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**TOWARD NET ZERO:
AN ENGINE ELECTRIFICATION STRATEGY APPROACH OF FUEL CELL AND STEAM INJECTION**

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ABSTRACT

The turbofan engine electrification is a promising element in the global effort to achieve the 2050 net-zero emission target. This transformative shift embraces alternative energy sources and amplifies system efficiency. Power injection, using the electric motor to provide power assistance for the gas turbine, is a promising concept. Batteries and fuel cells are emerging as prime candidates for replacing traditional fossil fuel power requirements, offering compelling advantages, particularly with electric powertrains offering superior efficiency compared to conventional gas turbines. This direct power injection assistance reduces the power requirement from the combustion, thus reducing the fuel flow and Turbine Entry Temperature (TET). As an outcome, this alteration yields favourable consequences, notably in the form of diminished Carbon Dioxide (CO₂) and Nitrogen Oxide (NO_x) emissions and lower engine fuel consumption. However, this transition comes at the cost of a potential thermal efficiency penalty, impacts engine stability, and adds extra weight. These drawbacks compromise the power injection's benefit, highlighting the necessity for introducing electrification strategies in future engine designs.

This paper presents an innovative electrification strategy using fuel cells as the power source for engine electrification. The strategy highlights the collection of water as a by-product, followed by treatment processes involving condensation, pressurisation, and superheating. In this configuration, the fuel cell is designed to provide power to the electric motor, which injects power into the low-pressure shaft of the engine and provides assistance. Additionally, steam injection, leveraging the by-product water, enhances the benefits derived from electrification by recovering and redirecting the waste heat from exhaust gases into the combustor.

To evaluate the potential impact of this electrification strategy, this research selected and modelled three representative engines, each representative of typical thermodynamic cycles. Two

different approaches to steam management were considered, including instantaneous injection with production and storage of steam during production for release during specific flight segments.

This research established the synergy between steam injection and different engine thermodynamic cycles, providing a visualised evaluation method. The impact of fuel cell electrification on fuel consumption has been quantified. An estimation of the weight penalty, including fuel cells, hydrogen storage and heat exchanger, is also provided. Furthermore, the sizing of the superheating heat exchanger is analysed to assess its influence on the electrification strategy.

This research discovered the impact of steam injection on different engine cycles, established the benefits and constraints, and explained the physics. This research has captured the physics of recovering the waste heat from exhaust pipes, which could compromise fuel consumption benefit and impose a penalty on electrification. This research also indicated under what conditions and phases it is better to use the fuel cell with steam injection.

The results and assessments reach the conclusion that the electrification strategy of fuel cell and steam injection is preferable for high-temperature, low-specific thrust engines. An improper deployment could lead to a penalty instead of a benefit. The temperature of the steam is the dominant factor in bringing fuel consumption benefits. Thus, the preferable steam management approach is to inject during T/O and climb.

Keywords: Aircraft Propulsion, Gas turbine, Electrification, Fuel cell, Steam Injection

NOMENCLATURE

T/O	Take-off
TOC	Top of climb
GT	Gas turbine
SFC	Specific fuel consumption
WET	Water-enhanced Turbofan
BPR	Bypass ratio
OPR	Overall pressure ratio

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η	Efficiency
TMS	Thermal management system
P	Power
$\dot{m}$	Mass flow [kg/s]
M	Molar weight [g/mol]
WRR	Water recovery ratio
FHV	Fuel heating value
Δm	mass [kg]
OER	Oxygen excess ratio
HEX	Heat exchanger
ST	Specific thrust
Q	Heat flux
C_p	Representative specific heat capacity [$\frac{J}{kg \cdot K}$]
T	Temperature [K]
ϵ	Heat exchanger effectiveness
h	Specific enthalpy [J/kg]
U	Overall heat transfer coefficient [$\frac{W}{m^2 \cdot K}$]
A	Heat transfer wall area
β	Surface area density
ρ	Density

1. INTRODUCTION

The 2050 net zero target is revolutionising the civil aerospace industry. During the past decades, civil aviation worldwide has expanded by 4% annually[1], and the increased number of passengers and cargo in the sky brings a significant demand for flights. According to the EU, the emission of CO₂ has risen by 40% compared to the year 2010[2] and will keep increasing. To decarbonise civil aviation, the aviation industry has two possible approaches: either enhance the efficiency of the conventional engine or introduce a new solution to aerospace propulsion. This revolution in the industry brings tremendous challenges as well as new opportunities. The industry has developed different approaches to increase the efficiency of the engine, including increasing the thermal efficiency and transfer efficiency. An increased temperature and pressure in the engine enhance its thermal efficiency but bring the penalty of reduced engine life[3–7]. Also, the high operation temperature requires a higher turbine cooling technology, which increases the cost of manufacturing and operation[8, 9]. Another approach is to increase the engine's bypass ratio to increase the transfer efficiency. On the other hand, the increased bypass ratio comes with a lower specific thrust, which requires a lower fan pressure ratio. With the increased bypass ratio, the fan pressure ratio needs to be decreased; consequently, at a point when the fan pressure ratio is lower than 1.45, the fan duct will need the introduction of a variable geometry nozzle to provide enough back pressure[10–13]. Also, the increased bypass duct means that the geometry size of the fan is bigger, which requires a bigger wing-to-ground space for the aircraft, which is difficult for single-haul aircraft platforms. This means that the approach of increasing the transfer efficiency of the engine also has a constraint, and it is difficult to enhance the engine efficiency with either approach.

For the reasons stated above, this paper studied a novel aircraft propulsion concept, engine electrification with fuel cell and steam injection. The innovative thermodynamic cycle has been described and analysed in this study to explore its potential for

fuel-saving.

2. CONCEPT DESCRIPTION

The turbofan engine electrification has been developed in the research over the past decade. The basic understanding of a hybrid-electric turbofan engine is to use a motor connected to the engine shaft to provide power assistance for the gas turbine or transfer power between the shafts[14]. Previous research has recognised that the power assistance/injection concept can help reduce fuel consumption and emissions and improve operation flexibility. Consequently, direct power assistance to the gas turbine would reduce the gas turbine's operation temperature, thus bringing a penalty to the engine's thermal efficiency. Also, the direct power assistance would push the compressor rotation speed and lead to a reduction in the surge margin. That drawback of the power assistance determines that electrification strategies are required to electrify the turbofan engine.

