino effect will continue to the mass consumption rate, where a drop is expected because less propellant being ignited between frames means that the combustion process should take slightly longer, thus having smaller mass consumption rates. This indicates that an increase in combustion time was expected, since more time was necessary to deflagrate the same amount of propellant mass.

The pressure-time behaviour should behave in a similar manner as the one observed during the closed vessel series in Figure 33, page 65, because the combustion process will continue behaving in the same way. Once the firing key activates, the ignition system was ignited, eventually reaching the propellant particles, which in turn generate a flame that spreads throughout the propellant tray and ignites all particles. Hot gases are produced from the chemical reaction, which slowly increase the pressure and temperature inside the vessel. The pressure will keep rising until the generation of combustion products is exceeded by the release of gases due to the presence of the ventilation valve. It is important

to note that for vented vessel series, no rested pressure will be observed as all gases were allowed to leave, until the overpressure is neutralised and reaches atmospheric conditions.

In summary, the expected changes were highlighted in Table 6 with a quick observation based on the explanations provided above.

Parameter	CV	VV	Observation
Mass	Fixed	Fixed	Fixed loading density to be combusted
Gaseous Products Inside Vessel	Higher	Lower	Gases are capable of escaping the vessel
Temperature	Higher	Lower	Less energy available due to hot gases leaving the vessel before reaching thermal equilibrium
Pressure Behaviour	Higher	Lower	Less gases present inside vessel
Peak Pressure	Higher	Lower	Smaller quantity of gases and temperature contributing to less gaseous expansion
Burn Rate	Higher	Lower	Smaller Pressure and temperature reduce burn rate
Combustion Time	Lower	Higher	With decreased Burn rate, more time required to combust the same mass
MCR	Higher	Lower	Smaller burn rate decreases MCR (both segmented and overall)
Luminosity	Higher	Lower	Smaller MCR and burn rate means smaller flame, therefore less luminosity

Table 6: Expected parameter differences between closed and vented vessel series.

4.2.1 Pressure Data

The data collected during the vented vessel series is shown below in Table 7.

	Small Vent		Large Vent	
Mass (g)	Peak Pressure (bar)	Combustion Time (s)	Peak Pressure (bar)	Combustion Time (s)
1	1.71	0.76	0.37	0.84
5	7.23	0.80	4.67	0.91
10	14.34	0.63	10.38	0.88
15	21.00	0.54	18.49	0.68
20	28.11	0.52	25.21	0.70
25	34.73	0.45	31.78	0.65
30	40.23	0.60	39.84	0.65

Table 7: Average Peak Pressure and combustion time measured during vented vessel series 1.

By keeping the vent valve opened during combustion, the combustion products created in the form of gases are allowed to escape the vessel once the pressure inside the vessel becomes larger than atmospheric pressure. Once this occurs, to stabilise the environment, the gases inside will be ejected out to match the pressure outside the vessel, to reach atmospheric conditions. Since some gases will be leaving before the combustion has completed, then the peak pressure should be expected to be lower compared to the closed vessel series.

Figure 57 includes 3 peak pressure behaviours, two data sets from the two vented vessel series, and the closed vessel data for comparison. All relationships observed seem to be affected by a linear rise in peak pressure when increasing the propellant mass consumed. The slope of each relationship decreases when increasing the ventilation valve, with the closer vessel series having the highest

slope at 1.69 bar/g of propellant combusted, followed by the smaller ventilation valve at a rate of 1.38 bar/g. Lastly, the large vent experiment provided the lowest rise at 1.27 bar/g rise.

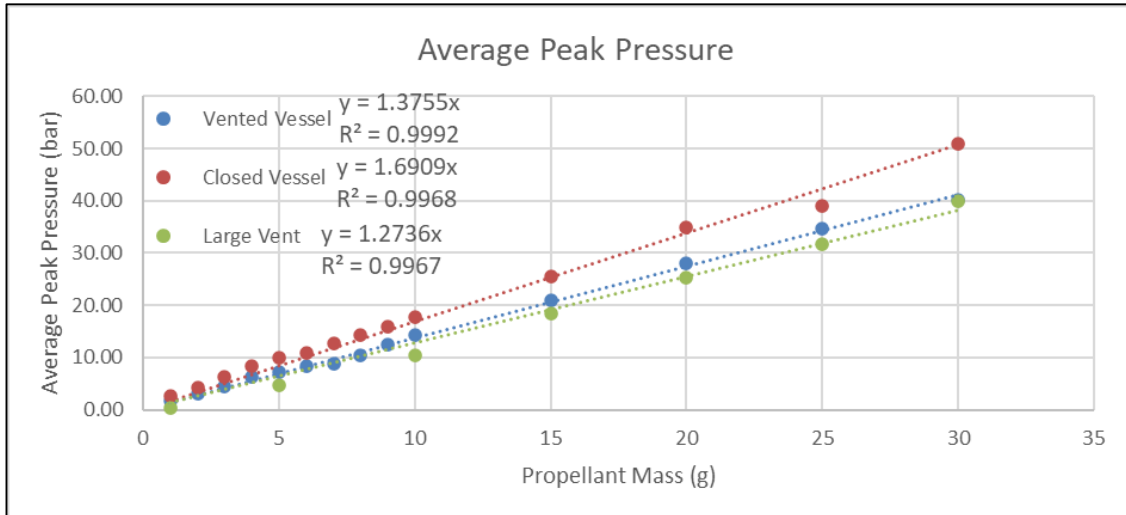


Figure 57: Average Peak Pressure data collected for Closed Vessel and both Vented Vessel series.

The data provided in Table 7 and Figure 57 shows a variation in behaviour observed for the larger ventilation series. The data shows that at smaller masses, the difference between the peak pressure observed are larger, however, as the propellant mass combusted reaches 10 grams, the peak pressure assimilates to the data collected during the small vent series. This is especially true during the combustion of 30 grams, where the average peak pressure was almost identical at nearly 40 bars of pressure achieved in both experiments.

In fact, if the data is split into two behaviours, depicted in Figure 58, one containing data from 1–10-gram experiments combustion, and the other consisting of 15–30-gram experiments, the pressure rise rates would be as follows:

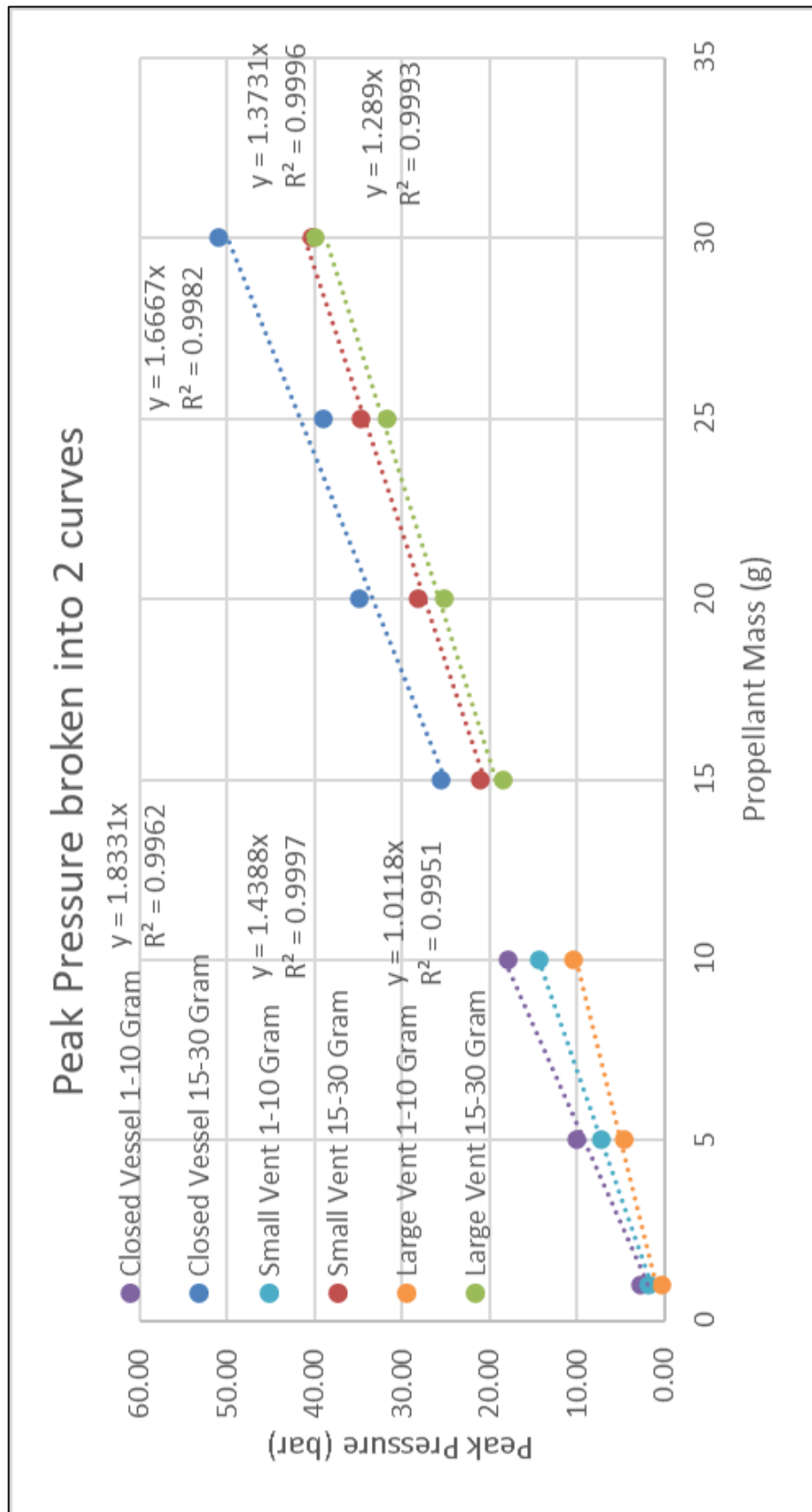


Figure 58: Peak Pressure collected at Large Vent series broken into two relationships.

A large discrepancy can be seen from the pressure rise rate within the large vent series, with nearly a 30% increase in the pressure to mass rate increase, rising from 1.01 to 1.28 bar/g. The same cannot be said for the smaller vent series, where the pressure increase rate remained similar, decreasing from 1.39 to 1.38 bar/g, nor the closed vessel series, with a decrease in rate from 1.83 to 1.67 bar/g. Had the pressure rise rate maintained at 1.01 bar/g, the expected pressure when combusting 30 grams of propellant would be 30.30 bar, a considerable drop from the data obtained.

The diminishing effect that temperature has on the peak pressure could be considered as a potential decrease in the slope observed. If we consider the case of deflagrating 100 grams of propellant instead of the limiting 30 grams used for these series, the gaseous contribution on the peak pressure can be calculated since it is related to a known and fixed parameter, which is the propellant mass. The mass of propellant dictates the number of moles of propellant present before the combustion, which will produce a fixed number of gaseous products due to the identical chemical reactions occurring. However, when focusing our attention on the temperature contribution, its contribution diminishes due to higher amounts of energy dissipation through radiation and conduction. This would have been observed with temperature data collected during combustion, where there will be a diminishing return in temperature rise with each increase in propellant mass added. This would diminish the rate of heat expansion occurring inside, hence leading to a decrease in peak pressure rate to be observed with increasing mass.

The increase in loading density led to an increase in pressure and temperature conditions inside the vessel, which translate to higher burn rates of the propellant particles. This indicates that less time is required for combustion, which translate to less time where the temperature dissipation is active. If this scenario has a more prominent role than the temperature increases rate drop, then it is expected that pressure rise slope would slightly increase in value. It was observed however, that the temperature rise drop had a stronger influence on the overall pressure rise slope, which led to a slight decrease from 1.83 to 1.67 bar/g.

Curiously, for the large vent series, the peak pressure rate increased when the propellant mass was beyond 15 grams, indicating that something occurred to generate a large increase in the pressure rate when it was supposed to maintain constant or have a slight drop. By running over the experimental design and the vent section of the experiment, it was noticed that the ventilation valve was a long, but narrow tube, which at the very end flowed downwards. It is believed that that when combusting up to 10 grams of propellant, the quantity of gases and pressure generated were small enough to be less noticeable. When testing 10 grams onwards, the flow gained strength, and the pressures achieved were high enough to propel the gases at supersonic speeds.

There are two parts in the design that could have caused resistance for the gases to escape:

- Long and narrow pipes are prone to choking the flow if supersonic, where the wall resistance will create a flow field of uneven speed [69], preventing the gases from escaping as fast as possible.
- End of ventilation valve points downwards for the last meter, instead of upwards.

In relation to the ventilation valve pointing downwards, the pressure inside the vessel was high enough to be force the gases downwards for only a metre, hence, this resistance can be assumed to be much smaller than the flow choking due to the narrow pipe.

4.2.2 Ventilation Pipe Removal

To address this question, an experiment was conducted to determine whether the long and narrow ventilation pipe was choking the flow. The same set up was used to combust 30 grams of propellant, however, the pipe attached to the large ventilation valve would be removed. The theory suggests that if the peak pressure achieved remains at 40 bar, there was no choking present and thus, the pipe presence was not obstructing the gaseous flow, however, if the pressure reduces to a value below 40 bar, then flow choking was present throughout the large vent

series, especially more prominent during the higher masses of propellant combustion of 15-30 grams.

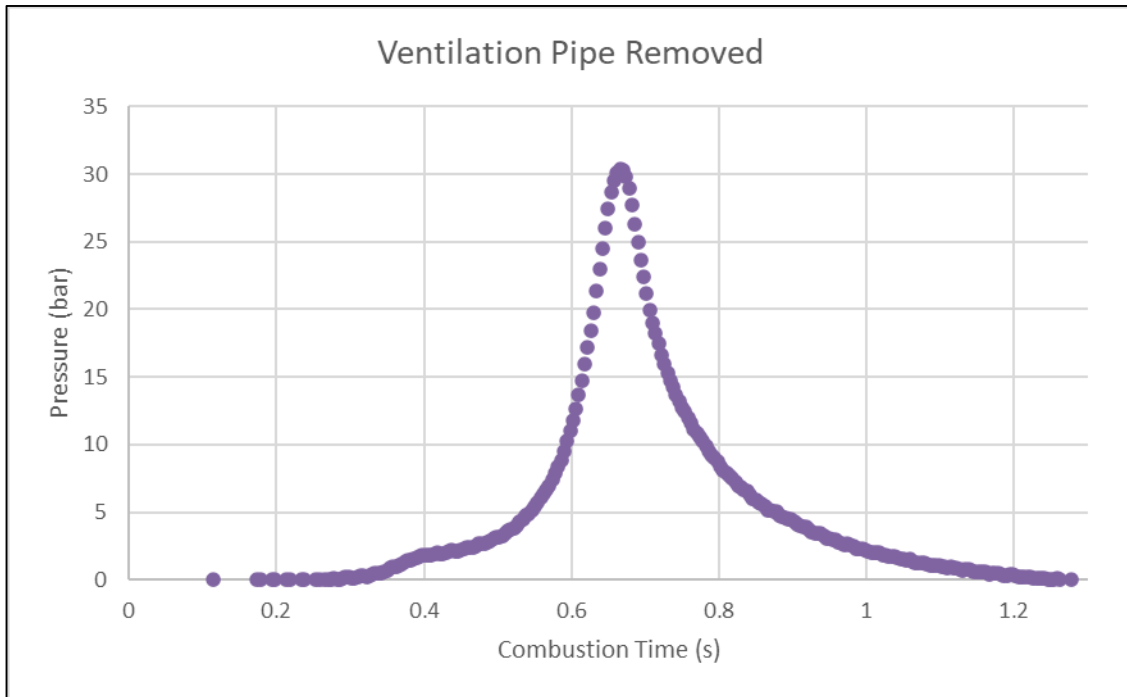


Figure 59: Pressure data collected without pipe connected to ventilation valve.

Data in Figure 59 confirms the peak pressure measured has reduced from 40 bar to 30.36 bar, proving that the long and narrow pipe was choking the flow of escaping gases. The flow choke slowed the rate at which the product gases were escaping the vessel. Since the pressure rise for the choked large vent series started at a rate of 1.01 bar, if this relationship was true at all times, combusting 30 grams of propellant should reach a pressure peak of 30.30 bar, which was almost achieved by the 30.36 bar during the combustion when the pipe was removed.

4.2.3 Luminosity Data

The luminosity data measured with the planetary camera was used to record videos of the combustion processes during both vented series. All calculations and assumptions used during the closed vessel calculations were carried out for the data obtained for the vented series.

Similar to the pressure data, it was estimated that the normalised luminosity slope rise would maintain constant or have a slightly decrease with the addition of a ventilation valve, and a further decrease when increasing the vent diameter. This was hypothesized because the pressures and temperatures inside the vessel would be lower compared to the closed vessel series, hence, the burn rate would be smaller for similar masses, and thus, less propellant mass would be consumed between each frame, translating to less light being generated per frame. The data collected for both series was included in Table 8, with the addition of the closed vessel series data for comparison.

Mass (g)	Closed Vessel	Small Vent	Large Vent
1	2.53	2.03	1.00
5	21.80	11.08	9.40
10	47.50	28.44	22.57
15	101.50	60.90	44.29
20	142.15	91.74	82.73
25	147.10	128.41	110.65
30	184.35	147.07	134.14

Table 8: Normalised Luminosity data during all 3 series.

The data in Table 8 confirms the hypothesis stated above regarding the decrease in normalised luminosity, however, the decrease in normalised luminosity was diminishing with increasing propellant mass. At masses 1 and 5, the Large Vent data produced less than 50% of the calculated closed vessel data, whereas at larger masses, namely 25- and 30-gram experiments, where the large vent data ranged between 72-75% of the closed vessel luminosity data indicating a significant increase with increasing combusted mass. When plotting the data on a graph, it can be easier to identify certain behaviours.

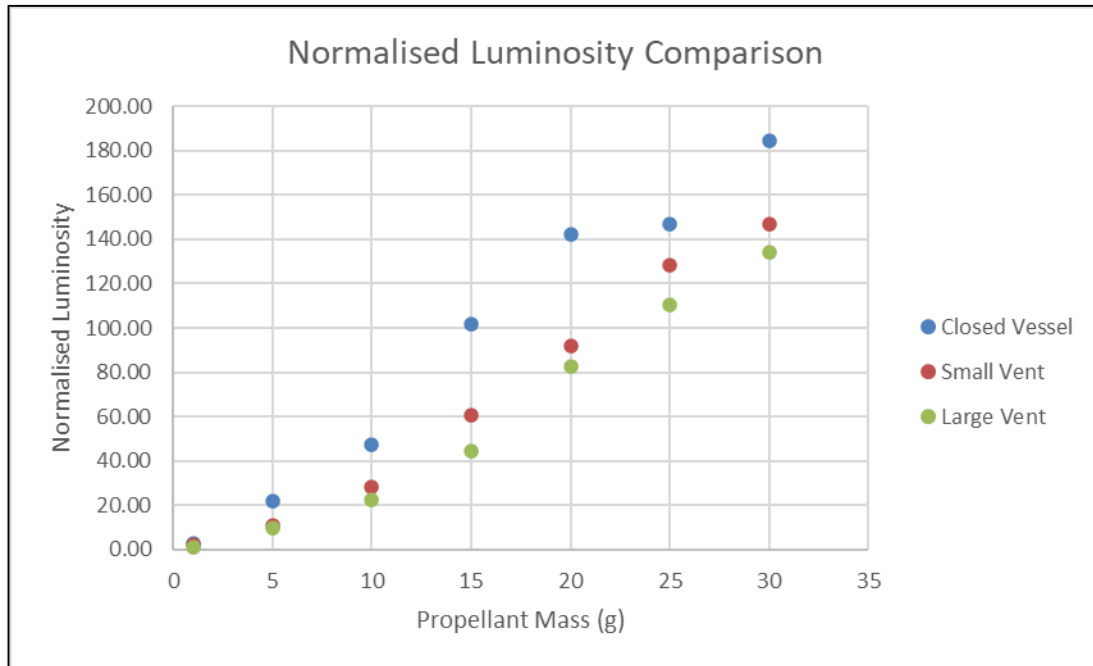


Figure 60: Normalised luminosity data collected for all 3 series.

In Figure 60, the relationships between normalised luminosity and propellant mass show the decreasing effect in normalised luminosity when increasing the vent size. When focusing on the Large Vent data points, it can be noticed that there seems to be two slopes influencing the result in different sections of the relationship. The behaviour observed during the 1–15-gram experiments demonstrate a smaller slope than the results plotted from 20–30-gram experiments. This was similarly observed during the pressure data analysis, however, the data points separating the slope change was between 1–10-gram experiments and 15–30-gram experiments, indicating that masses between 10 and 15 grams appear to act as a transition behaviour between laminar and turbulent flow. This effect is not as prominent in the closed vessel and small vent series, nevertheless, differences can be observed, which have been highlighted in Figure 57. Data from Figure 60 was split into two correlations and can be seen in Figure 61.

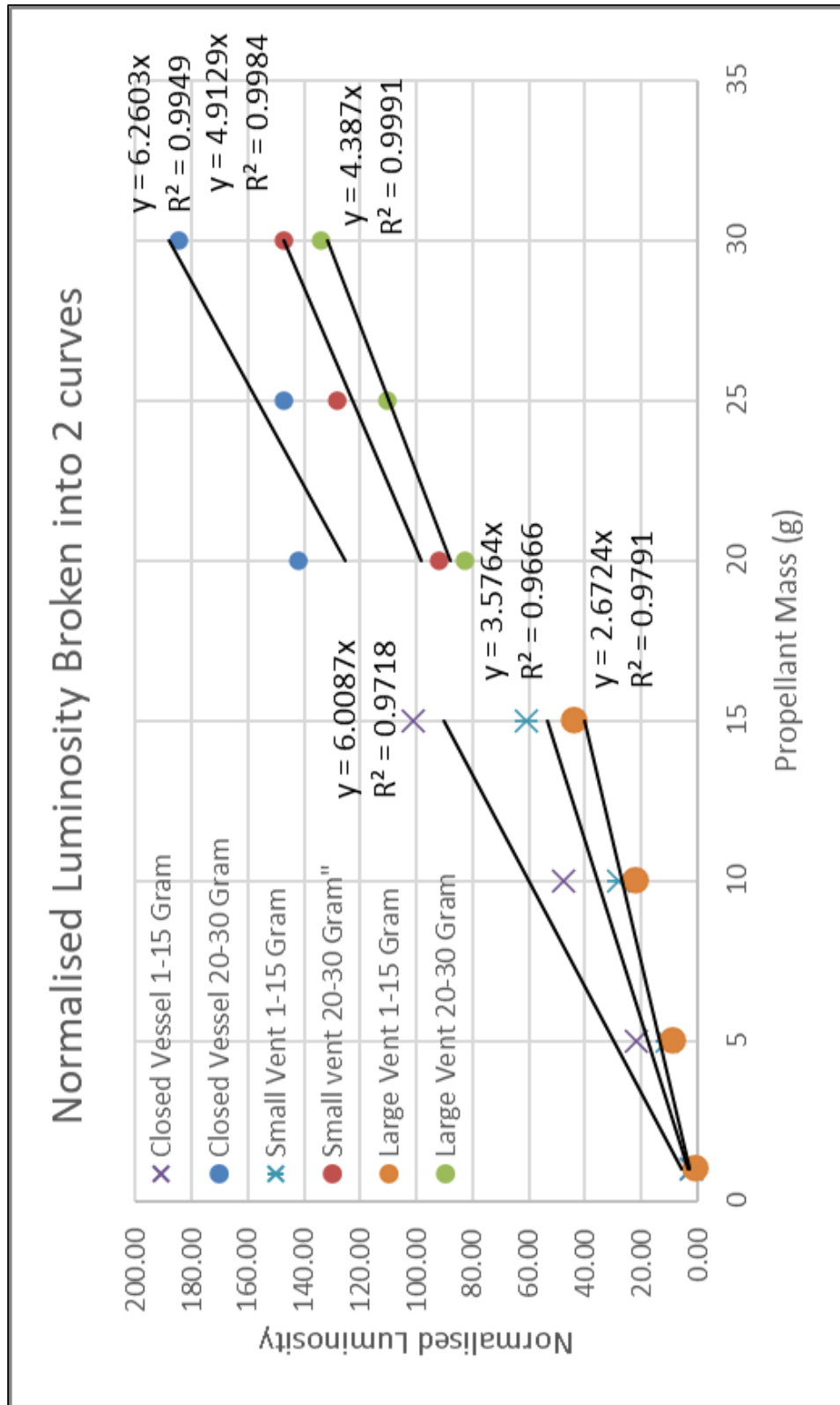


Figure 61: Normalised luminosity data broken at 15-gram data for all series.

The closed vessel data indicates a slight increase in the normalised luminosity slope rise, indicating that the faster combustion has a stronger influence than the temperature rise decrease on the luminosity slope rise than the pressure slope rise, where the slope rose from 6.01 to 6.26 luminosity. When adding a vent to the instrument, there was a larger effect observed, where the large vent and small vent slopes rose from 2.67 and 3.58 to 4.39 and 4.91 luminosity/g respectively.

The sharp increase in normalised luminosity slope observed after the 15-gram firing confirms the theory that the flow could be choking with the existing long and narrow pipe. This demonstrates that the measured pressure and normalised luminosity data observed are relevant if the same long and narrow pipe is present, however, do not represent vessels that are vented without any piping. To obtain these data points, a new series would be required where the vent was removed altogether.

4.2.4 Area Under the Curve

By focusing on the entire combustion process and measuring the total AUC, it is possible to have a clearer understanding of the firing as the entire luminosity data is captured by the camera as opposed to focusing only on the peak luminosity average frame. The addition of vents allows some of the luminosity to escape the vessel, reducing the total luminosity data obtained, hence, the AUC is expected to decrease slightly during the small vent series, followed by a larger decrease for the larger vent series, in theory.

Figure 62 confirms this theory, however, a smaller effect in practice than predicted. Considering that a vent of 0.1 and 1.0 cm represent a small and a large opening to the volume available for the instrument tested, the expected luminosity reduction was prevented by something else.

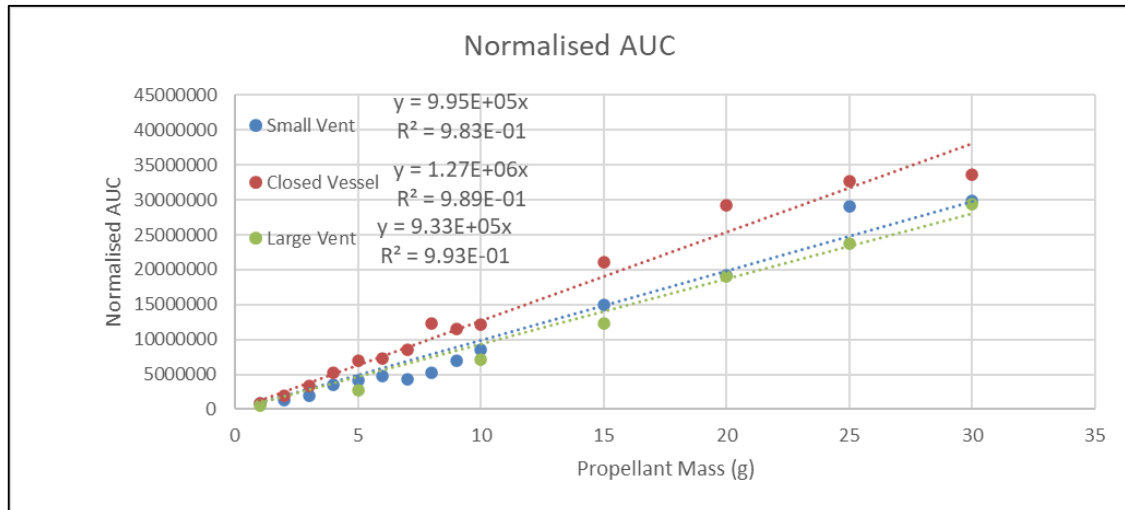


Figure 62: Normalised AUC data collected during the vented vessel series.

The addition of a small vent had a larger decrease in normalised AUC than the large vent, possibly further solidifying the theory of the flow being choked by the long and narrow pipe.

4.2.5 Mass Consumption Rate

Starting with the mass consumed in Figures 63 and 64 for both vented series, each figure will demonstrate the total amount of propellant mass being consumed after each frame. A useful observation from these figures refers to the frame range which the combustion started to accelerate, which could be observed by a sudden change in slope.

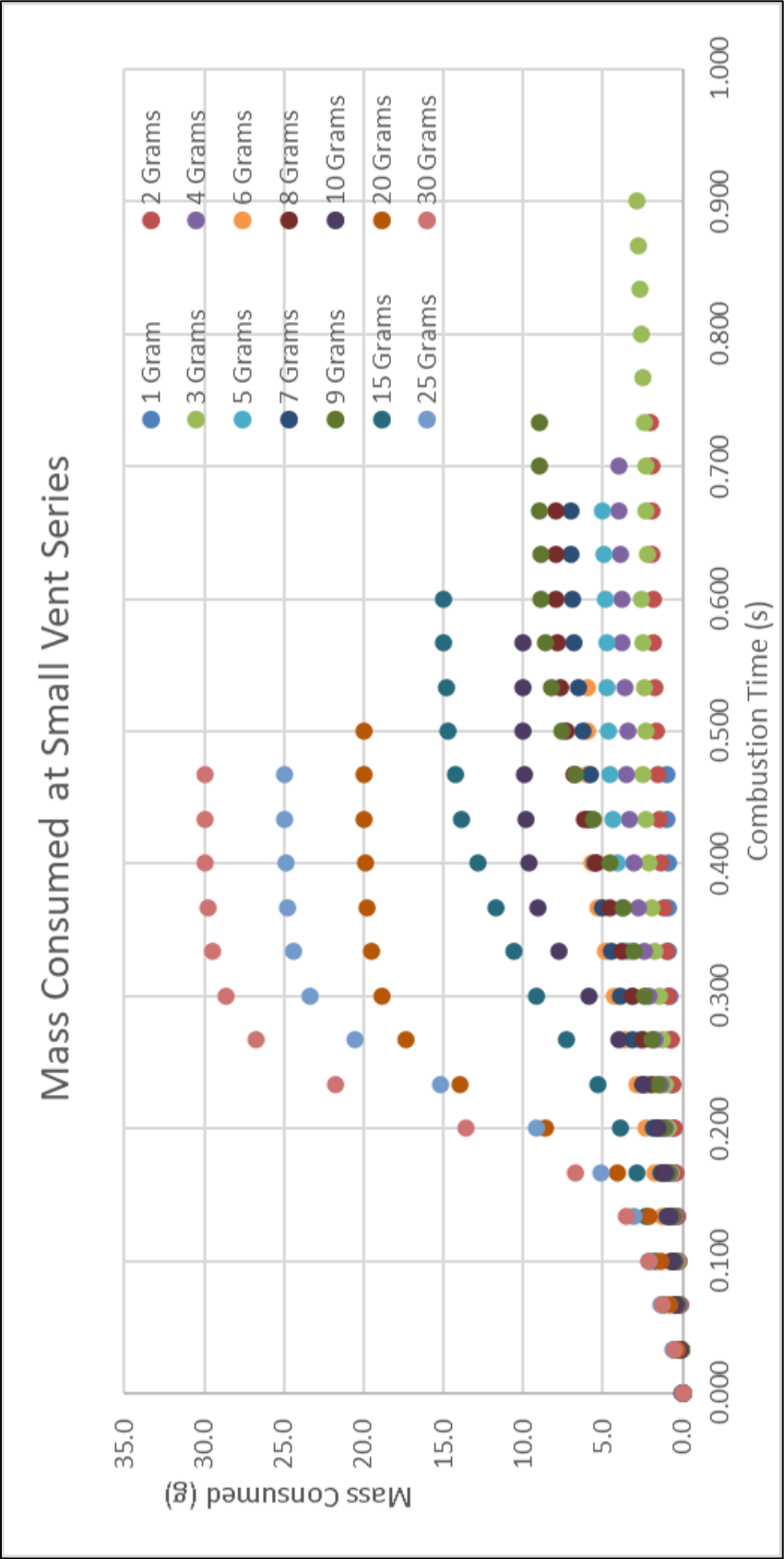


Figure 63: Mass Consumed during Small Vent Series.

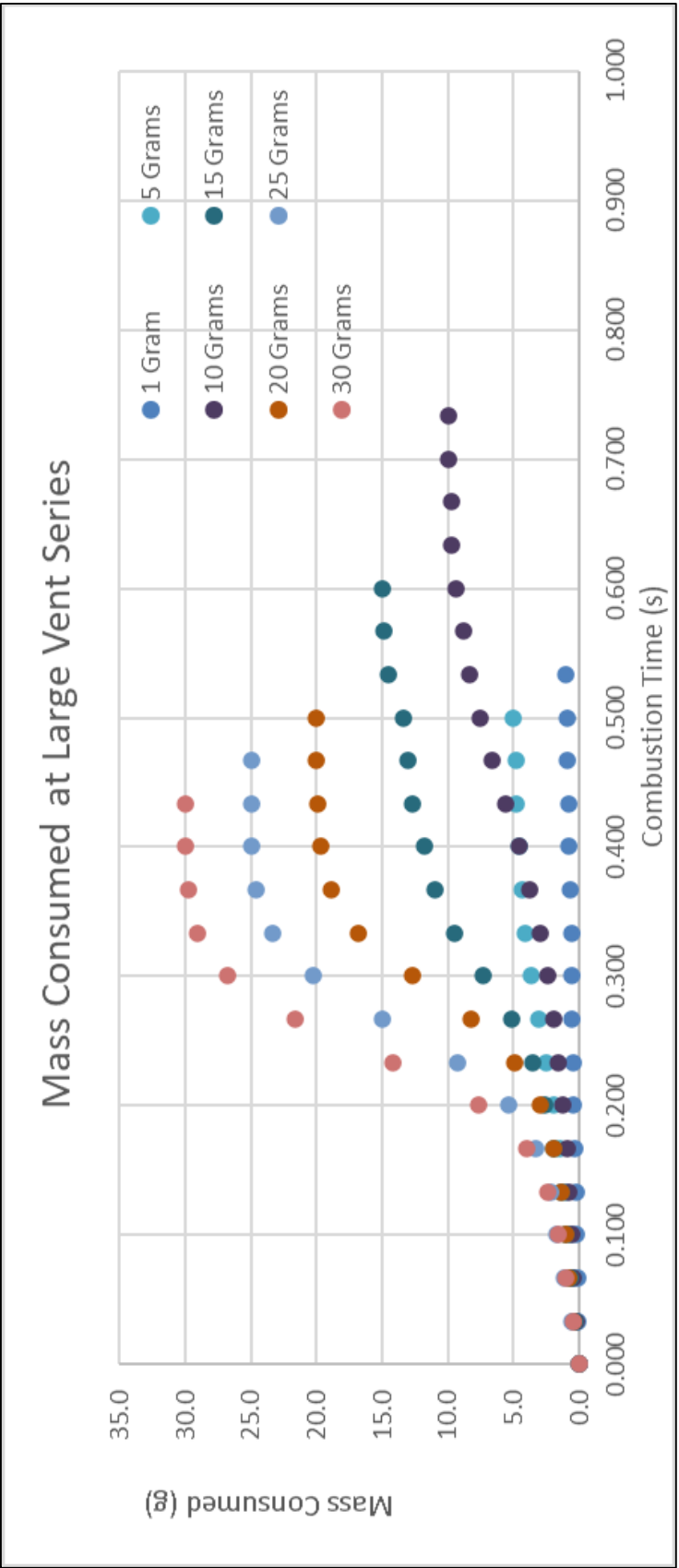


Figure 64: Mass Consumed during Large Vent Series.

By focusing on the frame representing the 0.2s of combustion time, it can be seen that the mass consumed was more advanced for the smaller vent, where the 30 gram firing has already combusted nearly 15 grams of propellant, and the 20 and-25 gram firings have consumed close to 10 grams each, whereas the mass consumed in the same time frame for the large vent series was still below 8 grams for all 3 large mass firings. This difference in combustion progress indicates that the increase in vent size allowed for an extra frame to be required for the luminosity data to build up to reach the same combustion progress.

Although Figures 63 and 64 may give the impression that the combustion processes were slightly longer during the small vent series, this was not particularly the case. Larger propellant masses generated faster combustion because of the faster build up in pressure, temperature, and luminosity, hence, a higher burn rate was achieved, which led to much faster combustion. During the large vent series, a shorter series was conducted, where only the masses of 1-, 5-, 10-, 15-, 20-, 25-, and 30-gram firings were conducted. The 7 experiments which were not included in the short series were of smaller masses.