This paper studied a novel turbofan engine electrification strategy; the low-pressure shaft of the turbofan engine is connected to an electric motor powered by a proton-exchange membrane (PEM) fuel cell system. The water product from the fuel cell is collected and injected into the gas turbine combustor after the process of condensing, pressuring and superheating. The condensing process proceeds with a condenser, transferring the combination of steam and water to a saturated water line, and a compressor pressurises the water to match the combustor pressure. A heat exchanger is placed in the engine core exhaust pipe to collect the waste heat from the exhaust gas and redirect it to the water in super-heated condition.

3. LITERATURE REVIEW

This research is motivated and inspired by a number of studies carried out by major research institutions. Research and study in related fields, including electrification, hydrogen, and gas turbines, have been reviewed in this study.

3.1 Aircraft and propulsion electrification

Aircraft electrification technologies and concepts have a long history, dating back to 1883 when the first ever electric-powered airship was built[15]. In 1973, the first manned electric-powered aircraft was flown solely by West Germany[16]. Although, nowadays, most civil aircraft are powered by fossil fuel, the concepts of aircraft electrification have been discussed and studied by major institutions, and major aircraft manufacturers have deployed many technologies. Boosted by lighter weight, higher reliability, and more efficiency, electric technology was reintroduced in civil aircraft design in the late 1980s. Airbus decided to deploy the 'fly by wire' technology in the A320, and later, this technology was also recognised by Boeing and used on the Boeing 777. Subsequently, the application of electricity has been extended to more sub-systems on the aircraft, such as the hydraulic, landing gear, and flying control. The concept of more electric aircraft (MEA) has been recognised and deployed on state-of-the-art aircraft such as B787 and A350[17]. Developed from the previous effort on aircraft components' electrification, the concept of aircraft propulsion electrification has risen and been studied in the past decade[18]. There are three primary domains

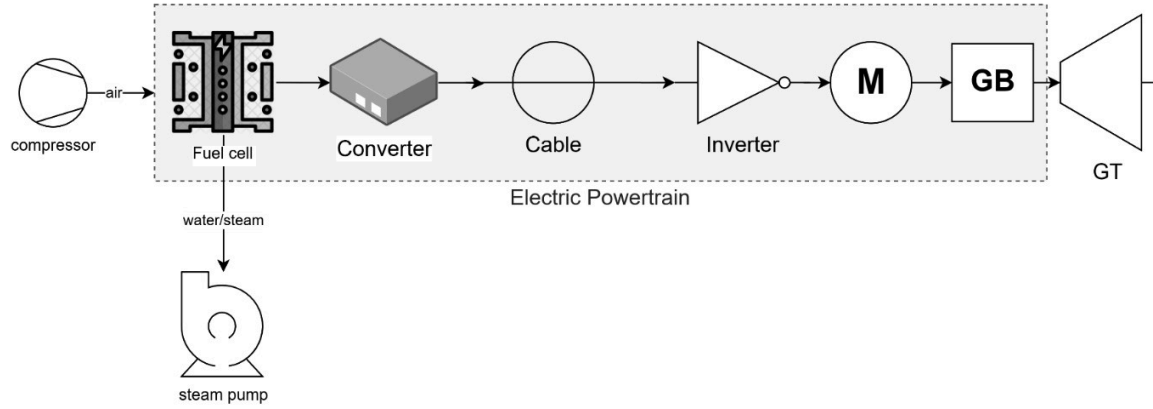


FIGURE 1: Electric power train

of propulsion electrification: fully electric, turbo-electric and hybrid electric. As a promising propulsion electrification concept, the hybrid electric has a more complex configuration but requires lower electric component technology levels such as the battery energy density. In a hybrid electric configuration, the aircraft is powered by a conventional gas turbine and equipped with an electric motor. The electric motor provides power assistance to the thrust generation by either mechanical integration[19] or cycle integration. Hybrid electric technologies are not only looking at replacing the power requirement from fossil fuel but also aim at increasing the efficiency of the GT. With the power assistance to the thrust, the gas turbine can be re-designed to be smaller and more efficient[20]. This concept has been widely explored by multiple institutions in many projects such as SUGAR-VOLT[21–23], UTRC geared turbofan project[24–26], Rolls-Royce North America (RRNA)-Electrically Variable Engine (EVE)[27–29].

3.2 Hydrogen technology

As a fuel does not contain carbon, hydrogen combustion and electrochemical conversion do not produce carbon-based emissions. Although, considering the full life cycle emissions, the production of hydrogen would require electric power, green hydrogen has been proven to outperform jet fuel as well as many other fuels in terms of CO₂[30]. There are two primary ways of deploying hydrogen technology into the aircraft: hydrogen combustion and hydrogen fuel cells. Hydrogen combustion is an easier way to achieve zero emission, but it requires long-term development of hydrogen storage and distribution systems. Compared to hydrogen combustion, the fuel cell has been well-developed in stationary and automotive applications. In the short term, the fuel cell system can provide a higher efficiency but the hybrid system requires a complex. regarding the integration and control.

Projects and research have been studied on using fuel cells to provide thrust for aircraft[31–37], but most of them are applied on small, regional aircraft[36, 37]. It has been argued that the fuel cell and hydrogen storage system are heavy and bring a big weight penalty. Though the weight penalty has been questioned, major research projects have been focused on the future application of

hydrogen technology, including the ENABLEH2[38], NASA’s N3-X[39], Bauhaus Luftfahrt’s Hyliner2.0[40], FlyZero[41], Cranfield University[14, 35–37, 42–46]. Reviewing this previous research shows that most of the research uses a fuel cell as an independent power supply to the electric motor and coupled with the propeller to provide thrust to the plane. The researchers from Bauhaus[47] have provided an initial assessment of integrating the fuel cell with the gas turbine, which provides sufficient discussion on the potential of this technology. From there, it is worth exploring whether different engine cycles and different steam distribution strategies will impact the steam injection and bring different results.

3.3 Gas turbine steam injection technology

Steam injection in gas turbines is not a recently developed concept. Steam injection has been proposed and applied in the industry since at least the mid-last century[48–50]. Compared to today’s operation, which normally uses water injection as a method of controlling the emission[51, 52], conventional steam injection is aimed as a thrust assistance for a short period. Typically, the steam is injected into the gas turbine from the inlet, combustor and turbine.

Nowadays, steam injection is commonly used in stationary gas turbines, which inject steam into the GT cycle to enhance the thermodynamic efficiency of the GT as well as the power output[53, 54]. The application is named as “steam-Injected Gas Turbine” (STIG) power plants. The application uses the wasted heat from the exhaust gas, heating the steam and injecting the hot steam into the combustor. The concept aims to recover the wasted heat and redirect the power into the GT cycle to enhance thermodynamic efficiency[55, 56].

The application of using steam injection on a civil aircraft has been discussed and studied. Ernesto et al. studied the concept of injecting steam into a turbojet engine combustor to control the NO_x emissions and suggested a reduction of 16% NO_x emissions can be reached when a steam flow which doubles the fuel flow is introduced[57]. Various research has been conducted with the water-enhanced turbofan concept[58–61], demonstrating a 13% reduction in terms of SFC and a reduction of 10% in fuel burn

TABLE 1: Engine design parameters

Parameters	Engine 1	Engine 2	Engine 3
BPR (-)	4.84	11.72	12.78
Maximum OPR	32.58	40.33	50.19
Maximum TET (K)	1578.9	1798.0	1703.0
ST (N/kg·s)	162.5	111.16	92.64
Gearbox	N/A	N/A	1:3

considering efficiency improvement, weight penalty, and added nacelle drag[60]. The WET concept is currently under initial assessment, analysis and demonstration[62, 63].

Research from Bauhaus demonstrates an initial assessment for the fuel cell electrification on a civil aircraft, recovering the water product from the fuel cell and injecting the steam into the combustor. Bauhaus suggested the PEM fuel cell steam injection could not lead to a reduction of fuel savings, but on the contrary, a SOFC fuel cell provided power up to 6.3MW with 74% stack efficiency provides an improvement of 7.1% in terms of fuel savings with the water-to-air ratio of 6.1% compared to the baseline aircraft[47]. The hybrid system brings 64.9% increase of weight of propulsion system, and 6.4% increase of maximum take-off weight.

4. METHODOLOGY

This research uses a model-simulation-based research methodology. Three turbofan engine models representing typical thermodynamic cycles have been modelled with TURBO-MATCH, a Cranfield University in-house gas turbine simulation software. The three engines represent a last regeneration engine, a state-of-the-art high-temperature engine, and a high BPR, high OPR geared turbofan engine, respectively. The parameters of the engines are introduced in the table.1 Typical one-hour mission profiles of short to medium-range aircraft have been simulated and generated with HERMES, a Cranfield University in-house mission profile simulation software.

The engine is power-assisted during the segment of take-off and climbing; a motor connected to the low-pressure shaft is powered by the fuel cell on board and provides power assistance to the gas turbine. The motor is designed to provide power up to 1MW to the gas turbine. The power train electric motor includes a fuel cell, converter, cable, inverter, motor and gearbox. The efficiency of the components in the power train has reasonable assumptions. A thermal management system has been reasonably sized to cool down the components in the power train.

With the same energy management strategy of distributing electric power, two different ways of distributing the steam have been developed and analysed in this study. The steam is processed and injected instantaneously with its production from the fuel cell, and another approach is to store the water in storage equipment and process and inject it during the cruise segments. Both approaches have been modelled and analysed in this research and compared to assess the preference.

The weight of the components in the power train has been captured with reasonable assumptions of power and energy density. The assumptions are made with a reasonable roadmap of the 2035 technology level. The weight penalty of hydrogen storage

TABLE 2: Efficiency and Power Density of Components

Components	Efficiency [%]	Power Density [kW/kg]
Fuel cell (With BoP)	70	2.5
Converter	98	10
Cable	98	N/A
Inverter	98	10
Motor	96	10
Gearbox	99	N/A
TMS	N/A	2

equipment has been estimated with the total amount of hydrogen required for the designed energy management strategy to provide necessary hydrogen during the take-off and climb. The super-heating heat exchanger has been modelled, and this research has done a parametric analysis of sizing/efficiency to capture the trade between its weight penalty and the benefit of steam injection. This research assesses the benefits and drawbacks of electrification with criteria including fuel consumption and weight penalty.

4.1 Power train sizing

The structure of the power train is shown in fig.1 below. This research assumes that the peak power injected into the gas turbine is 1MW, and the efficiency of the components in the power train is shown in table.2. The power loss and efficiency of the power train can be described as eqn.1. The stack efficiency of the fuel cell is assumed with the 2035 technology-level roadmap [64, 65] introduced by the major research institutions.

$$\eta_{\text{power train}} = \eta_{\text{GB}} \cdot \eta_{\text{motor}} \cdot \eta_{\text{inverter}} \cdot \eta_{\text{cable}} \cdot \eta_{\text{converter}} \quad (1)$$

The air supply of the fuel cell is supplied by a compressor to maintain a constant air pressure during the flight. The size of the air compressor is sized to match the maximum airflow of the fuel cell and the maximum pressure ratio designed to feed sufficient air to the fuel cell.

The fuel cell also supplies power to the steam pump, which is designed to provide steam with sufficient pressure to match the pressure in the combustor. The size of the pump is determined by the maximum mass flow of the steam and the maximum pressure ratio between steam and combustor pressure.

With the power train structure stated above, the power requirement of the fuel cell can be described with eqn.2, shown below.

$$P_{\text{stack,el}} = \frac{P_{\text{injection}}}{\eta_{\text{power train}}} + P_{\text{steam pump}} + P_{\text{air compressor}} \quad (2)$$

4.2 Fuel cell model and steam production

This research uses a chemical balance-based fuel cell model to assess hydrogen consumption and water production. The water mass flow produced from the fuel cell can be estimated using eqn.3[47]. The fuel cell uses the parameter of water recovery ratio to describe the ability to recover water product from the fuel cell; the mass of water captured can be described with eqn.4. With the consideration of chemical balance, the required hydrogen supply