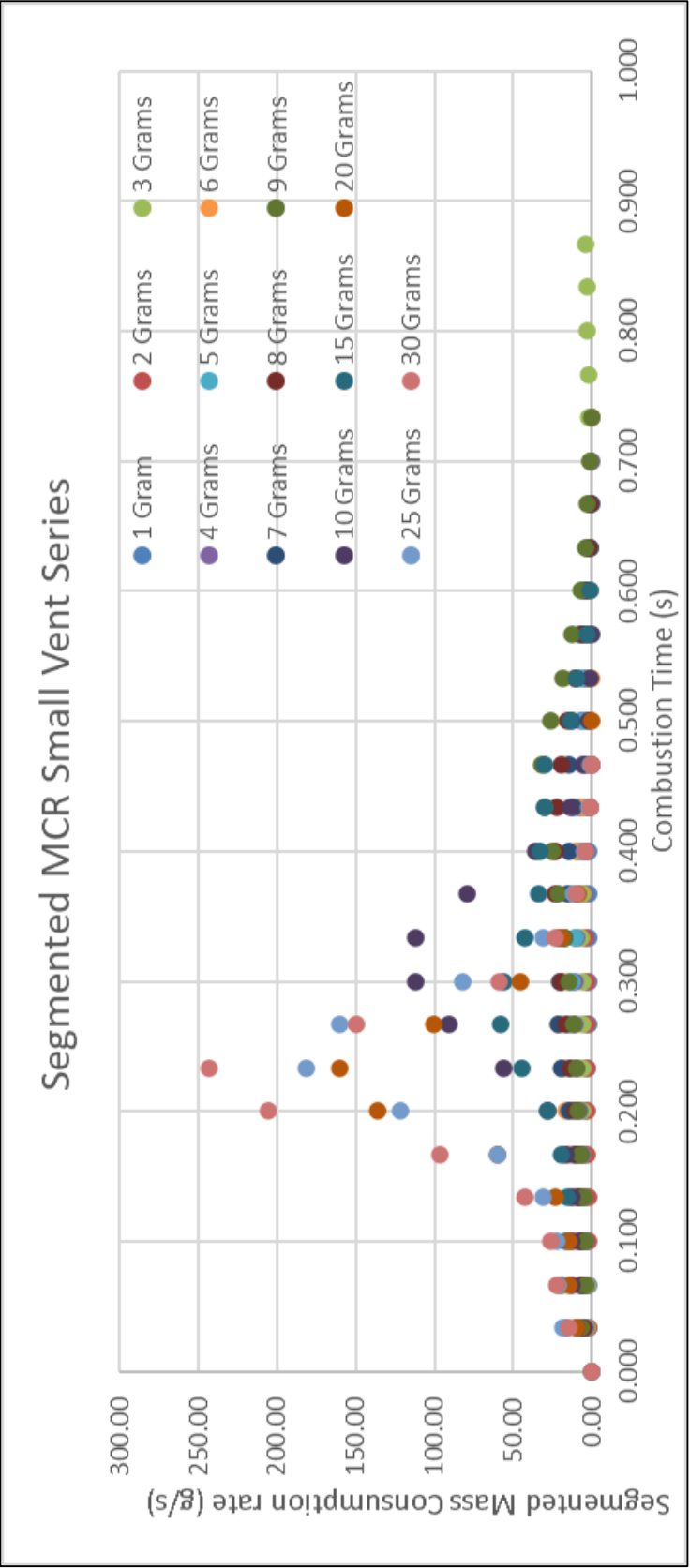


Figure 65: Segmented MCR during the Small vent Series.

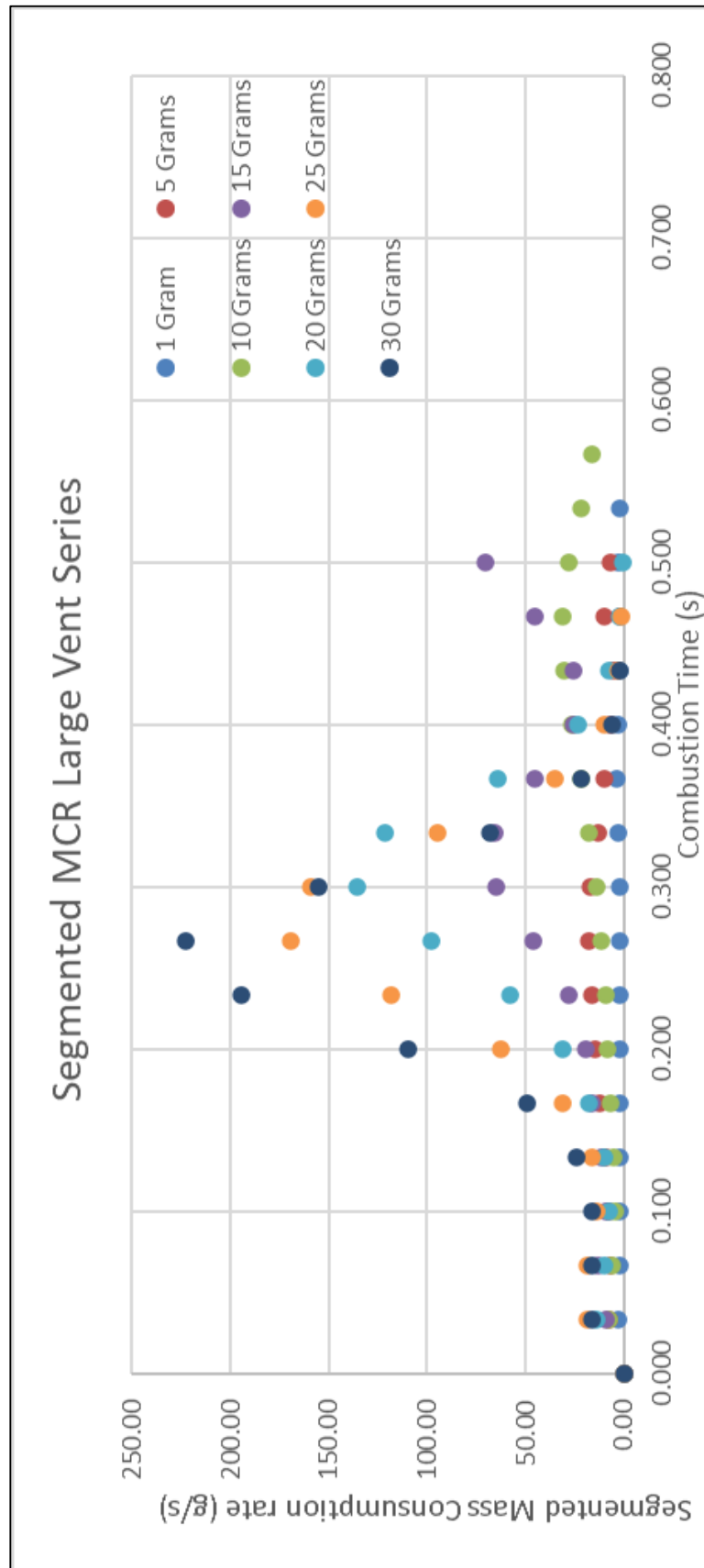


Figure 66: Segmented MCR during the Small vent Series.

As observed from mass consumed in Figures 63 & 64, the more advanced mass consumed data seen in the small vent series is reflected in the segmented MCR figures above. Figure 65 demonstrates slightly higher MCR values at a few earlier frames, indicating that the combustion is occurring faster and reaching its peak a few frames faster than the larger vent series.

The difference between the peaks in segmented MCR Figures 65 and 66 is slightly above 20 g/s higher for the small vent series. This is equivalent to a 9.45% rise in segmented MCR peak at the highest condition. A larger increase was expected since the vent diameter was increased by a factor of 10, further confirming the prediction that something other than the vent was choking the flow and preventing the hot flame from escaping the vessel.

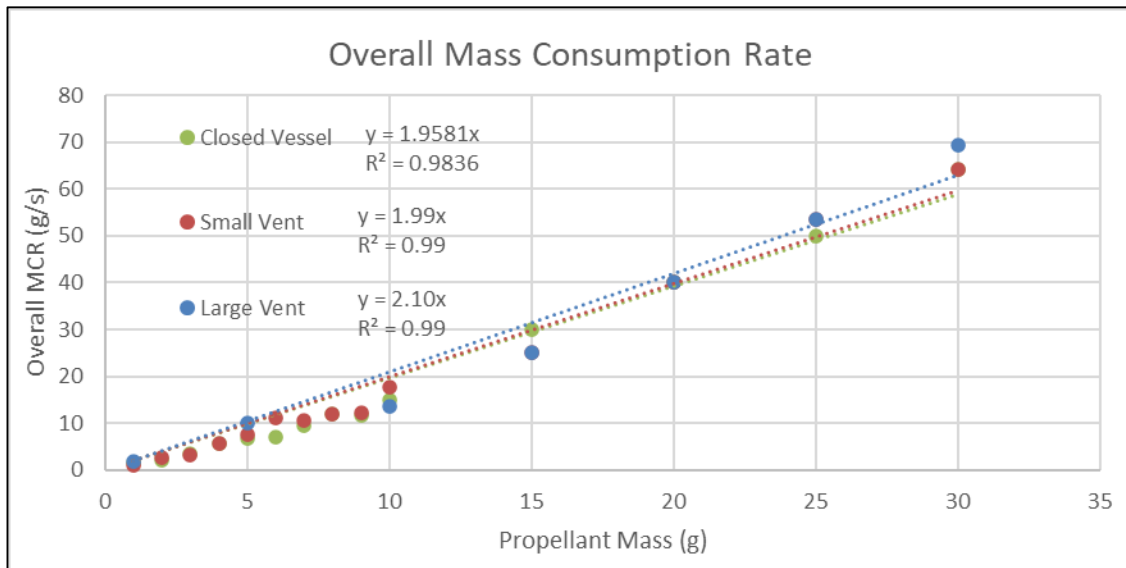


Figure 67: Overall MCR data for Vented Vessel Series.

Figure 67 shows the overall MCR calculated for both vented vessel series and includes the closed vessel series data for comparison. The relationships above clearly indicate that the addition of a vent and its increase had no impact on the overall MCR, which can be traced back to no difference in the combustion time during combustion. In order for the combustion time to have been kept similar, it would be only possible if the combustion was occurring instantaneously, in which case it would not have made any difference whether the ventilation valves were opened or not, or if something was preventing the instrument from behaving

naturally. The lack of confidence in the dataset shown in Figure 67 once again highlights the evidence that the long and narrow pipe was choking the flow in an unnatural way, misrepresenting the data obtained for adding a vent to the instrument.

Relating this to a real-life situation, it is desired to have larger vents present in warehouse storages of propellants because of both the effects registered above. Having a lower MCR signifies that less mass of propellants was ignited at any given time, which will limit the pressure and especially temperature reached. A smaller MCR will also delay the time required to reach the peak conditions, which allow even further time for hot gases to dissipate, decreasing further the MCR.

Since the mass of all the experiments was identical, the overall MCR can only vary by the combustion time, therefore, having a camera capable of capturing more frames every second would increase the accuracy in this measurement by providing more accurately the combustion time.

4.3 Vented Vessel – Pipeless Series

The data obtained during the vented vessel combustion series in the previous Chapter was skewed by a flow choking present in the system. To obtain more realistic representation of the desired scenario, the long and narrow pipe was removed. The gases generated would be released immediately to the blast cabinet, which had its ventilation turned on and the doors to the laboratory closed, hence, no gases would be released near any personnel.

During the pipeless series, there were 3 vent sizes tested:

1. A valve of 0.1 cm in diameter, denoted as Small Vent.
2. A valve of 1.0 cm in diameter, denoted as Large Vent.
3. No valve attached, leaving a hole of 2.5 cm in diameter, denoted as No Valve.

4.3.1 Pressure Data

Table 9 contains the pressure data obtained during the three firings. The data obtained during the closed vessel data was also included as reference of the highest pressures collected.

From the data present in Table 9, it can be observed that the peak pressure was at its highest values for all masses during the closed vessel series, as expected due to the trapped combustion products. The addition of any valve, regardless of the size, would result in a lower peak pressure observed because the combustion products would be leaving the vessel.

The addition of Small Vent valve was enough to reduce the pressure inside the vessel with varying effects. It can be seen that the pressure reduction was more prominent for lower masses, especially during the 1-gram firing, which a pressure drop was observed from 2.64 to 0.76 bar, equating to a 71% reduction. The increase in mass combusted, however, decreased the efficiency of the valve observed. At the highest mass, the pressure dropped from 50.89 to 45.98 bar, a 10% decrease.

	Peak Pressure (bar)			
Mass (g)	Closed Vessel	Small Vent	Large Vent	No Valve
1	2.64	0.76	0.31	0.00
5	10.00	6.78	0.40	0.02
10	17.83	15.03	1.24	0.11
15	25.63	22.39	10.63	0.11
20	34.88	29.94	16.65	0.11
25	38.98	38.33	22.18	0.24
30	50.89	45.98	30.91	0.25

Table 9: Peak Pressure data collected during the pipeless series.

By increasing the vent diameter to a large vent, the pressure reduction was increased for all masses, boasting a drop of 88% when combusting 1 gram of propellant, and 39% during the firing of 30 grams. The pressure data rose at a slower rate until 10 grams, where 1.24 bar was observed. When 15 grams of propellant was combusted, a drastic increase in pressure was observed to 10.63 bar, indicating that a choking condition was reached for this vent size. This choking condition was not related to any instrumentation limiting the capability of the experiments, instead was associated with the large quantity of gasses being released by such a small vent size.

When removing the valve entirely, the pressure did not rise past 0.25 bar overpressure, showing a pressure reduction of 99.5% and above for these masses. This demonstrates that when no valve was attached and 2.5 cm in diameter was opened for an instrument with a volume of 3.8 l, and combustion of mass of up to 30 grams, the pressure rise closely resembles a vessel opened to the atmosphere.

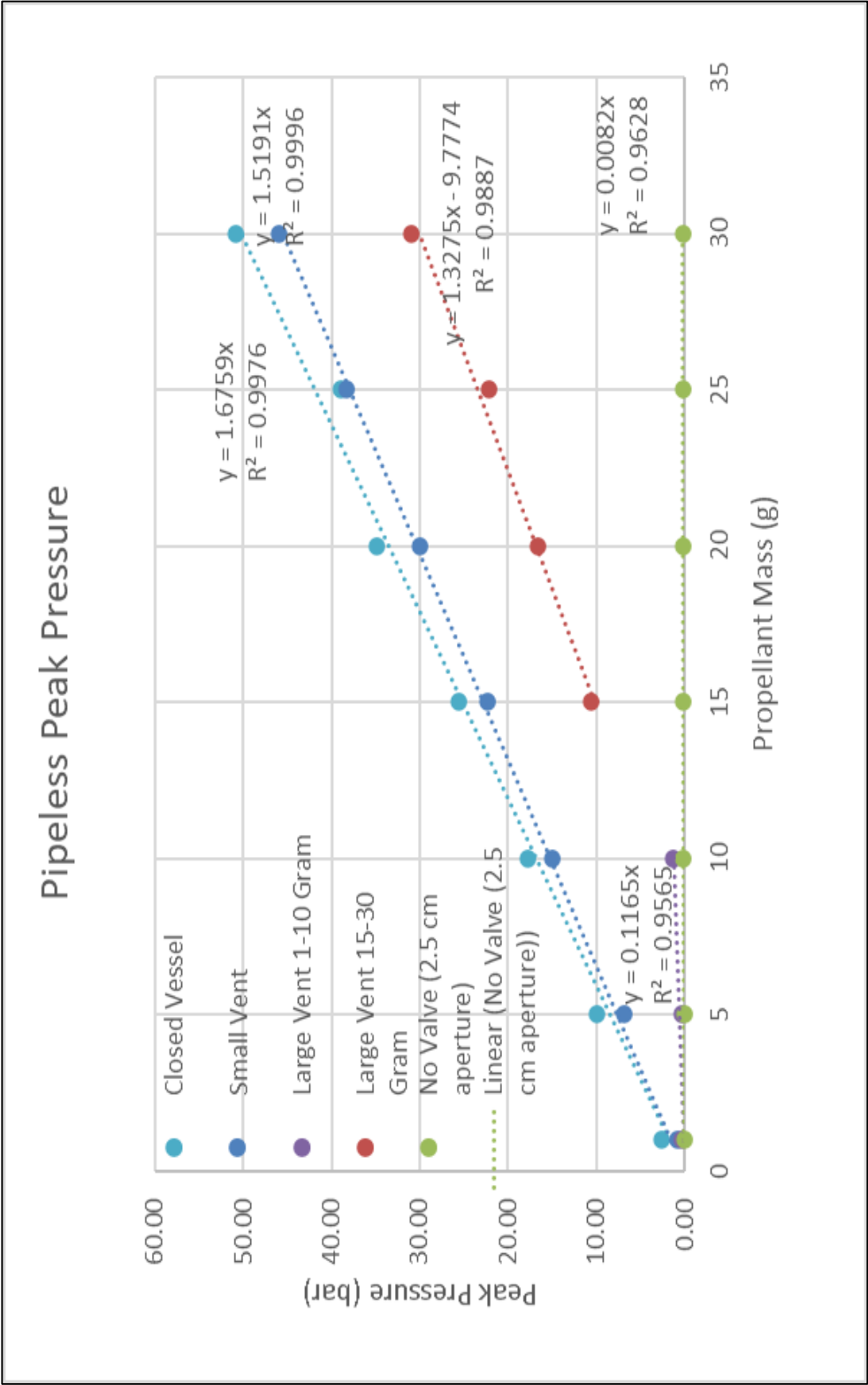


Figure 68: Peak Pressure data collected during the Pipeless series.

Figure 68 demonstrates graphically the data obtained as visual aid. The closed vessel, small vent, and no valve series are all represented by one single relationship since their behaviour was linear for the conditions provided by the experiments run. The large vent series was represented by 2 relationships because of the drastic change in behaviour. The relationship observed by the purple data points represent this series when the masses tested ranged between 1–10-gram experiments, while the red relationship represents the pressure data when combusting 15-30 grams of propellant. It can be predicted that if experiments were run with masses between 10 and 15 grams of propellant, an exponential rise would be observed within this propellant mass range until it reached the linear relationship observed. This region represents a transition period, where the flow begins to show signs of being choked due to the severe change in slope.