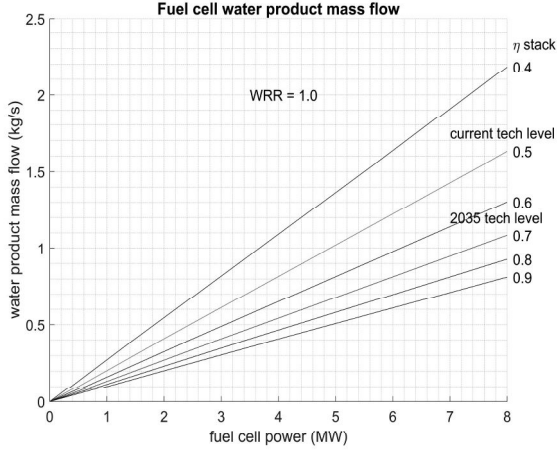


FIGURE 2: Impact of stack efficiency on water mass flow

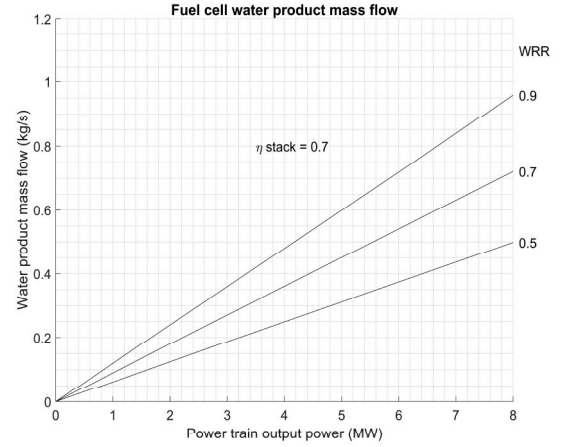


FIGURE 3: Impact of WRR on water mass flow

of the fuel cell can be described with eqn.5. In the fuel cell air supply equation, a parameter of excess air ratio is included to ensure the fuel cell has necessary and excess air supply. The parameter of oxygen excess ratio is introduced and assumed to be 1.9. The mass flow of the oxygen inlet for the air compressor is thus written as eqn.6.

$$\dot{m}_{\text{stack,H}_2\text{O}} = \frac{P_{\text{stack,el}} \cdot M_{\text{H}_2\text{O}}}{\eta_{\text{stack}} \cdot FHV_{\text{mol}}} \quad (3)$$

$$\dot{m}_{\text{H}_2\text{O}} = \dot{m}_{\text{stack,H}_2\text{O}} \cdot \text{WRR} \quad (4)$$

$$\dot{m}_{\text{H}_2} = \frac{P_{\text{stack,el}}}{FHV_{\text{H}_2} \cdot \eta_{\text{stack}}} \quad (5)$$

$$\dot{m}_{\text{O}_2 \text{ required}} = \frac{\dot{m}_{\text{H}_2\text{O}}}{2} \cdot M_{\text{O}_2} \cdot \text{OER} \quad (6)$$

This research assumes that the ambient oxygen ratio is fixed for different altitudes. Thus, the mass flow of the air inlet for the compressor can be calculated with eqn.6. Based on the equations stated above, the work requirement from the compressor can be calculated with the air mass flow, ambient air pressure and the compressor outlet pressure. The ambient air pressure varies with the flight altitude, and the compressor outlet pressure is set at a fixed value to provide air with sufficient pressure to the fuel cell.

A parametric analysis has been conducted in this study to explore the relationship between power output from the power train, fuel cell stack efficiency, water recovery ratio and water product mass flow. The influence of water stack efficiency and water recovery ratio is shown in fig.2,3.

This research uses reasonable assumptions for fuel cell stack efficiency and water recovery ratio (WRR), as shown in Table.3. WRR is related to the technology level, product pressure, temperature and condenser design.

TABLE 3: Fuel Cell Parameters

Fuel cell parameters	Value
Fuel stack efficiency	70%
Water recovery ratio	0.7

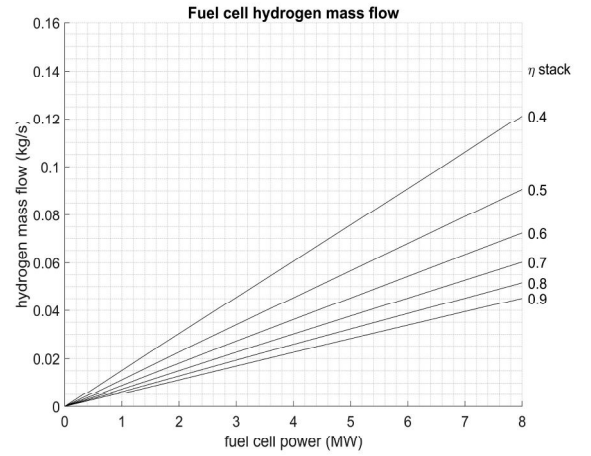


FIGURE 4: Hydrogen consumption rate

The fuel cell's hydrogen supply is calculated with the equation introduced above. The parametric analysis suggests that hydrogen consumption is shown in fig.4.

The steam collected from the fuel cell is injected into the gas turbine combustor after the steam treatment process. The process includes condensation, pressurisation and super-heating. The system of the steam treatment and processing system is shown in fig.5. The condensation process condenses the liquid/gas mixture product from the fuel cell into liquid. Then, a pump pressurises the liquid water to match the pressure in the combustor to ensure the flame and hot gas in the combustor would not reverse flow into the steam injection system. The high-pressure water then goes through the heat exchanger placed in the exhaust pipe of the turbofan engine. Considering the turbofan engine generates thrust mainly from the bypass duct, the heat in the engine core exhaust is mainly a waste of power. The water that goes through the heat exchanger is re-vaporized and superheated in the heat exchanger and turns into high-temperature steam. After the treatment process, the high-temperature, high-pressure steam is injected into the combustor to provide extra enthalpy to the gas turbine.