Although the addition of a small vent closely resembled the behaviour observed during the closed vessel series, the slope describing both series has a considerable effect. The closed vessel series has the highest slope measured at 1.68 bar/g compared to 1.52 bar/g from the small vent addition. Any increase in vent size decreased the slope effect, where the large vent had a linear slope of 1.33 bar/g from the 15–30-gram experiments, while a slope of 0.12 bar/g was observed from 1–10-gram firings. Lastly, the no valve series resembling an open vessel showed negligible rise in pressure, with a slope of 0.0082 bar/g.

The observations made above can prove helpful to predict the appropriate vent size necessary when a known propellant loading density will be stored in an instrument of known volume. For this particular instrument, it is possible to interpolate the vent size necessary for a peak pressure to be achieved, if necessary to prevent any damage to the instrument.

4.3.2 Luminosity Data

The luminosity data was also collected during the pipeless series to strengthen the theory that the mass consumption rate can be calculated through the observable light during combustion. For these series, it is important to keep in mind that for the tests in which the flow was not choking, part of the flame, and

thus combustion, was occurring outside the vessel, hence, it was not possible to observe the full extent of the luminosity generated by the combustion.

There are two factors that are believed to force a decrease in the luminosity observed when adding ventilation valves. Firstly, the flame to be ejected by the valve opening will not be accounted with the camera currently set up. Also, the lower pressures and temperatures achieved due to the escaping hot gases will indicate that the burn rate of each individual particle will occur slightly slower, which causes the combustion time to increase. This sequence of events will lead to having less propellant being combusted at any given time of the combustion, which translates to a lower quantity of photons being emitted, hence, another factor leading to a decrease in luminosity observed.

Table 10 contains the normalised luminosity data collected, which represents the peak luminosity intensity recorded divided by exposure time selected for the camera. Similar to the peak pressure data above, the closed vessel series data was included as a reference value of the highest luminosity peak.

	Normalised Luminosity (ms^{-1})			
Mass (g)	Closed Vessel	Small Vent	Large Vent	No valve
1	2.53	1.19	2.51	0.00
5	21.80	8.38	1.85	0.00
10	47.50	40.63	1.04	0.00
15	101.50	45.56	20.75	0.00
20	142.15	N/A	28.54	0.00
25	147.10	143.85	55.10	0.00
30	184.35	152.06	67.33	0.00

Table 10: Normalised luminosity data measured during the Pipeless Series.

The addition of the smallest vent had a comparable behaviour to the peak pressure data, where for the first two experiments conducted, there was a decrease in peak luminosity observed, however, any further increase in mass caused the flow to start choking, and thus, trapping the flames inside for longer, which allows for the luminosity to be collected. As the propellant mass was increasing, the difference in luminosity observed between the closed vessel and the vented vessel was diminishing, which can be seen at its most obvious during the 25-gram firing. Unfortunately, the luminosity during the 20-gram firing was lost due to an error in the software.

By increasing the vent valve to a large vent, it was expected for the luminosity data to undergo a further decrease due to flames escaping the larger vent. Surprisingly, the luminosity result for the first experiment was almost identical to the closed vessel data. This could have happened because the pressure achieved inside the vessel was not sufficient to force the gases and flame to be driven outward during the short combustion time. It was only after during the 15-gram firing and higher where the luminosity data went through a drastic change, indicating the transition conditions for this vent size. The highest luminosity value was obtained from the 30-gram firing at 67.33, a 63.5% decrease compared to the same mass experiment during closed vessel mode of operation.

The removal of the entire vent valve resulted in no luminosity being observed for all firings, demonstrating that for a vessel of dimensions that we have, 2.5 cm in diameter was behaving in a similar manner as open-to-atmosphere mode. The data shown in Table 10 can be seen represented as a graph in Figure 69.

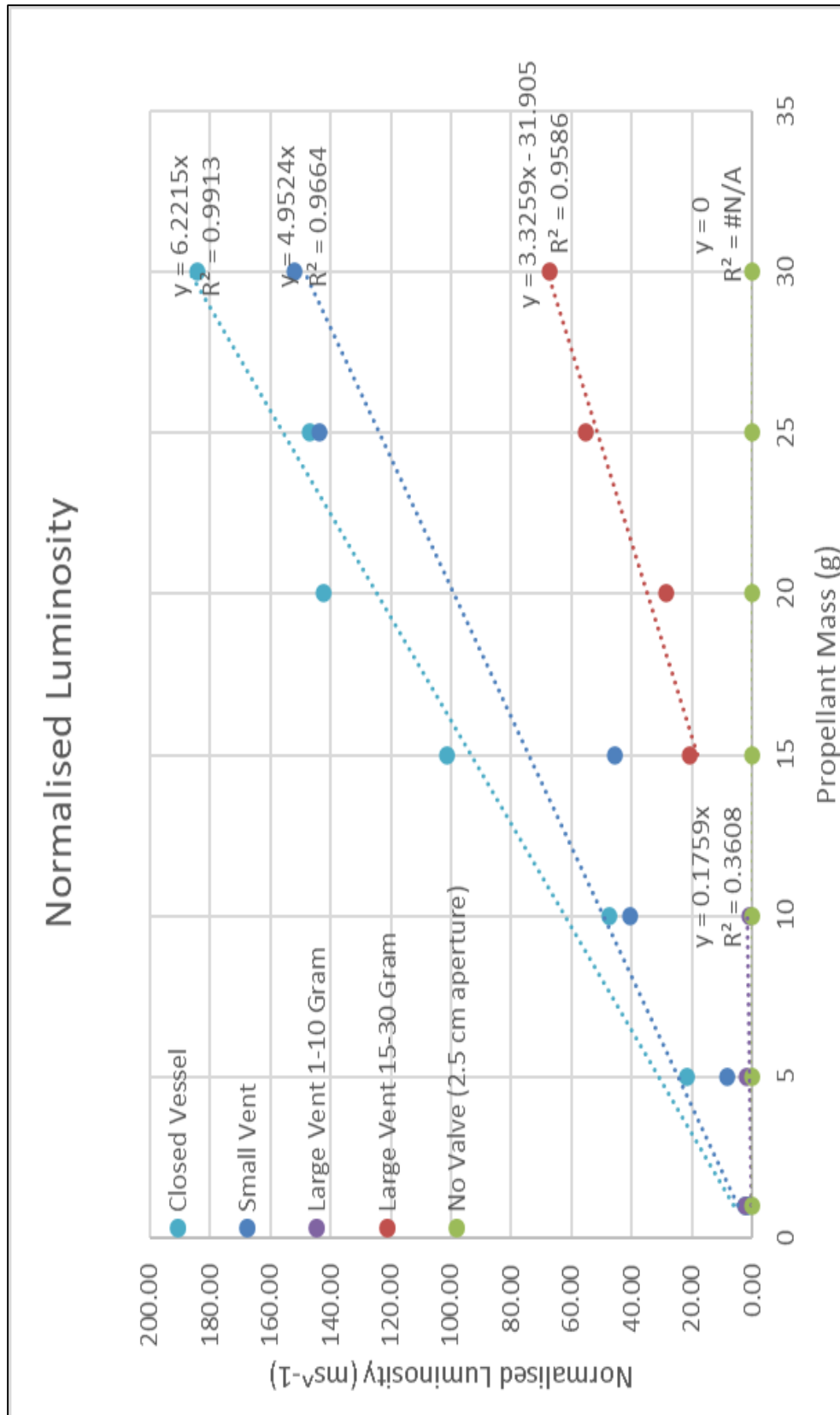


Figure 69: Luminosity data measured during the Pipeless Series.

When interpreting the data visually, there are three relationship behaviours observed for each ventilation size scenario. When the vent diameter selected is small, the luminosity data behaves in a linear increase, similar to the closed vessel series, indicating that the diameter was not large enough to prevent the pressure and luminosity to reach uncontrollable conditions. This was observed when focusing on the dark blue relationship representing the small vent series. On the other side of the spectrum, a vent too large will overwhelm the pressure and temperature generation, leading to small or negligible rises in overpressure, temperature, and luminosity. The removal of the vents describes this behaviour as seen that the luminosity data did not rise from 0, represented by the green relationship. With no luminosity data collected, it will not be possible to accurately predict the mass consumption rate during combustion.

Vent sizes between these extreme scenarios will behave in such way where a transition period is observed separating two distinct slope rises. This was represented above during the large vent series, where the purple relationship represents the data where the vent size overwhelms the pressure and luminosity rise, leading to low conditions measured; the red relationship contains the data after the transition period is reached, which shows a much larger slope, and thus increase in conditions for every mass of propellant added. If several masses were tested between these two extreme behaviours, it is believed that an exponential rise would be observed, for both pressure and temperature. It is possible to predict the range of propellant mass where the transition point begins by equating the relationship equations:

$$0.1759x = 3.3259x - 31.905$$

$$3.1499x = 31.905$$

$$x = 10.13 \text{ grams}$$

Equation 19: Propellant Mass Calculations where two Normalised Luminosity curves meet.

An important fact to remember is that the volume of product gases generated by the combustion is known because the chemical reaction occurring is constant,

hence, once the combustion reaction reached a condition where the generation of hot gases was higher than the expulsion from the instrument, the slope describing the pressure and luminosity rise would shift from unchoked to choked. For the above graph, it would represent the change from the purple relationship slope rise to the one observed on the red relationship.

Similar to the closed vessel series, both parameters demonstrated to rise in a linear pattern when increasing the propellant mass, and by plotting the peak pressure rise against the normalised luminosity, a correlation can be seen in Figure 70.

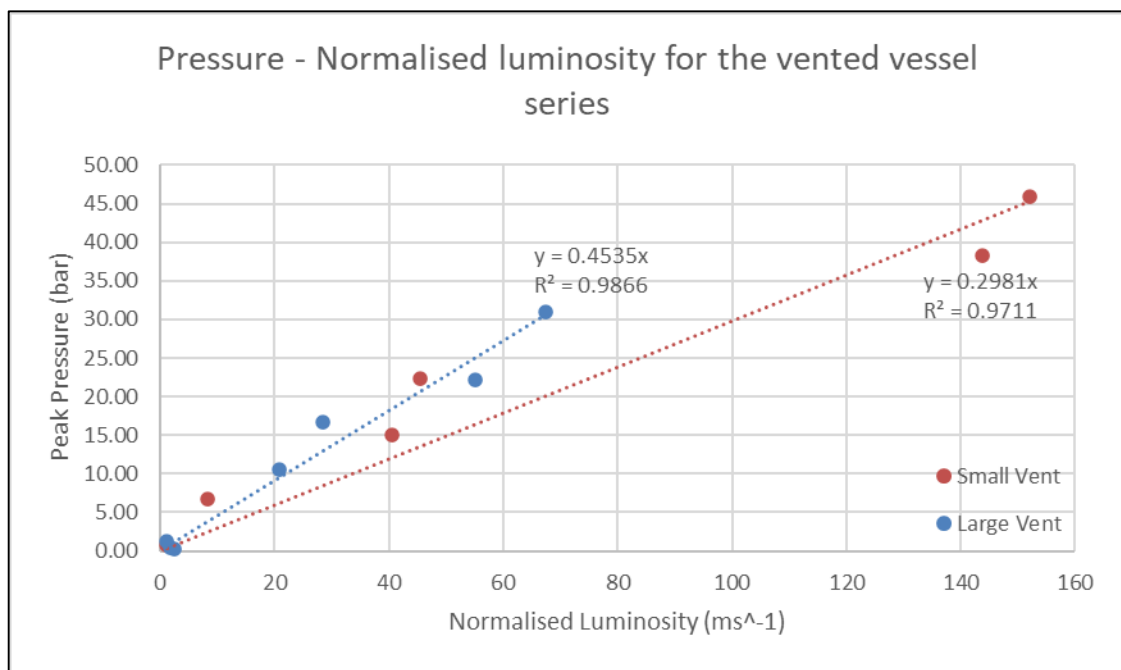


Figure 70: Peak Pressure - Normalised Luminosity in Vented Vessel.

Despite the presence of a vent, the correlation between peak pressure and normalised luminosity remains consistent. A slight rise can be observed in the coefficient of determination when comparing to the closed vessel correlation between these two parameters, boasting a rise from 97.9% to 98.66% for the large vent series, while a slight decrease to 97.11% for the small vent series. The ability to connect the peak pressure to the peak normalised luminosity can prove significant in situations where either a camera cannot be utilised to measure the luminosity, or when pressure sensors aren't or cannot be present.

4.3.3 Area Under the Curve Data

Instead of focusing solely on the luminosity peaks, which are representative of the pressure peak as the point at which the parameters are most intense, we shift our attention to the entire combustion process, by focusing on the total area under the curve observed by the luminosity data. Similar to the closed vessel and vented vessel series chapters above, the normalised luminosity was displayed, which accounts for the total luminosity during an experiment and the combustion time required. For the pipeless series, the normalised luminosity data is shown in Table 11, and visually described in Figure 71.

	Normalised Intensity (ms^{-1})			
Mass (g)	Closed Vessel	Small Vent	Large Vent	No Vent
1	1.59E+06	7.68E+05	1.22E+06	0.00
5	7.70E+06	6.94E+06	3.47E+06	0.00
10	1.37E+07	1.00E+07	8.35E+05	0.00
15	2.42E+07	1.56E+07	8.31E+06	0.00
20	3.17E+07	N/A	8.97E+06	0.00
25	3.56E+07	3.44E+07	1.45E+07	0.00
30	3.84E+07	3.66E+07	2.05E+07	0.00

Table 11: Normalised intensity (AUC) during the Pipeless Series.

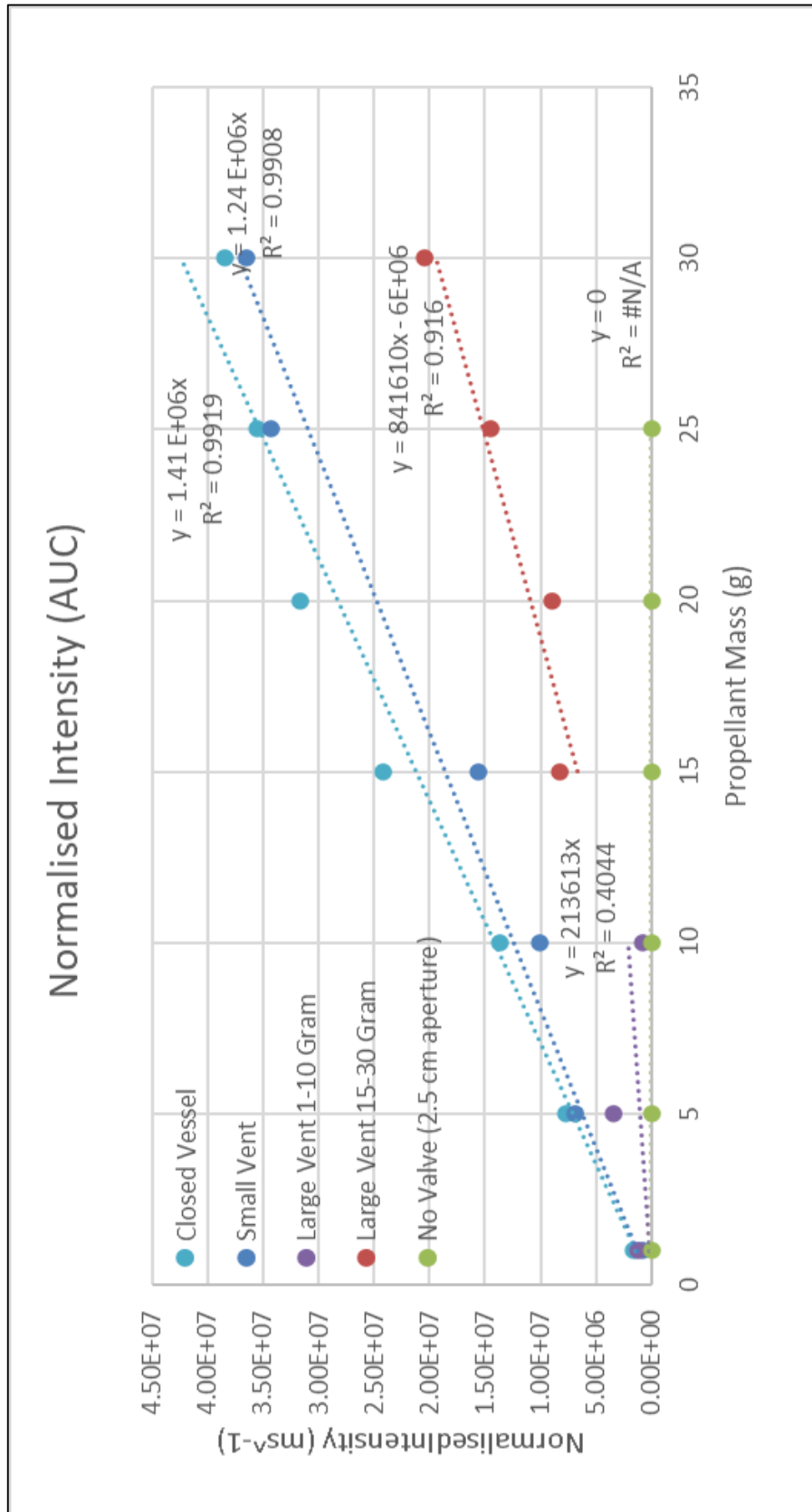


Figure 71: Normalised intensity (AUC) during the pipeless series relationships.

Despite representing different aspects of the luminosity generated during combustion, both the normalised luminosity calculated from the AUC and the peak luminosity value produced similar behaviours, strengthening the claim that the luminosity observed from the combustion has correlations to other combustion parameters. The analysis made for the normalised peak luminosity data are all valid for the normalised combustion luminosity, since the relationships observed for all series are similar. The smallest vent closely resembles the closed vessel data, only with slightly lower intensity at a lower slope rise. The largest vent size had no observable luminosity recorded. The large vent has a slow rise until a certain propellant mass was reached, at which point the slope drastically increases to a linear equation, where the slope is still lower than the observed slope for the Closed Vessel and small vent. Once again, the propellant mass test where this transition period where the flow appears to be choking hovers around 10 grams.

There are two data points that cast some doubt to the data, the 30-gram value for the Closed Vessel series, and the 5-gram value for the large vent series. The 30-gram data during the closed vessel series had a slower increase in value than expected, which resulted in the relationship seeming to transition to a logarithmic or asymptotic behaviour. As for the 5-gram data point for the large vent, it produced a much steeper rise. A sharp increase in normalised intensity was observed when increasing the propellant mass up to 5 grams, followed by a sharp decrease when the mass was further increased to 10 grams. This can be explained by a weakness in the method used to calculate the normalised intensity. As previously described, the normalised intensity is calculated by Equation 20:

$$\text{Normalised Intensity} = \frac{\text{Normalised Area Under the Curve (Norm AUC)}}{\text{Combustion Time}}$$

Equation 20: Normalised Intensity.