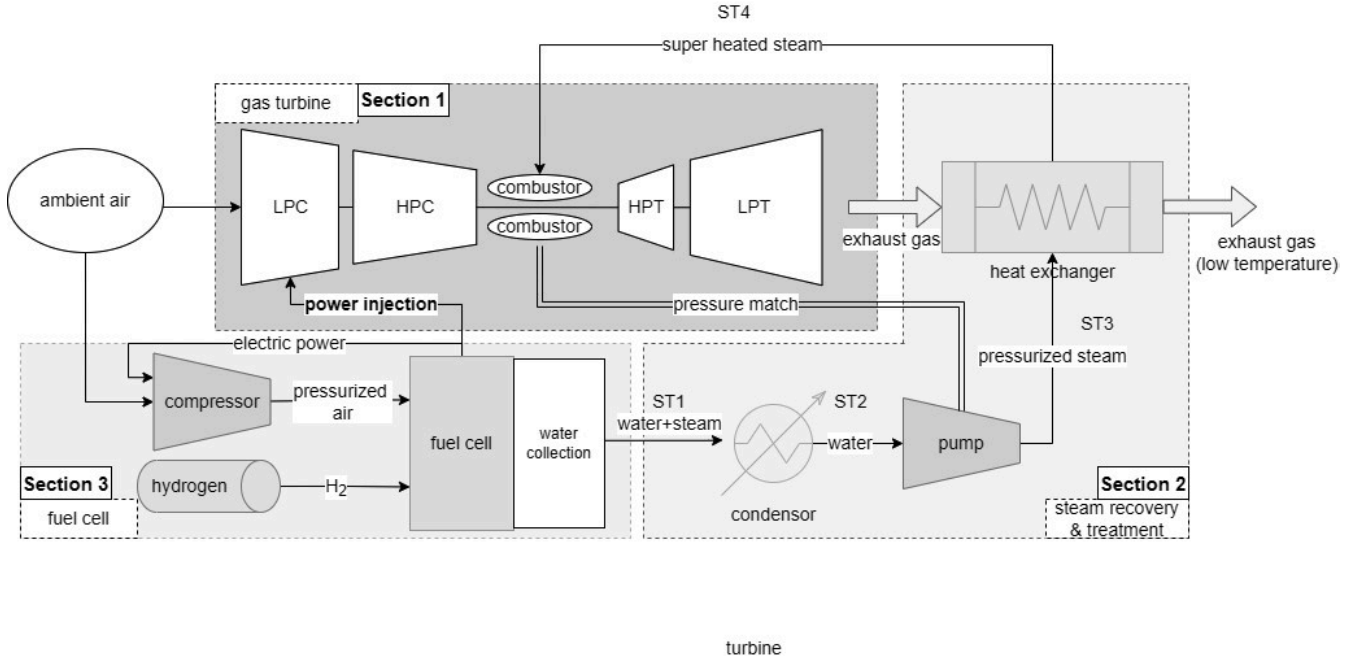


FIGURE 5: Steam processing system

4.3 Steam processing and injection

In the treatment process, though the gas temperature in the engine core exhaust pipe is considered waste heat, the hot gas in the engine core still generates some thrust through its expansion. Considering this phenomenon, this study has captured the loss of thrust in the engine core exhaust due to the temperature loss. This loss has been captured through the gas turbine simulation with the heat exchanger model. The heat exchanger in this study has been modelled with a typical heat exchange model.

The overall steam/water treatment process can be described with the T-S diagram in fig6. In the treatment process, the start point is the steam/water recovered from the fuel cell as ST1. The fuel cell is assumed to operate at 353K, with a pressure of 28kPa. The condensation process condenses the steam/water mixture to the saturated water line, as the ST2 shows; this process is assumed to have fixed pressure. The pump then pressurises the water from ST2 to ST3 regarding the pressure of different engines. fig6 uses the cruise segment as a representation of the combustor pressure. The ST3 is different in different operation cases for different engines and flight segments. The high-pressure water is then superheated in the super-heat exchanger to the ST4. Again, the ST4 is various with different engines and operation segments. Also, the sizing and the design of the heat exchanger vary this temperature outcome. This outcome temperature of the super-heated steam is captured with the heat exchanger model introduced in a later chapter. The research recognize there will be a pressure loss in the steam injection components, for both steam and exhaust gas. A reasonable assumption for a 5% steam pressure loss in the condenser and a 5% exhaust gas pressure loss has been set for the super-heat HEX[47]. The assumptions are summarized in the table 4.

This research considers two ways of distributing the steam

during the flight, including processing and injecting the steam instantly with the production, and another strategy is to store the steam and use it during the cruise.

TABLE 4: Assumptions of steam injection components pressure loss

Components	Property	Assumption
Condenser	Pressure loss	5%
Super-heat HEX	Pressure loss	5%

4.4 Weight penalty

This research recognises that one of the principal controversies of aircraft electrification is the weight penalty from the equipment and energy storage components. As a response to the difficulty of battery technology development, this research chooses to use the fuel cell as the replacement for energy storage. For a long period of operation time, the state-of-the-art hydrogen technology brings a lighter weight since it only needs to bring more hydrogen but the same stack. This research estimates the weight penalty for different components and assesses the potential weight penalty for the mission.

The weight penalty from an electric power train has been assessed with typical assumptions of power density, with projected technology level of 2035. The fuel cell and hydrogen storage systems use a representative technology roadmap from major research institutions as the assumptions [65]. The power density of the fuel cell includes the stack and BoP. Hydrogen consumption has been assessed using the methodology introduced in the previous section, and the storage system sizing is based on this calculation. The power density assumptions and the sizing of the

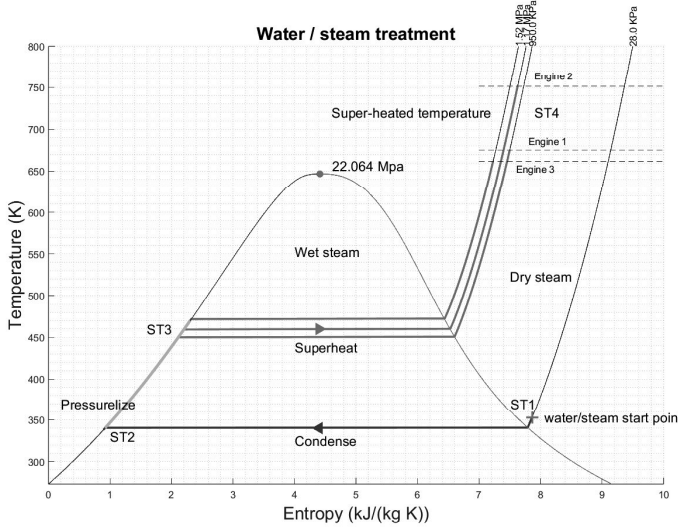


FIGURE 6: Steam treatment cycle

electric power train components used in this research are introduced in Table 2. For hydrogen storage, this research assumes a typical system gravimetric capacity of 0.057 kg H₂/kg system.