Since the normalised intensity value in question was much higher than expected, this was either caused by a large, normalised AUC value, or by an unrealistically small combustion time. Upon further inspection, it was concluded that for this

firing the combustion time was calculated to have lasted only 2 active frames, which wrongly indicates that the entire propellant was combusted in 66 ms. This is a limitation present on the imposed method selected to calculate the combustion time based on the luminosity, which involves only accounting for the frames in which the luminosity data recorded remains above an arbitrary value based on the exposure time selected. This has probably occurred because the exposure time selected was higher than necessary, which led the light being visible to be dim, despite the arbitrary number being adjusted accordingly. Despite having a limited or simplistic approach, this methodology has worked for most cases and managed to properly describe the combustion methods for the majority of the 300 experiments conducted throughout this project.

If this data point is assumed to be an anomaly and was excluded from Figure 71, the new relationship observed can be seen in Figure 72 below.

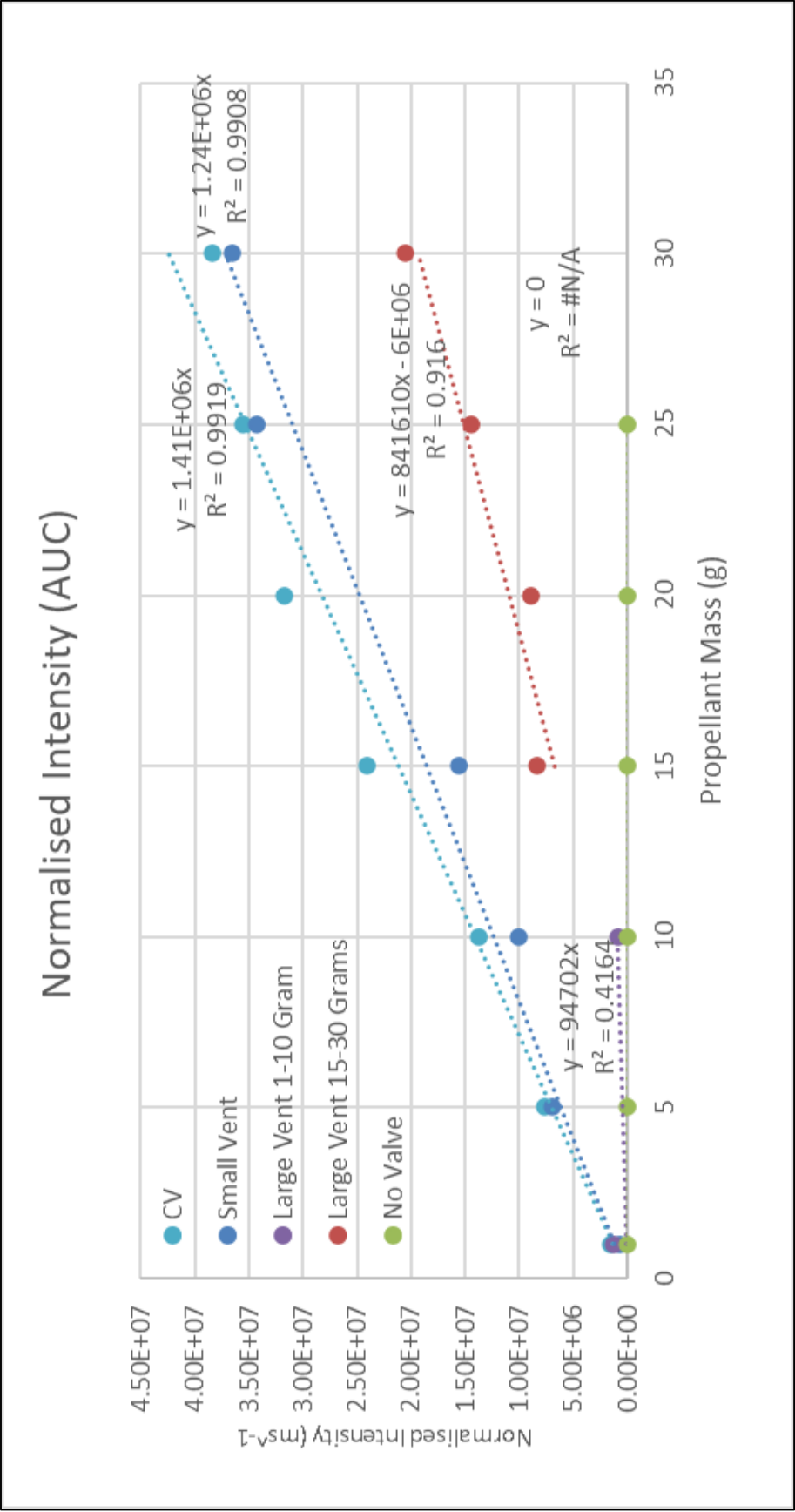


Figure 72: Normalised intensity (AUC) during the Pipeless Series relationships without anomaly.

Removing the anomaly discussed in the paragraphs above has resulted in the relationship being identical to the one observed for the normalised peak luminosity.

4.3.4 Mass Consumption Rate Data

By applying the same methodology to measure the total mass consumed for each frame, we obtain then following two figures. Figure 73 shows the mass consumed during the smallest vent size of 0.1 cm while Figure 74 describes the same parameter for the large vent.

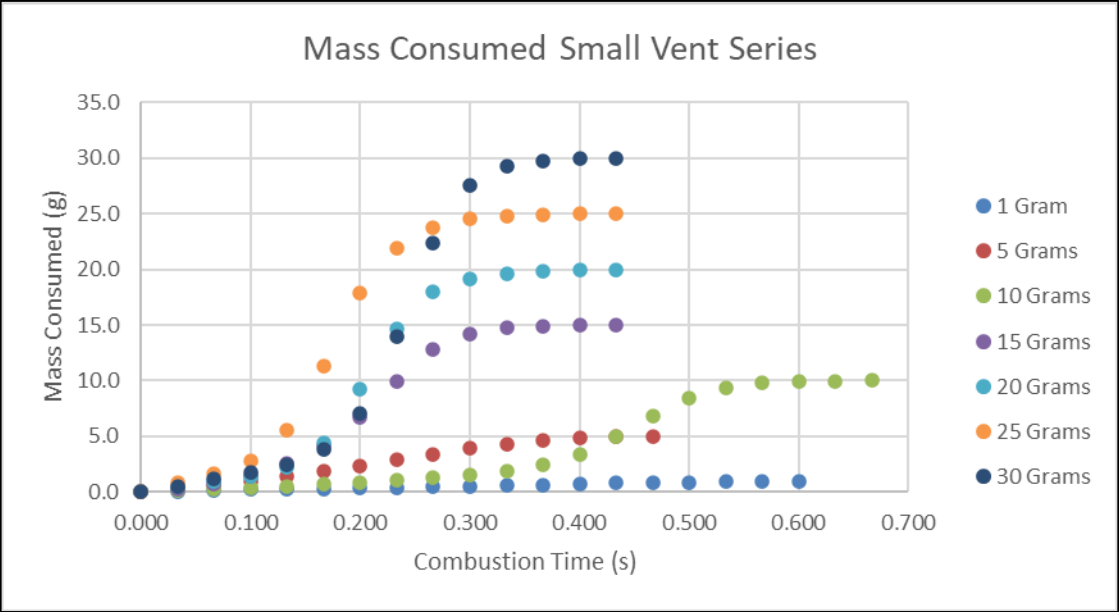


Figure 73: Propellant mass consumed with Small Vent attached.

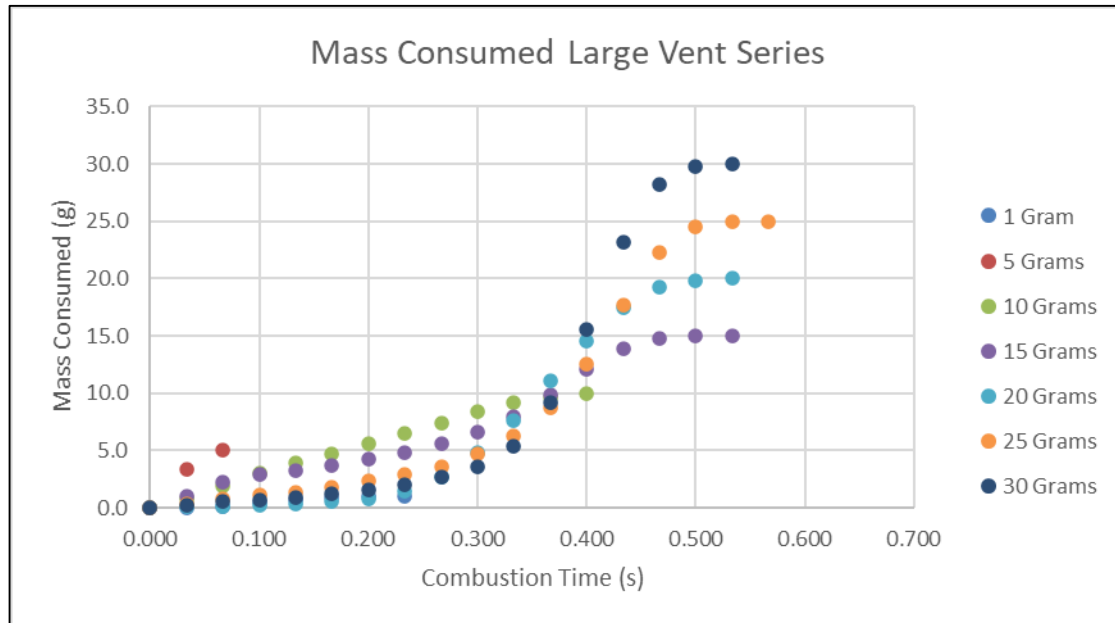


Figure 74: Propellant mass consumed with Large Vent attached.

When comparing the two figures, there are certain observations that can be made:

1. Smaller vent contains sharp increase in consumption rate at earlier stages.

The sharp increase in mass consumption is observed more clearly for larger masses, where for a few frames, a small proportion of the propellant mass is igniting, hence the pressure and temperature slowly rise until a certain threshold is achieved that overwhelms the vent size, causing the pressure and temperature rise to increase rapidly, increasing the burn rate, which in turn increases the mass being consumed per frame. At a smaller vent, the threshold point is smaller, which has caused the rise in mass consumed to be at an earlier point compared to the larger vent.

Figure 73 indicates that a rise in consumption rate starts between 0.1 and 0.2 s for the larger masses of 15–30-gram experiments, whereas a slightly delayed rise is seen in Figure 74, especially true for the 30-gram firing, at 0.3 s. It can also be noticed that it takes longer to completely consume all the propellant as the consumption rate is smaller.

2. Combustion time is shorter during the smaller vent.

It has been established from the previous point that the consumption rate observed during the larger vent firing is smaller, indicating that the same propellant mass being combusted would require longer to completely combust. Once again, focusing on the larger masses of 15–30-gram data, combustion time rose from 0.433 s from the small vent series to 0.533 s in the large vent series.

It must be understood that this is the period of time where luminosity was being observed inside the vessel which glows bright enough to be considered an active frame. Part of the combustion was occurring outside the vessel, since the flame was ejected through the vent, which indicates that the combustion could be even longer. This observation gains importance as the vent size increases, as it can be seen from the 2.5 cm vent data in Table 11, where no luminosity was observed inside the vessel, however, clearly not meaning that no luminosity was generated. This explains why the combustion time was longer for the smaller masses during the small vent series.

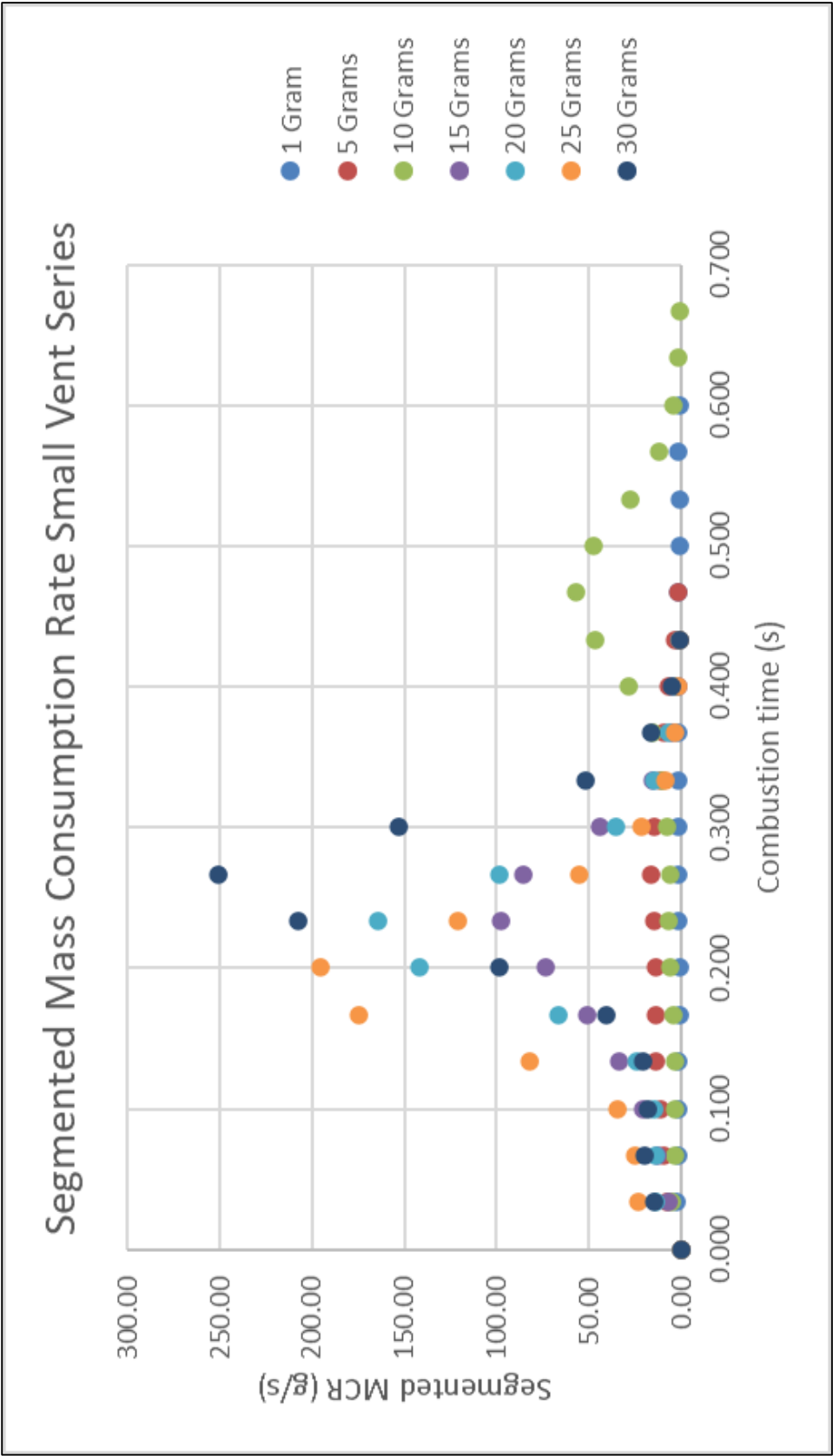


Figure 75: Segmented mass consumption rate calculated with the Small Vent data.

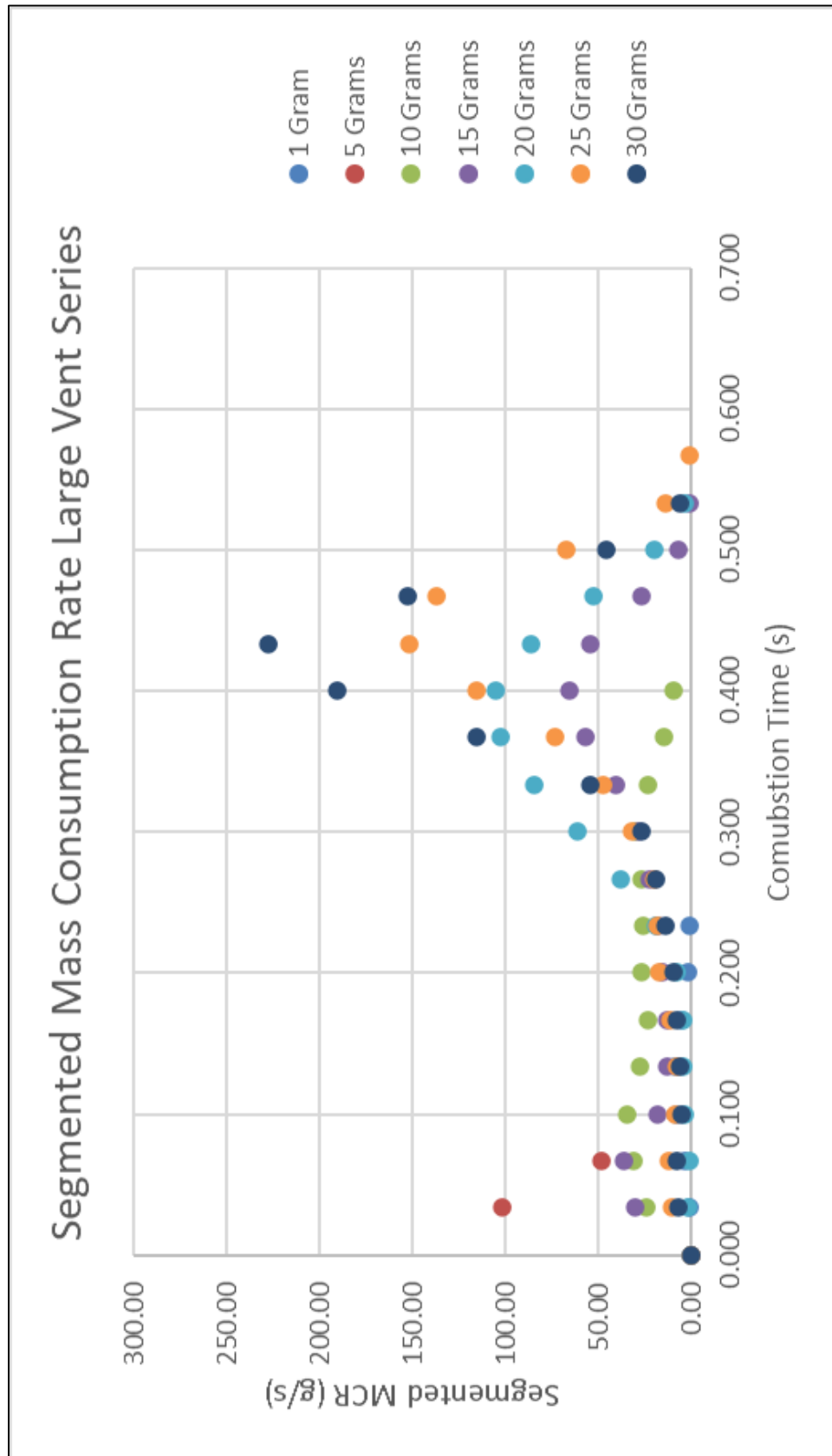


Figure 76: Segmented mass consumption rate calculated with the Large Vent data.