The weight estimation of the heat exchanger has been captured by the heat flux. For different steam distribution strategies, the heat exchanger is differently sized to assess the weight penalty. The area of the heat exchanging surface is estimated with a reasonable assumption of heat transfer coefficient. The volume of the heat transfer components is then estimated with a typical area density [66]. The calculation is described in the eqn. 7-9 below.

$$Q = \dot{m}_{air} \cdot C_p \cdot (T_{exhaust,in} - T_{exhaust,out}) \quad (7)$$

$$= \dot{m}_{steam} \cdot (h_{steam,out} - h_{steam,in})$$

$$Q = U \cdot A \cdot \Delta T \quad (8)$$

$$m_{heat\ exchange} = \frac{A}{\beta} \cdot \rho \quad (9)$$

5. RESULTS AND DISCUSSION

5.1 Steam temperature and heat exchange

The research recognised that steam temperature is one of the most important factors affecting the potential of steam injection. The mass flow and temperature of the steam reflect the power recovered from the exhaust and redirected into the combustor. The mass flow of the steam, which in this research depends on the degree of hybridisation and the distribution of the steam, is included in the analysis as a parameter of the steam.

Three factors are considered in the heat exchange modelling: steam mass flow, heat exchange effectiveness of the heat exchanger, and exhaust temperature. As discussed in the previous chapter, this research highlights the loss of the engine core exhaust temperature. As a result of the temperature loss, the steam temperature calculation captures this physics by iterating the calculation. The mass flow of the steam represents the different

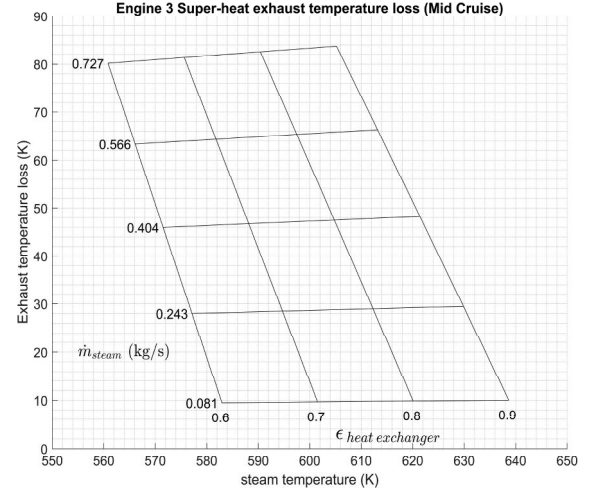


FIGURE 7: Core exhaust temperature loss (steam stored for cruise)

steam distribution strategies, and the heat exchange effectiveness demonstrates the size and technology level of the super-heat heat exchanger.

Fig. 7, 8 demonstrate the relationship between the heat exchange process and indicate the gas turbine core exhaust temperature loss.

Following fig. 7, as the result of heat exchange, the dominant factor of the exhaust temperature loss is the steam mass flow, and the heat exchange effectiveness stands in the minor position.

A higher steam distribution rate brings more loss to the exhaust temperature, thus resulting in more penalty to the gas turbine efficiency. Following fig. 8, both steam mass flow and heat exchange effectiveness hold equal importance in the steam temperature results. A smaller mass flow of steam will result in a higher steam temperature from the heat exchanger, thus recovering more heat from the exhaust. On the other hand, for the same amount of steam, higher heat exchange effectiveness will bring higher steam temperatures without a significant penalty to the exhaust temperature. In terms of steam mass flow, heat exchange effectiveness, exhaust temperature loss and hot steam temperature, it can be concluded that the steam injection electrification strategy prefers lower steam mass flow and higher heat exchange effectiveness to achieve a higher hot steam temperature and lower exhaust temperature loss.

5.2 Parametric analysis of steam injection's impact on fuel consumption

This research recognised two of the most important factors: steam temperature and steam mass flow. It is important to discover the importance of these two parameters in terms of their effect on the gas turbine's fuel consumption. A parametric analysis is designed and conducted in this research to reveal which is the dominant factor in the steam injection. Hence, to answer the question, "Should the steam injection electrification chase for high-mass flow steam injection or high-temperature mass flow?".

To answer this question, this research uses engine 3 as a typical representative of the gas turbine steam injection electrifi-

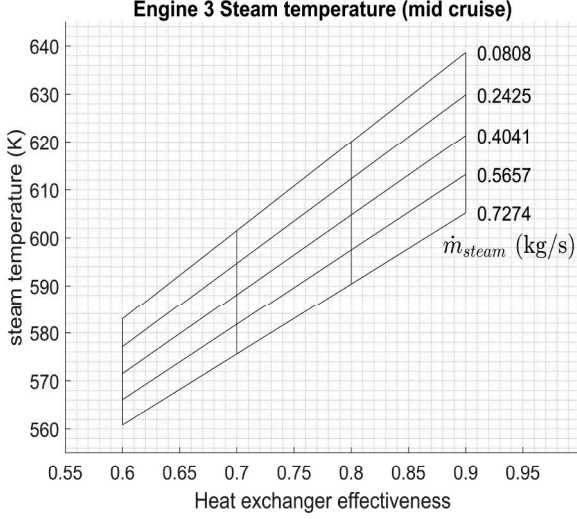


FIGURE 8: Super-heated steam temperature (steam stored for cruise)

cation and chooses the mid-cruise operation point to exclude the influence of power injection. The result of the analysis is shown in fig.9. This analysis does not consider the exhaust temperature loss and thus only captures the effect of hot steam injection. The results of the analysis suggest that both the steam temperature and steam mass flow have significant effects on the reduction of fuel consumption. It cannot be determined which factor is the dominant in terms of fuel consumption benefit from steam injection.

Considering the fact stated in the previous discussion, steam mass flow greatly impacts the exhaust temperature loss. This research recognised that the loss of exhaust temperature would bring a penalty to the gas turbine fuel efficiency, which will be explained later. High mass flow steam injection would lead to fuel efficiency penalties that compromise the benefits of steam injection. On the contrary, the high steam temperature, which is a result of high heat exchange effectiveness, comes with a relatively lower penalty on the exhaust temperature loss.

Alternatively, from the mission level, the total amount of steam available for the steam injection depends on the size and operation of the fuel cell and the total FC operation time. For a fixed mission profile and FC operation condition, the total amount of steam is the same, no matter what the steam distribution strategy is. fig.9 shows that the relationship between steam mass flow and fuel consumption benefit is linear for a fixed steam temperature. A conclusion can be made for the mission level: for a fixed total amount of steam injected into the gas turbine, the fuel consumption benefit is majorly related to the steam temperature rather than the mass flow. The steam injection electrification should focus on high steam temperature rather than high steam mass flow.

5.3 Core exhaust temperature loss

Compared to the previous literature, this research identifies and underlines the core exhaust temperature loss due to the superheat heat exchange process. As a matter of fact, the state-

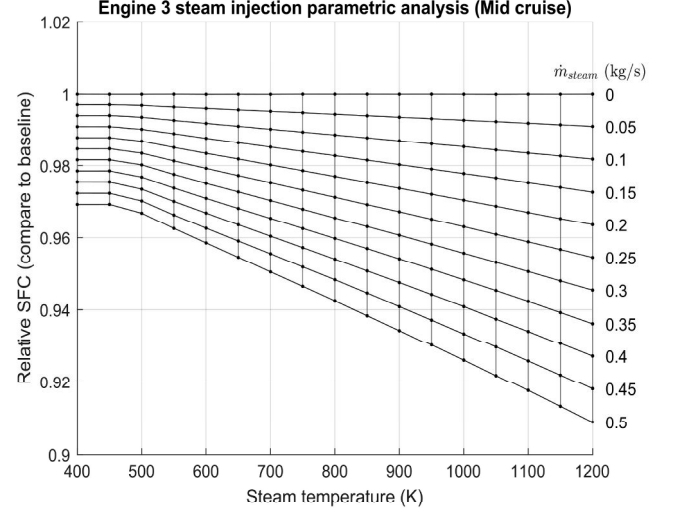


FIGURE 9: Steam injection's impact on SFC (theoretical)

of-the-art civil turbofan engine normally has a high bypass ratio, and the future engine design roadmap also looks at increasing the transfer efficiency. It is clear that the current and future turbofan engine design is and will keep focusing on improving the fuel economy by increasing the efficiency of bypass duct flow. However, it can not be denied that the engine core still provides thrust; thus, it cannot be stated that the exhaust temperature on a modern turbofan engine is completely wasted. This research recognised from preliminary results that the benefit from steam injection itself could be small, and doubt if the penalty of exhaust temperature loss would compromise this small benefit.

The research uses engine 3 as a representative model to discover this potential and chooses the mid-cruise as the operation condition. The mid-cruise segment is chosen because it is the segment that comes with the lowest exhaust temperature; thus, the steam temperature would be the lowest among the mission points. The previous discussion has stated that steam temperature is the dominant factor in fuel consumption benefit; thus, steam injection during the cruise segment would bring the lowest benefit for fuel economy while resulting in a penalty to the exhaust temperature.

Two simulations have been conducted and compared to quantify the impact of exhaust temperature loss. The results are analysed and shown in fig.10. The Figure captured multiple factors, including the steam mass flow, heat exchange effectiveness, exhaust temperature loss, steam temperature and the SFC benefit brought by the steam injection. The simulation group uses the red colour to demonstrate the theoretical benefit of steam injection. This simulation group neglected the reduction of core exhaust temperature, similar to the industrial gas turbine steam injection, using an external heat source to superheat the steam and inject it into the combustor. Conversely, the corrected simulation group, marked as black, includes the exhaust temperature loss, demonstrating the real case.

It is clear that through the comparison in fig.10, the exhaust temperature loss brings a dramatic and significant penalty to the steam injection. The loss of exhaust temperature has compro-

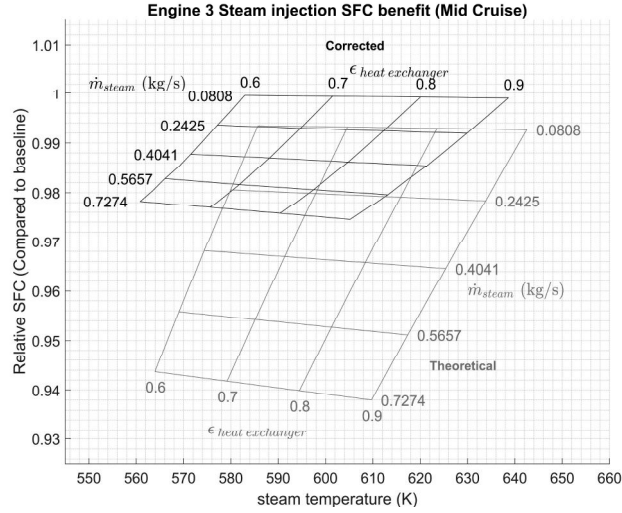


FIGURE 10: Theoretical and corrected SFC benefit of steam injection (steam stored for cruise)

mised more than 60% of the fuel consumption reduction. However, the steam injection does not bring a penalty to the fuel economy by increasing fuel consumption.

It needs to be emphasised that this penalty from the exhaust temperature loss is related to the engine design. For an engine with a lower specific thrust, the ratio of thrust produced from the core flow to the thrust produced from the bypass flow is lower. This means that for a low-specific thrust engine, the thrust production relies less on the core exhaust; thus, the exhaust temperature loss would be less significant. For future engine design, focus on a high bypass ratio and low specific thrust; this discovery means that the steam injection would be more suitable for future engines' thermodynamic cycles regarding exhaust temperature loss.

5.4 Weight penalty

As discussed in the previous chapter, the weight penalty of electrification is analysed in this research, including the fuel cell, electric components, hydrogen storage, and steam superheat heat exchanger. Toward these components, the weight penalty from the heat exchanger needs to be emphasised and highlighted. As demonstrated previously, the steam temperature is one of the most important factors affecting the results of steam injection. The steam temperature is directly proportional to the size of the heat exchanger and the steam mass flow. This research assumed the heat exchanger is sized based on two factors: the maximum mass flow and the heat exchange effectiveness. The HEX is differently sized for different steam distribution strategy. In this case, the heat exchange effectiveness is a result of the fin area; thus, a heat exchanger with higher heat exchange effectiveness results in heavier weight. The relationship can be described as a more efficient heat exchanger leading to higher steam temperature, thus leading to higher fuel benefit, but results in more weight penalty. A higher steam mass flow, which carries more heat, requires a bigger heat exchanger but also results in heavier weight.