Figures 75 and 76 describe the evolution of the segmented MCR throughout the combustion for the small vent series (Figure 75) and the large vent series (Figure 76). The same observations made during the mass consumed figures can be seen, which highlights the earlier bulk combustion during the small vent series because the flow choked at much smaller masses, hence accelerating the combustion. Since a smaller quantity of hot gases was allowed to escape due to the difference in size of the vent, the calculated MCR was vaguely higher for all propellant masses tested during the smaller vent series.

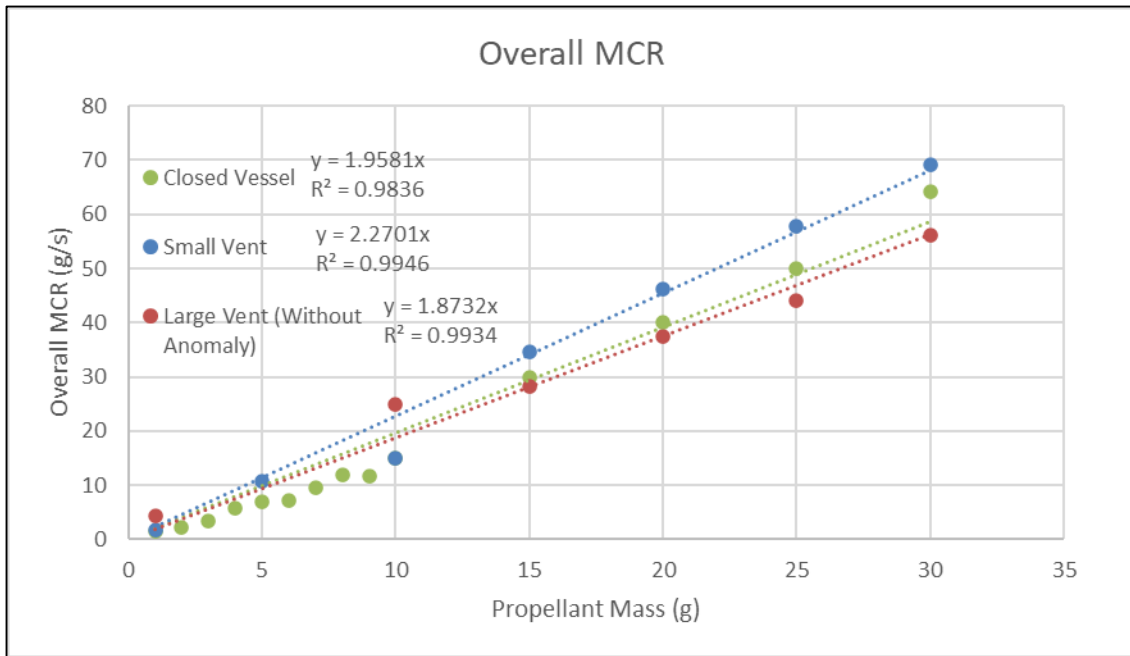


Figure 77: Overall Mass Consumption Rate throughout the Closed Vessel and pipeless series.

The overall MCR shown in Figure 77 was calculated simply accounting for the total mass of propellant combusted and the combustion time.

$$\text{Overall MCR} = \frac{\text{Propellant Mass}}{\text{Combustion Time}}$$

Equation 21: Overall Mass Consumption Rate.

The three relationships demonstrate that a linear rise in overall MCR is expected when increasing the propellant mass while increase the size of the tray holding the propellant at a ratio of 10:1 of length-to-breadth.

At a first glance, it seems surprising that the closed vessel relationship did not have the highest slope. This was the hypothesized scenario because all the luminosity was accounted for during the closed vessel series, hence, the combustion time would be more accurate. Instead, the overall MCR was higher during the pipeless series with the small vent attached. This situation could be explained by the loss in luminosity observed by the camera due to the vent expelling the flame outside of the vessel. Since less light was visible inside, the luminosity average gave the impression that the combustion time was shorter by observing less frames where the luminosity average was higher than the arbitrary number for each specific mass.

	Combustion time (s)		
Mass (g)	Closed Vessel	Small Vent	Large Vent
1	0.57	0.60	0.23
5	0.65	0.47	0.07
10	0.60	0.67	0.40
15	0.45	0.43	0.53
20	0.46	N/A	0.53
25	0.47	0.43	0.53
30	0.46	0.43	0.40

Table 12: Combustion time measured with luminosity average methodology for closed vessel, small vent and large vent pipeless series.

While only a small decrease in average luminosity was observed during the small vent series compared to the closed vessel series as depicted in Figure 72, it was

enough to reduce the combustion time by a larger margin, especially for larger masses. Since the propellant mass being combusted was the same, the decrease in combustion time would result in an apparent increase in overall MCR.

Given that the pressure, temperature, luminosity, and thus burn rate decrease with the addition of a vent, it does not make sense for the combustion time to decrease. It seems that the luminosity methodology provided was useful in creating a technique to measure the MCR of gun propellants, however, needs some adjustments to combat changes made to the system. The addition of a vent allowed some luminosity to be lost during the combustion as the flame were expelled by the higher pressure inside the vessel. If this luminosity was also recorded, then the total luminosity would still be available, which then it would be possible to have a more accurate estimation of the combustion time, which would provide more realistic segmented and overall MCR.

4.3.5 Pipeless Series Observations

The processed data obtained during the pipeless, and 2 vented series proved to have solved the choking flow issue present in the Vented series in Section 4.2. The pressure and luminosity data were much lower, indicating that the long and narrow pipe was indeed choking the flow before the actual vent size had an effect, which generated relationships of similar patterns, indicating a connection between them to be far stronger than anticipated. The only dubious dataset came in the form of the overall MCR, which was addressed using data obtained from the pipeless series itself and some logic addressing a weakness in the methodology.

When planning for these pipeless series, it was hypothesized that the removal of the long and narrow pipe would reduce the pressure and luminosity, however, unknown by what factor, hence, it proved a difficult task when selecting the exposure time to record the light data. Since the luminosity was expected to be reduced, the only options available were to maintain the exposure time the same as for the closed vessel series, or to increase slightly. However, the exposure time for the 1-gram firing was already at the limiting value of 30ms to still obtain 30 frames per second, hence, it was not possible to increase the exposure time

without losing the number of frames obtained during the combustion process. Therefore, it was decided to maintain the exposure time as chosen for the closed vessel series for the smaller masses and adjust at larger masses if the luminosity average reduced significantly. This proved to be a successful choice for the small vent pipeless series because of the small size of the vent, hence, it was expected for the flow to choke once larger propellant mass were deflagrated. When planning for the large vent pipeless series, however, the luminosity reduction observed was much higher than anticipated, which resulted in the luminosity average values being much lower. Perhaps, if the selected exposure time were slightly higher, the luminosity reduction might not have been as extreme. Unfortunately, due to the time restraints, it was not possible to revisit this experimental series to address this difficulty.

4.4 Supporting Experimental Series

After completing the several experimental series in Sections 4.1, 4.2, and 4.3, there were a few topics of interest that could help further understand the methodology used if studied separately.

4.4.1 Variable Exposure Time

A fixed exposure time was selected for each propellant mass based on testing carried out beforehand, which allowed the luminosity to be observed, and where the average luminosity was intended to fall within the range of 40-80. The average luminosity data highlighted the natural randomness associated with the combustion of powder propellant, strongly influenced by the voids between propellant particles allowing the flame and hot gases to travel at random directions and lengths, heating or even igniting particles at nonlinear rates. Despite this randomness associated with this methodology, several predictable patterns were observed, indicating that there can be some confidence in the prediction even when certain parameters cannot be controlled. This was observed when the exposure time was selected and fixed for a specific propellant mass chosen, however, will the same behaviour occur when changing the exposure time for a fixed propellant mass combustion?

In theory, any change to the exposure time should affect the average luminosity measured and normalised AUC. An increase in exposure time will increase the time the aperture remains opened, hence, more light should be absorbed, whereas a decrease in exposure time expects a decrease in luminosity captured by the camera. This would be true for all cases if the combustion was linear, however, as previously discussed, powder propellants do combust linearly. Hence, there could be a case where the luminosity was at its highest during the period where the camera aperture was closed for all collected data, which would result in a lower measured luminosity average compared to a case where the highest luminosity generated by the flame was captured by the camera during all active frames. In order to address this limitation, a camera capable of collecting more frames per second would facilitate in having a true representation of all the luminosity data collected.

It is important to remember the differences between the luminosity parameters of interest. The peak luminosity average measured shows only the highest luminosity data point which can be useful when investigating the worst-case scenario of the combustion to highlight the frame that contain the most combustion occurring, which couples with the highest-pressure rise. The AUC does a better job at highlighting the overall combustion process since it accounts for the luminosity measured throughout the entire firing process. Since this experiment focuses on investigating the effect of the exposure time while combusting a fixed propellant mass, more importance should be given to the AUC data rather than the peak luminosity average for this supporting experiment.

The propellant mass selected to test this theory was 5 grams, which used an exposure time of 4 ms during the closed vessel series. The exposure times selected to be tested were of 3, 4, and 5 ms. The data obtained is shown in Table 13, where the closed vessel series data was included for comparison.

Experiment	Exposure (ms)	Luminosity Average	Normalised Luminosity (ms^{-1})	AUC	Normalised AUC
Closed Vessel Series	4.00	93.4	31.8	20079	7529597
3 ms ER	3.00	51.7	29.3	13595	5184349
4 ms ER	4.00	49.8	19.0	13344	7553471
5 ms ER	5.00	45.5	12.6	14127	3912089

Table 13: Variable Exposure Time Luminosity Data

Despite a significant change in exposure time of 25% in either direction, the peak luminosity average measured was only slightly affected. The most noticeable data point in the peak luminosity average comes from the closed vessel series average, which was only included as a reference, however, it was the one that varied the most from the tested experiments. The theory hypothesized was not

reflected in the results above, at least for the peak luminosity average, where the highest value was obtained for the lowest exposure time and vice versa. When normalising the result by accounting for the exposure time and combustion time, the 3 ms data produced a similar normalised luminosity value, indicating that it can be possible for a camera to collect the same luminosity information at different exposure times. The 4 and 5 ms experiments, however, highlight the variability present due to the presence of powder propellant combustion and its non-linear progression by presenting much lower normalised luminosity averages.

The area under the curve data collected followed a similar pattern to the peak luminosity average, where the unprocessed data had similar averages even with a considerable change in exposure time, and the normalised AUC showed a high degree of variation while one firing was similar to the closed vessel series data. The exposure time of 4 ms produced an almost identical normalised AUC to the closed vessel series. Both normalised AUC values for the 3 and 5 ms exposure times were lower than at 4 ms due to the experimental variability. The fact that the variable data originated from an exposure time higher and lower indicates that the camera aperture being opened for different periods of time did not influence the luminosity data collected towards only one direction.

Retrospectively, the choice of deflagrating 5 grams of propellant was not the most sensible since the exposure time used for this propellant mass setting was 4 ms, which makes up a small increment of time when the camera aperture was opened. For better understanding of the reproducibility of the results using our camera, a propellant mass more appropriate would require an exposure time closer to the limit of 30 frames per second, at 33.3 ms. Table 5 in page 75 shows that at 1 gram of propellant combusted, an exposure time of 30 ms was selected, hence, the time the camera aperture was opened occupied most of its time recording the luminosity generated, allowing the data to represent and record the entire combustion process.

A different glass window was used to record the luminosity data during the closed vessel series, which brings an interesting observation: after a few firings, it is

possible to notice the glass window getting darker with each shot. Regardless of how thoroughly it was cleaned, it does so only to a limiting effect, which means that after a firing, some combustion products are permanently obscuring the glass window. Several methods were tested to clean out the glass window, including soap and water, acetone, ultrasonic bath, however, none of these methods managed to properly remove all the combustion products generated after a firing.

4.4.2 Bulk and Separate Trays

From the explosive regulations 2014 document [70], the two factors that define whether an explosive storage location is suitable are the total mass of explosive substance to be stored and the safety distance to the nearest structure. This could be a section of the explosive regulations system that could be improved upon, where it does not include any description as to how the explosive substance was processed and stored, if split in equal parts throughout the storage location, or stored entirely in a bulk. As a method to illustrate the differences that can be obtained, the following experiment will combust certain propellant masses which were separated in equal piles or were ignited as the entire propellant mass altogether. The methodology aims to highlight that combusting a certain quantity of an explosive substance as a bulk or in separate quantities influences the combustion time, overall pressure peak achieved, and thus the stress imposed.

4.4.2.1 Combustion of 20 grams of propellant

In the first experiment, 20 grams of Vihtavuori N120 propellant was combusted inside the burning vessel, where it was possible to see any subtle change to the system. The 20 grams were divided in 2 trays of 10 grams, followed by 4 trays of 5 grams, all of which would be connected by plastic igniter cord (PIC). Figure 78 illustrates the experiment idea, however, 4 equal trays of 5 grams were utilised instead of 2 trays of 10 grams. One run was made without the lid attached to identify any relevant information that might need adaptation. It was noticed that the flames were powerful, even when only igniting 5 grams, hence, metal plates were placed between each propellant tray to prevent the flame from igniting the neighbouring tray before the PIC could initiate the propellant from the desired location. The addition of such metal plates could prevent the flame from being visible, hence the luminosity data might not accurately describe the events occurring inside the vessel. The metal tray addition is shown in Figure 79. Therefore, the pressure data collected was the parameter with strongest influence on the conclusions for this supporting experiment.



Figure 78: 20 Grams of propellant divided into 4 equal trays of 5 grams.

The first supporting experiment highlighted the importance of selecting an appropriate exposure time to prevent the data from being skewed. When separating the 20 grams of propellant in 2 trays of 10 grams, the exposure time was the same one selected during the closed vessel series of 1 ms while for the 4 trays of 5 grams, an exposure time of 4 ms was chosen. These exposure times were selected because of the expectation that each tray will burn individually, and once finished, the PIC will ignite and burn along until igniting the next tray.



Figure 79: Metal plates placed between propellant trays to prevent ignition before PIC.

Both parameters describing the luminosity data provided unexpected results. The normalised luminosity was significantly lower for both separated experiments compared to the bulk data, whereas the normalised AUC was roughly half for two trays and with further reduction for 4 trays. The metal plate effect on the luminosity was disruptive by preventing the flames from being visible to the camera.

Test	Exposure (ms)	Luminosity Average	Normalised Intensity (ms^{-1})	Normalised Luminosity (ms^{-1})
1 Tray 20g (CV Series)	0.50	71.1	142.1	309.0
2 Trays of 10g	1.00	75.4	75.4	144.4
4 Trays of 5g	4.00	126.8	31.7	39.6

Table 14: 20 grams of N120 combusted in separated trays (Part 1).

Test	Exposure (ms)	Area Under Curve	Normalised AUC (ms^{-1})	Normalised Intensity (ms^{-1})	Peak Pressure (bar)	Combustion Time (s)
1 Tray 20g (CV Series)	0.50	7295	14590	31716715	34.9	0.46
2 Trays of 10g	1.00	7212	7212	13811036	34.41	0.52
4 Trays of 5g	4.00	22297	5574	6967781	31.09	0.80

Table 15: 20 grams of N120 combusted in separated trays (Part 2).

Turning the attention to the pressure data, however, the peak conditions were similar to the bulk value, especially 2 trays of 10 grams. A 10% decrease was observed for the experiments with 4 trays of 5 grams, which can be attributed to the time delay on initiation. The recorded video clearly demonstrates a single event occurring, and the same can be seen in the pressure trace, where a single rise depicts the combustion. Therefore, the metal plates did not prevent the flame from reaching the other propellant trays. Considering that the total mass combusted is the same, hence, the gaseous contribution to the peak pressure remains constant, it must mean that the pressure drop observed is a result of the longer time required for the flame to reach all 4 propellant trays, seen by the increase in combustion time from 0.46 to 0.80 s. Because of the longer combustion time, the temperature was allowed to drop for longer, and thus, achieve lower peak pressure conditions.

The combustion flame comprises mostly of gases; hence it is lighter than air, meaning it will flow upwards. Once it reached the ceiling of the closed vessel, the flame started to travel sideways. Since the metal plates left a gap at the top, it provided enough room for the flame to ignite the other propellant trays before the PIC. If instead, the vessel was taller rather than wider, it could be possible to store larger quantities of propellant before the flame reached the ceiling and circled back down to ignite other propellant trays.

Another property that influenced the combustion process was the lack of flame resistance. N120 is a highly combustible substance, hence, its ignition was spontaneous once in contact with the flame from the first tray. For substances that are more flame resistant, it would be possible for the flame to come into contact with the explosive substance in the secondary trays without igniting immediately.

4.4.2.2 Combustion of 10 grams of propellant

As a goal to reduce the combustion flame to prevent the early ignition of trays 2, 3, and 4 before the intended time, the total propellant mass was cut in half. Similar to the previous set up, the total mass would be separated into 2 trays of 5 grams and 4 trays of 2.5 grams.

Test	Exposure (ms)	Luminosity Average	Normalised Intensity (ms^{-1})	Normalised Luminosity (ms^{-1})
1 Tray of 10g (CV Series)	1	47.5	47.5	70.4
2 Trays of 5g	4	46.7	11.7	19.8
4 Trays of 2.5g	4	32.9	8.2	7.1

Table 16: 10 grams of N120 combusted in separate trays (Part 1).

Test	Exposure (ms)	Area Under Curve	Normalised AUC (ms^{-1})	Normalised Intensity (ms^{-1})	Peak Pressure (bar)	Combustion Time (s)
1 Tray of 10g (CV Series)	1	8219	8219	12176549	17.8	0.68
2 Trays of 5g	4	9907	2477	4205694	16.1	0.59
4 Trays of 2.5g	4	7460	1865	1621643	7.0	1.15

Table 17: 10 grams of N120 combusted in separate trays (Part 2).

The luminosity data showed a sizable decrease across both parameters when separating the total mass. If the metal plates were not necessary to be present, it would be possible to capture a more realistic luminosity from the combustion. The normalised luminosity decreased from 70.4 during the 10-gram firing to 19.8 and 7.1 for the 2 and 4 trays experiments respectively. The AUC data was also affected by the limited luminosity being captured, which resulted in the normalised AUC being much lower when the metal plates were present.

The combustion time measured by both methods indicated that separating 10 grams into 2 equal piles of 5 grams was still producing conditions favourable enough to ignite the second tray before the PIC, hence the combustion time was

of similar magnitude to the 10-gram bulk firing. Separating the total mass into more trays did cause the total combustion time to reduce further to 1.15 s, almost double the time necessary to combust 1 or 2 propellant trays, demonstrating that there must have been a longer delay between some or all propellant tray combustion.

The pressure data collected demonstrates that separating into 2 trays only resembles the bulk propellant mass combustion, where the peak pressure change reduced from 17.8 to 16.1 bar. This indicates that the flame was still too large for the propellant burner instrument, hence, igniting the second propellant tray earlier than desired, causing most of the propellant to ignite nearly simultaneously, which raised the peak pressure to higher values. Further separating the total propellant mass into 4 trays of 2.5 grams finally achieved the desired condition, where a significant decrease in peak pressure was observed, with an average of 7.0 bar across the 3 repetitions.

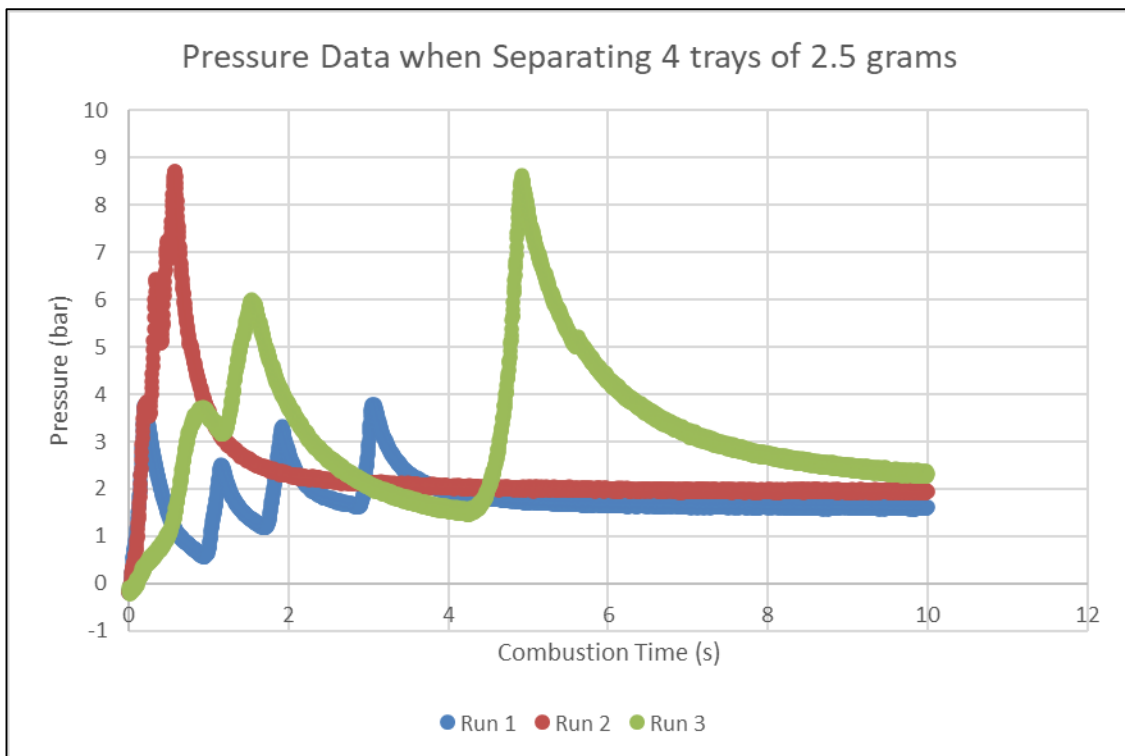


Figure 80: Pressure data collected from 4 trays of 2.5 grams combustion.

Despite the experiment preparation being identical, three different burning behaviours were observed during the three repetitions as shown in Figure 80. In

the first run, the pressure data indicates that each propellant tray was ignited by the PIC linking each tray as opposed to the flame overwhelming the metal plate's height, since there are 4 distinct pressure rise peaks, and a decay sections after each peak. Enough time had passed to reduce the temperature in the form of convection to the air and conduction to the instrument, which meant that when the following propellant tray ignited, the pressures achieved were not considerably higher than the behaviour seen in the previous tray. The peak pressure measured during this run was 3.80 bar, noticeably lower than the average for this experiment.

The second run generated a much higher peak pressure, which can be explained by the short time between a sudden pressure rise caused by the combustion of the four propellant trays igniting in succession with one another, yet each individual peak can be observed. The pressure data suggests the flame was overwhelming the metal plates because the 4 propellant trays had ignited before the peak pressure had been achieved by the second propellant tray in run 1, and the known fact that PIC burns much slower than propellant. The continuous combustion occurring during this firing has given less time for the temperature to stabilize, therefore, the pressure inside the vessel was significantly higher.

The third run contains traits from both runs, where two consecutive pressure rise sections of the data can be clearly observed at the earlier stage of the pressure trace, and a sudden pressure rise to a similar pressure seen in run 2 of 8.7 bar at 8.6 bar. It must be acknowledged that the peak pressure achieved during the combustion of 10 grams as a bulk during the closed vessel series 17.8 bar, which demonstrates the importance of separating propellants when stored.

4.4.2.3 Combustion of 5 grams of propellant

Further reduction in the propellant was carried out to prevent the combustion flame from igniting all propellant trays at undesired locations. By doing so, the peak pressure was drastically reduced, and the combustion time was largely increased. With a total propellant mass of 5 grams to be ignited, the trays were split into 2 trays of 2.5 grams and 4 trays for 1.25 grams.

Since the metal trays were preventing the total luminosity from being captured, and thus, limited analysis was given with confidence, no luminosity data will be discussed for these firings.

Experiment	Peak Pressure (bar)	Combustion Time (s)
1 Tray of 5g (CV)	10.00	0.80
2 Trays of 2.5g	5.73	2.55
4 Trays of 1.25g	2.12	4.61

Table 18: Data collected during combustion of 5 grams of N120 in a variation of tray quantities and sizes.

The total propellant mass being combusted has been decreased to a point where any separation into multiple trays significantly reduced the pressure observed. Separating into 2 trays of 2.5 grams measured an average peak pressure of 5.73 bar, a considerable reduction from the 10-bar observed when 5 grams was combusted in a single tray during the closed vessel series. In fact, it was the only experiment in which two trays had a convincing reduction in pressure. Further reducing the propellant mass in each tray to 1.25 grams caused the average peak pressure to drop to 2.12 bar across the three firings. This represents a 78.8% pressure reduction simply by separating the propellant mass into different piles rather than storing the entire quantity as a bulk. The combustion time has increased with increasing number of trays, which indicates that the trays were igniting at a separate time from each other, and so confirming that the flame generated was not high enough to reach the next trays before intended to.

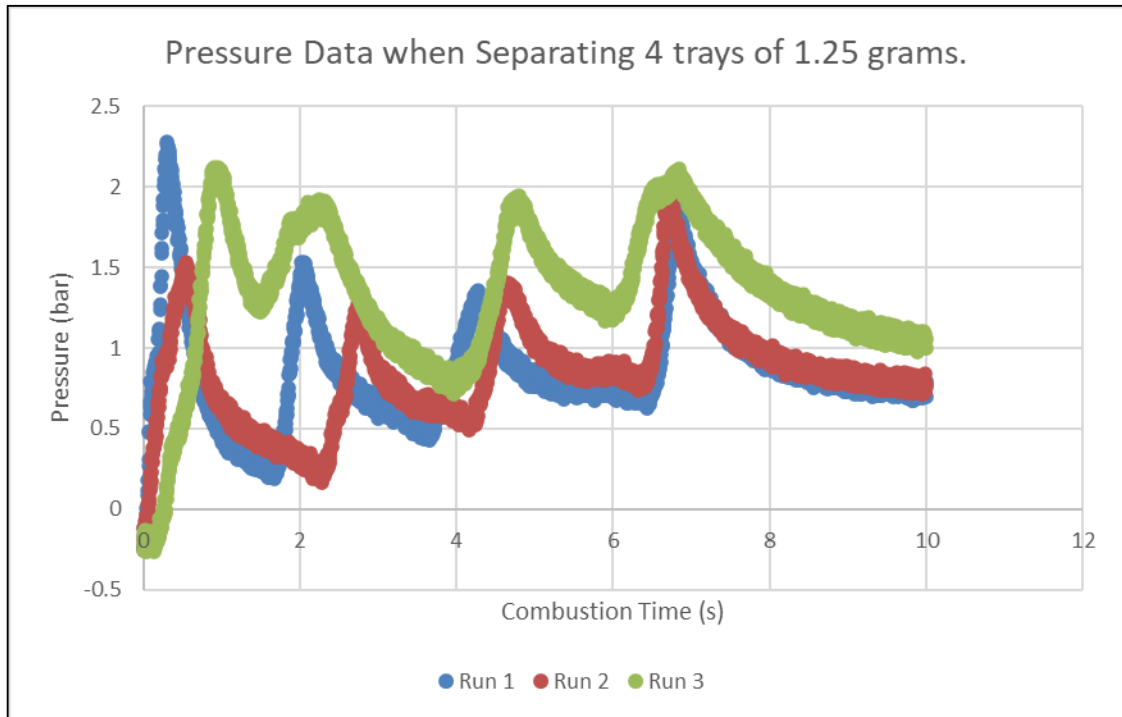


Figure 81: Pressure data collected from 4 trays of 1.25 grams combustion.

Figure 81 contains the pressure-time history describing the combustion of 4 trays of 1.25 grams inside the closed vessel. The behaviour describing the combustion can be seen for all three firings, where each individual pressure rise reached a peak, followed by a slight decrease in pressure while the PIC was being ignited. The combustion time during all the firings demonstrated some consistency in the burn rate of the combustion, since it can be observed that the peaks for all firings of each tray occurred in within similar times, especially, the fourth tray, which appeared to have ignited nearing 7 seconds for all runs.

4.4.3 Safety Distance Between propellant Trays

In Section 4.4.2 “Bulk and Separate Trays”, a metal plate was placed between trays in an attempt to prevent the flame generated from the initial ignition from reaching the other trays full of propellant before the PIC. During all the experiments carried out, it was observed that the peak pressure started to reduce significantly when using trays of 2.5 grams rather than higher masses, seen in the total of 5- and 10-grams series. For this reason, 2 trays of 2.5 grams were chosen for this experiment, to investigate the effect that safety distance has on the combustion of separate trays.

Three safety distances were tested, of 5, 7.5, and 10 centimetres between the centre of each propellant tray. The removal of metal plates ensured the possibility of capturing a more accurate reading of the luminosity generated by combustion. The data collected would be analysed in contrast to the data collected when 5 grams was combusted in one single tray, demonstrating if no safety distance was ever present, hence, all the propellant was placed in a single tray. In this set of firings, the combustion time describes the total time required to combust all propellant samples, not one propellant tray specifically.

Test	Exposure Time (ms)	Normalised Intensity (ms^{-1})	Normalised AUC (ms^{-1})	Peak Pressure (bar)	Combustion Time (s)
CV (1 tray)	4.0	21.80	5031	10.00	0.80
5 cm	10.0	11.00	3641	8.94	0.47
7.5 cm	10.0	7.92	2751	9.00	0.44
10 cm	10.0	8.44	2911	8.91	0.47

Table 19: Data Collected when Propellant was Combusted at various Safety Distances.

When a safety distance of 10 cm was selected, each tray was at the edges of each side of the closed vessel because of their long and narrow shape.

Remembering that the camera was set up to capture most, if not all of the base of the vessel, however, if the combustion occurred at the very edge of the instrument, part of the luminosity generated at the edges could be lost since the brightest section would flow upwards. A drastic decrease in normalised luminosity was seen from 21.80 when only 1 tray of 5 grams was used to as low as 7.92 with a safety distance of 7.5 cm.

If the combustion time and pressure data indicated that the trays were combusted separately, then it could have been accepted that the luminosity data was similar to half the normalised luminosity observed when 5 grams was combusted instead. Nevertheless, the peak pressure of 9.00 bar and combustion time of 0.44 s confirm that the flame from the first propellant tray was used to ignite the second tray across the other side of the instrument. Hence, the difference in luminosity was caused by the lost light captured outside the camera scope.

Since the AUC data also requires an accurate measurement of the total luminosity captured by the camera, it makes sense for the normalised AUC to be lower for all separation distances, indicating only that a larger glass window or a wider camera were necessary to conduct this experiment to obtain luminosity data more accurately.

The peak pressure, however, was less impacted by the separation of the total mass into separate trays, as it was kept close to 9 bar for all 3 safety distances. Although the peak pressure of 10 bar was measured when 1 propellant tray was combusted with 5 grams, indicating that roughly 1 bar was lost due to the safety distance, indicating that there could be a small pressure loss associated with the time taken for the flame to reach from one tray to its neighbouring tray.

4.4.4 Separate Trays and Large Vent

Separating the total mass of propellant into several trays served as a technique to reduce the peak pressure observed if an undesired initiation occurred when storing propellant. For the series completed so far, this indicated that when the flame was contained and did not reach the following propellant tray, the peak pressure was drastically reduced because it was given time for the temperature to disperse into the instrument and the air. If the flame was large enough to reach the other propellant trays before the PIC had arrived, then the peak pressures acquired resembled more closely the magnitude similar to combusting as a bulk. It must be noted that the propellant trays used here are not covered at the top, where storage facilities of such materials might include a cover to prevent any flame, spark, or any other ignition method from occurring.

Another technique currently used in warehouse storages exists in the presence of a vent, usually as windows and doors. Adding a vent allows the hot gases to escape the vessel during combustion, resulting in a decrease pressure build up due to the gases escaping, and a decrease in temperature of the air and instrument because the gases did not have time to spread its heat. Therefore, the combination of both techniques expects the lowest peak pressure rise. A similar approach was conducted in Sections 4.2 and 4.3.

Trays	Peak Pressure (Bar/%)	
Closed Vessel	10.00	100.0%
Vented Vessel	6.78	67.8%
4 Trays of 1.25 grams	2.12	21.2%
4 Trays of 1.25 grams with Large Vent opened	0.31	3.1%

Table 20: Pressure data of combustion of 5 grams of propellant during several experiments.

As previously analysed during the closed vessel series combustion, the temperature contribution to the total peak pressure observed during closed

vessel experiments was above 85% for masses up to 30 grams, therefore, by allowing the temperature to drop between each tray being combusted, the peak pressure observed was more closely associated with each individual tray mass. The addition of a vent, whether small or large, allows some of the gases to escape the vessel, thus reducing the pressure inside the vessel by means of a reduction in gaseous and temperature contribution.

When combining these two methodologies used to reduce the pressure observed when the same quantity of stored material ignites, it was expected to see a much larger pressure drop compared to running the methodologies separately. When separating the 5 grams into 4 trays of 1.25 grams of propellant, while having an open large vent of 1.0 cm in diameter generated the largest pressure drop observed so far, at 96.9% reduction compared to the closed vessel data. The result demonstrates that working in advance to include methodologies that can be used to mitigate the pressure rise can lead to much safer storage conditions.

4.4.5 Open Vessel

The luminosity data gathered up until this point could not have been compared with any other preliminary data, hence, there was no real way to confirm or deny whether this methodology was producing realistic data. There is an argument that the stronger part of the flame combusting the propellant will be present in the centre of the vessel, directly in the line of sight of the camera, indicating that the brightest part of the flame was indeed being captured. Nevertheless, it must be acknowledged that there are a few blind spots in the current design, despite the wide lens used by the camera.

In an attempt to eliminate the existence of the blind spot, the lid and top plate were detached from the instrument body, and raised by a distance of 20 cm, to a total distance between the camera lens to the propellant tray to 30 cm. To prevent the camera from getting damaged, it was still placed on top of the lid, which was held together by two clamp stands. This modification was intended to record the entire luminosity generated by the combustion. Since the combustion will be occurring in atmospheric conditions, the pressure and temperature will have little to no influence on the burn rate or mass consumption rate, which means that less propellant will be combusting between any given frame, however, the combustion will occur for a longer period.

During a train test, followed by the EMTAP manual [71], the combustion progression observed was much slower than the closed vessel series, where 15s were required to combust 15 grams of propellant in a metal tray of 30 cm in length. The length tested in the train test was longer than the highest propellant tray used during this project's experiment, however, the train was much thinner. Hence, it is expected for the complete combustion time with the propellant trays to fall between the closed vessel series values and the train test combustion time, therefore, between 1 and 15 seconds.



Figure 82: Open Vessel Setup.

The exposure times chosen during the closed vessel series were done by aiming to maintain the average luminosity between 40-80 throughout most masses and by predicting the appropriate exposure time for larger masses when a linear rise was observed. The removal of the lid will allow sunlight to be present during the experiment, therefore, higher exposure times will be required to measure the difference between sunlight and luminosity generated by the combustion flame. A testing series was conducted to determine the appropriate exposure times for all propellant masses to be tested. The open vessel setup is shown in Figure 82.

Due to the fixed length-diameter-width ratio of the propellant tray, when increasing the total propellant mass, a slight increase in propellant tray width and height were also observed. This is an important observation since there will be an increase in actively burning propellant area by the increased width and height of propellant trays. Nevertheless, the combustion will occur at atmospheric conditions, where pressure and temperature will not be able to further accelerate the burn rate.

Mass (g)	Exposure Time (ms)	Luminosity Average	Area Under Curve	Normalised AUC (ms^{-1})	Normalised Intensity (ms^{-1})	Combustion time (s)
1	50	15.69	5554	111.1	37189	3.02
5	50	46.43	31868	637.4	130514	6.66
10	50	97.17	93331	1866.7	314005	5.96
15	30	59.51	139730	4657.7	9315343	9.57
20	25	55.16	108532	4341.3	8682566	7.54
25	20	45.58	105411	5270.5	10541079	7.87
30	15	50.52	105430	7028.6	14057268	9.86

Table 21: Open Vessel Series Data

Data from Table 21 and Figure 83 indicate a slight increase in most parameters measured when increasing the propellant mass being combusted, with the exception of the exposure time, which has to decrease to prevent any saturation from occurring.

It must be noted that the Open Vessel mode has limited influence from pressure and temperature, hence, MCR values were expected to be of smaller magnitudes than Closed Vessel series MCRs, which translates to longer combustion periods. This was observed, with the lowest combustion requiring 3.02 s to completely combust 1 gram of propellant at ambient conditions due to its small size, while needing 9.86 s to deflagrate 30 grams. While the combustion being longer decreases the normalised peak luminosity, there should be limited impact on the overall normalised AUC, since it accounts for the entire combustion process. The normalised AUC data can be seen in the graph below, where data collected from the closed vessel series was included in red to highlight the difference.

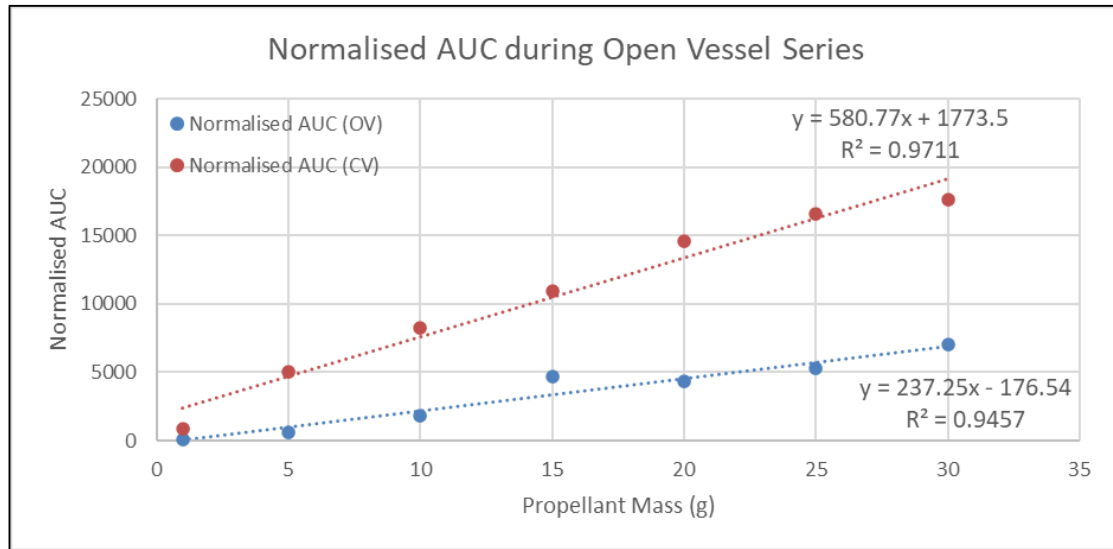


Figure 83: Normalised AUC data comparison between Open Vessel (blue) and Closed Vessel (red)

The difference observed from both equations come in the form of higher initial total luminosity observed and slope. The y-intercept increase by a 10-fold while the slope increased at a rate of 2.5. The lower luminosity data was expected due to the distance increase between the camera lens and the propellant tray.

4.4.5.1 Distance effect on Luminosity

The luminosity data requires a normalisation process to account for the longer distance between the camera and the combustion flame. A useful scientific law that explains the effect that luminosity is perceived at various distances is explained by the inverse squared law. The relationship used to correlate these factors can be seen below:

$$Intensity \propto \frac{1}{Distance^2}$$

Equation 22: Inverse Square Law.

$$\frac{Intensity (1)}{Intensity (2)} = \frac{(Distance (2))^2}{(Distance (1))^2}$$

Since the distance between the camera lens and the propellant tray was increased from 10 cm to 30 cm, the distance ratio increase was of 3, therefore:

$$\frac{Intensity (1)}{Intensity (2)} = 3^2 = 9$$

$$Intensity (1) = 9 * Intensity (2)$$

According to the inverse square law, the same luminosity collected at a distance of 10 cm will be 9 times more intense than the luminosity observed at 30 cm away. This theory behaves for point sources, and scenarios where no significant changes were observed to the source of the luminosity. The overall flame generated by the combustion changed in intensity, height, and width, which means the inverse square law might not accurately describe the behaviour seen in the closed vessel.

The normalised AUC slope increase observed from closed vessel to open vessel series was by a 2.5 multiplier in a linear fashion throughout the entire series. This can be assimilated to the multiplier used by the inverse square law equation for higher propellant masses once the y-intercept was only affected by the initial brighter environment due to the available sunlight. For smaller masses, the multiplier should be larger than 2.5, while shouldn't go over the limit of 9 due to the distance being three times higher.

The reason behind the smaller multiplier ratio can be attributed to the combustion flame being capable of achieving its intended height, therefore, the luminosity observed by the camera lens was much closer compared to the flame that was trapped inside the vessel during the closed vessel series. This reasoning confirm that the nature of the combustion flame was more assimilated to an extended source of light rather than a source point, which decreases the validity of the inverse square law. By measuring the multiplier between each propellant mass, it is possible to understand how tall the average flame height was.

Propellant Mass (g)	Normalised AUC – CV (ms ⁻¹)	Normalised AUC – OV (ms ⁻¹)	Multiplier Ratio	Distance Ratio	Distance to mean luminosity (cm)
1	898	111	8.09	2.84	28.44
5	5031	637	7.89	2.81	28.10
10	8219	1867	4.40	2.10	20.98
15	10952	4658	2.35	1.53	15.33
20	14590	4341	3.36	1.83	18.33
25	16614	5271	3.15	1.78	17.75
30	17671	7029	2.51	1.59	15.86

Table 22: Normalised AUC ratio between closed vessel and open vessel data.

As seen by the multiplier calculated, the initial values are considerably higher than 2.5 while still lower than 9, keeping true to the distance being tripled. Once the propellant mass combusted reached 15 grams, the multiplier decreased considerably to 2.35 and maintained within this range until 30 grams. For smaller masses, the multiplier was higher due to the bulk of the luminosity captured by the camera being located close to the propellant tray, close to the base of the experiment. As more propellant combusts, the flame height, width, and intensity increase, incidentally, increasing the mean luminosity height, which translates to having a smaller ratio, and thus a lower multiplier.

By assuming the consistent luminosity generated by the combustion of a fixed propellant mass, it was possible to identify the distance at which the mean luminosity was being captured by the camera. Further research is required to understand the concept in more depth. With optimal understanding of this relationship, it would be possible to identify the important factors relevant to luminosity when scaling up experiments to larger masses.

Although the above supporting experiment did not prove that the luminosity captured by the combustion of propellants is consistent for all scenarios, it was possible to conclude that the multipliers observed follow the inverse square law for smaller propellant masses when described as a source point, while the multipliers calculated for larger masses deviate from the same equation, and relies on smaller multipliers instead due to the increased flame behaviours resembling an extended source of light instead.

5 Conclusion

The project targeted the investigation of potential correlations between the luminosity generated during the combustion of gun propellants and its combustion parameters, including pressure and temperature. The luminosity measurements were split into two parameters, the peak luminosity point and the total luminosity across the entire combustion process. The peak luminosity focuses on the highest luminosity value obtained while working in unison with the peak pressure since both represented the point at which the burn rate was at its fastest condition. The total luminosity was measured under the term of area under the curve, targeting the integration of the luminosity-time data measured and accounted for the total light captured by the camera during the combustion process.

Combustion of Vihtavuori propellant was carried out in three modes of operation in the form of closed vessel, semi-closed vessel, and open vessel series, all of which measuring the peak luminosity and total luminosity data. These modes of operation differ by the utilisation of a ventilation valve and presence of lid during combustion. The ventilation valve was closed during the closed vessel series, while left opened during the vented series. The size of the ventilation valve had an impact on both luminosity data gathered and the combustion parameters. When the ventilation valve was closed, the combustion products were trapped inside the closed vessel, hence, the hot gases were raising the temperature and pressure captured by their respective sensors, while the combustion flame was prevented to flow outwards, therefore, the luminosity was recorded throughout the combustion via the planetary camera. The addition of a ventilation valve, regardless of size, causes the system to search for equilibrium. Once combustion starts, increasing the pressure and temperature, the difference in pressure from inside the vessel to the atmospheric pressure outside the vessel creates a pressure differential, forcing combustion products outside the vessel to reach equilibrium. The expulsion of combustion products generates a flow with direction, forcing some of the combustion flame to flow outward too.

Data collected from the closed vessel series suggests a linear correlation between propellant mass and peak pressure, and a similar pattern was observed for the peak luminosity. Individually, these findings were expected because of the associated process that generates both parameters. The peak pressure rises in accordance with Vieille's law by the influence of total energetic content, number of moles, temperature achieved and burn rate. At higher burn rates, more energetic material was combusted per unit time, hence, a more intense combustion flame was generated, which was reflected in the higher normalised luminosity captured by the camera. When plotting the peak pressure rise against the normalised luminosity, a near perfect linear correlation was observed at 97.9% coefficient of determination, indicating a high level of reliability, and so confirming the existence of a quantifiable correlation between the luminosity of combustion flame and combustion parameters.

The closed vessel series were also useful to distinguish between temperature and gaseous contribution on the peak pressure recorded. By providing enough time for the temperature to dissipate through the steelwork into the atmosphere, it was seen that the temperature contribution was controlling the peak pressure rise, instead of the gaseous contribution, where the temperature contribution varied between 88.0% and 97.5%.

In semi closed vessels, the vent size defines the area where combustion gases escape, and so, impact the combustion parameters and luminosity measured. Larger vent sizes resemble open vessel mode of operation, while smaller vents produce data that assimilates closer to close vessel data. These findings were obtained during the vented vessel series Section described in Chapters 4.2 and 4.3. The smallest vent size caused a slight decrease in peak pressure and luminosity throughout all firings, while the largest vent prevented the pressure from building up inside the vessel, and as a result, atmospheric pressure was measured for all propellant mass and no luminosity was captured. The large vent, however, demonstrated both behaviours, where the combustion of up to 10 grams of propellant allowed the combustion to behave similar to an open vent

and the data measured was low, while any further increase in propellant mass generated a drastic rise in both pressure and luminosity data.

Comparing the peak pressure and normalised luminosity data for the small and large vent series result in a linear correlation for both vents. A slight rise can be observed in the coefficient of determination compared to the closed vessel data, from 97.9% to 98.66% for the large vent series, while a slight decrease to 97.11% for the small vent series. The similarities in correlation between these two parameters once again demonstrate a strong association of the luminosity to the pressure. Unfortunately, the temperature data collected was skewed by instrumentation error and was not utilised in correlation to the luminosity. The positive association between pressure and luminosity suggests the possibility of a similar pattern when comparing the luminosity to temperature and becomes a strong case supporting the hypothesis that the combustion flame luminosity has a strong connection to other combustion parameters and might be useful in certain scenarios where the other parameters may not be possible to be measured.

Given this research has only scratched the surface, it does become a starting point with positive correlations. There were several sections of the methodology that could be improved upon, which might facilitate the understanding of either the combustion parameters, or the luminosity data capture. One limitation was identified and highlighted during the supporting experiments, in Chapter 4.4.1, showcasing the variable luminosity data gathered. Despite maintaining the experimental set up identical, different normalised luminosity values were obtained when changing only the exposure time set by the camera. It was discussed at the time that a possible reasoning could be associated to the use of a different glass window during the closed vessel series, justifying the 93.4 normalised luminosity average instead of the measured 45.5-51.7 with the new glass window. Nevertheless, inconsistent luminosity was also discussed in chapter 4.1.8, where in 5 repetitions of firing 1 gram of Vihtavuori propellant yielded 5 different pressure-time behaviours. Although, within the inconsistencies

throughout the combustion process, the average combustion values generated consistent and predictable rises when increasing propellant mass and pressure.

Chapters 4.4.2 through 4.4.4 in the supporting experiments discuss alternative combustion behaviour when separating the total propellant mass stored within a vicinity into piles of 2 and 4, attempting to mitigate the worst case-scenario, depicted by the peak pressure and peak normalised luminosity. Chapter 4.4.2 utilised metal plates to prevent the combustion flame of the first propellant tray from igniting the remaining unburnt trays, however, was only achieved for the lowest total mass of 5 grams, when 4 trays of 1.25 grams were utilised. Due to the presence of the metal plates, no luminosity was measured since all trays were placed closer to the wall of the closed vessel. The metal plates were removed in Chapters 4.4.3 and 4.4.4, however, the propellant trays were still not placed in the centre of the vessel, hence, the camera was not directly facing the combustion flame, which led to a considerable amount of luminosity to be out of the camera's reach. Instead, the pressure measurements were utilised to evaluate the efficiency of mitigating the highest pressure measurable by comparing to the pressures obtained during the closed vessel series where the total mass was combusted as a single propellant tray. It was concluded that by separating the total propellant mass into smaller quantities and more trays managed to have the highest effect in mitigating the peak pressure, however, if the propellant flame was still considerable enough, it could nearly instantaneously ignite all remaining propellant trays to achieve high peak pressures. Separating the propellant trays into 4 trays of 1.25 grams while opening the large vent generated the smallest peak pressure rise, just above atmospheric pressure, at 0.31 bar overpressure.

The open vessel series generates an interesting circumstance, where the luminosity of the combustion flame can be captured because the planetary camera was still placed directly above the propellant tray, albeit a higher distance away, however, no pressure could have been recorded because the lid of the instrument vessel was removed entirely, hence the pressure remained atmospheric. For this situation, the correlation between peak pressure and

normalised luminosity cannot be linear due to the negligible pressure rise attained, while the combustion was taking place.

In conclusion, the findings related to the normalised luminosity data demonstrated the hypothesised theory of a correlation to combustion parameters, specifically pressure during closed and semi closed vessels. Once the same methodology was utilised for open vessel, the correlation was not present because no pressure was recorded, indicating one situation in which this relationship does not hold.

5.1 Practical Implications

Throughout this project, there were several areas of research of focus, including the design of a new technique targeting the luminosity generated during combustion processes, safety storage orientations, and closed and vented vessel combustion firings. These areas were investigated to further understand topics that had potential gaps within their knowledge in literature. As discussed in the literature review, the luminosity of chemical reactions has been investigated, however, very briefly for propellant combustion, hence, it was believed to be an interesting approach to research possible improvements to existing methodologies.

The novel aspect to understand the luminosity data of combustion processes was also chosen because of the capability of utilising simple equipment. To record a combustion process, only a camera is required, and the data can be processed at a later date. With further understanding of this technique and its correlation to performance parameters, this could be a useful method in evaluating the performance of accidents and disasters, since there were several videos and security cameras recording such scenarios. This usefulness comes from the fact that security camera can be placed anywhere on streets and storage facilities, while methodologies utilised to evaluate the performance parameters, such as pressure sensors are not typically utilised.

In propellant research, powder propellants burn at different rates to homogenous propellants due to the presence of voids. For powder propellants, the linear burn

rate cannot be measured accurately, requiring a new methodology to track propellant combustion. This project has begun the process of proving that the luminosity data has the potential to measure an alternative parameter in the form of mass consumption rate, describing the rate at which the propellant gets consumed.

Data collected from the closed vessel series in chapter 4.1 and pipeless series in chapter 4.3 demonstrated a strong correlation between the peak luminosity data and the peak pressure observed during firings of various propellant masses. Both scenarios describe most uses of propellant research, since the use of confinement allows the increase in pressure, translating to an increased thrust. Applications such as rocket propelling and military encompass most uses of propellant, and in most instances, if not all, confinement has an important role in maximising the thrust applied to projectiles. Therefore, having more information available that can be used to further understand the pressure behaviour in adverse situations can only be beneficial. Propellant combustion in situations described by the open vessel series is typically limited to disposal of unnecessary propellants.

Vented situations can also be applied to safe storage conditions. Energetic materials can be stored in warehouses or bunkers, subject to factors such as total quantity of energetic material of a specific hazard type and distance to nearest relevant populous area, which includes roads, houses, and buildings. These storage facilities behave initially as closed vessel, and quickly transform into vented vessels. Before any pressure build up, the warehouse remains completely sealed, and once combustion starts, the pressure will accumulate similar to a closed vessel. Windows and doors are designed to break at low pressures to prevent the uncontrollable rise in propellant, allowing the warehouse to behave as a vented vessel.

The objective of venting in warehouse storage relies on reducing the pressure and temperatures inside warehouse for two purposes:

- Reduce pressure and temperature to diminish stress applied to overall structure.

- Reduce pressure and temperature to diminish propellant burn rate, to decrease the production of gases.

Safer storage conditions can also be obtained by better storage orientation of energetic materials. This concept was discussed within some supporting experimental series, in chapters 4.4.2 and 4.4.4, where it was possible to lower the peak pressure recorded with the same overall propellant mass by mitigating the propellant combustion into various trays. It might not be possible to manipulate storage of energetic materials in all cases, however, when possible, this has proved to effectively diminishing the damage that could be caused by an undesired initiation. The aim of this research aspect was not targeting an increase in the total propellant quantity to be stored in the same facility, but rather to provide alternative storage methodology to further mitigate accidents and damage to personnel and infrastructure

5.2 Future Work

Further research will be required to confirm all the findings identified during this project. Since this project was carried out with gun propellant, research on the luminosity of other propellant classifications such as single base, double base, composite, and several others might benefit from their findings, whilst always keeping in mind that this technique works best with smoke-less propellants. Improvement on the equipment could yield beneficial results, such as replacing our utilised planetary camera, which might not have been the most appropriate camera to be selected.

The addition of a second camera on vented series could complement the technique developed by recording the vent outlet to attempt to combine the luminosity generated by both cameras and investigate whether the total luminosity recorded would yield the same luminosity measured during closed vessel series, where all the flame was trapped inside the burning vessel.

The correct implementation of the break wire technique to record the combustion could be a useful addition to this technique as it would at the least provide one more combustion time data to compare with the data collected from the pressure and luminosity data.

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Appendices

Appendix A Ethical approval letter



6 November 2020

Dear Mr Durazzo ,

Reference: CURES/12396/2020

Title: Effects on Structures from Burning Type Events

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/12396/2020 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team



17 July 2024

Dear Mr Durazzo ,

Reference: CURES/23045/2024

Project ID: 13354

Title: Novel Combustion Flame Luminosity Methodology to Track Gun Propellant Combustion Progress in Closed Vessel and Semi-Closed Vessel.

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your project title change request, reference CURES/23045/2024 has been approved.

If you have any queries, please contact CURES Support.

Regards,

CURES Team