The weight penalty of the heat exchanger is analysed in fig. 11 for instantaneously injection strategy. It is clearly demonstrated

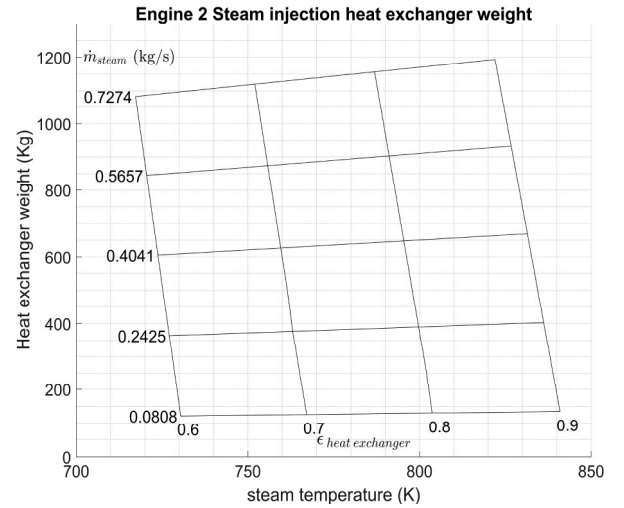


FIGURE 11: Heat exchanger weight penalty (inject instantaneously)

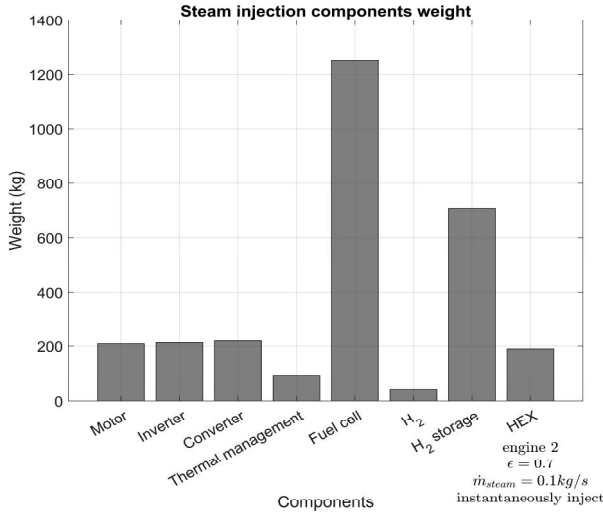


FIGURE 12: Power train and hydrogen weight penalty

that the steam mass flow is the dominant factor in the heat exchanger weight penalty. The heat exchange effectiveness also holds a minor impact on the weight penalty, but it's relatively less significant. The analysis of heat exchangers suggests that a lower steam mass flow and higher heat exchange effectiveness would be an ideal approach for heat exchanger sizing and designing. Following the weight analysis and the previous steam injection benefit analysis, both discoveries suggest that the steam injection should target high temperatures rather than high mass flow.

Besides the heat exchanger, this research also looked at the weight penalty results from the electric components, hydrogen, and storage equipment. fig.12 demonstrates the weight penalty brought by the steam injection following the EMS used in this research and the assumption made. As observed, the fuel cell and hydrogen storage are the most significant factors in the weight penalty, bringing around 2000 kg. The total weight penalty is around 2800 kg, excluding the heat exchanger. The weight penalty is significant in the steam injection electrification strategy and will obviously bring compromise to its benefit.

5.5 Steam distribution strategy

Combining the previous analysis of steam temperature and steam mass flow, the analysis in this research has proved that the steam injection should target high steam temperature rather than high steam mass flow. This discovery guides the design of the steam distribution strategy. The previous chapter stated that there are two potential steam distribution strategies: inject instantaneously while producing and processing or store the steam for later distribution. Based on the existing discovery, it can be concluded that the steam injection is preferable for a high TET segment to achieve a higher steam temperature. As the figure.7 suggested the relationship between steam mass flow and SFC benefit is linear. Hence, a short-period, high-mass flow steam distribution strategy would not lead to extra benefits compared to instantaneously being injected at a high temperature. The fuel benefit of electrification strategies is captured with a mission simulation, and the fuel flow during the T/O, climb and cruise

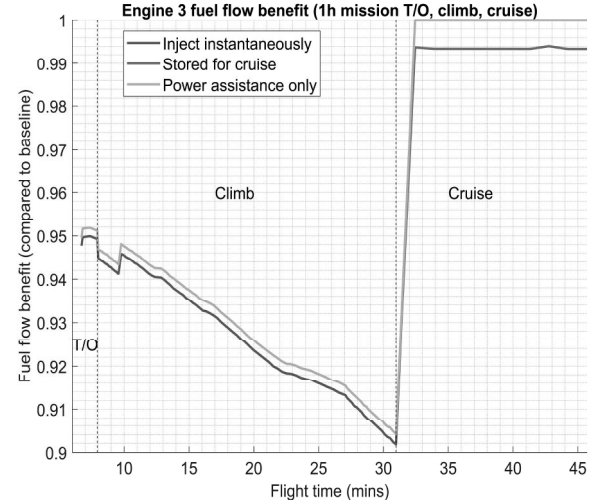


FIGURE 13: Engine 3 fuel flow benefit (T/O, climb, cruise)

segment is simulated and shown in the fig.13. A segment block fuel consumption change compared to the conventional engine has been analysed and shown in table.5.

Considering the fact that during the take-off and climb segment, the exhaust temperature is higher than in the cruise segment, it would be preferable to inject the steam incautiously with production rather than store it for the cruise segment.

5.6 Steam injection in different engine cycle

It is important to understand if the steam injection is suitable and performs similarly in other engine cycle designs. This research chose and modelled three representative engine thermodynamic cycle designs and deployed the steam injection electrification strategy into all three of them.

Engine one. Steam injection shows a penalty for fuel consumption when deployed in engine 1, as fig.14 suggested. The steam temperature has a similar impact on the fuel consumption as the engine 3.

Compared with engine 3, engine 1 has a higher specific thrust. Hence, as stated previously, the thrust produced by engine 1 is generated relatively more by the engine core. Considering the steam superheat process brings a penalty to the core exhaust temperature, in the case of engine 1, the steam injection brings a significant penalty to the gas turbine. It compromises the heat recovered from the exhaust.

It can be recognised that the steam injection is not favourable for high specific thrust engines, considering these engine cycles produce more thrust from the core exhaust, and the loss of exhaust temperature would require higher TET in the combustor to correct the loss.

Engine two. As stated in the previous discussion, the steam injection is not favourable for the engine cycle with high specific thrust. The research is curious if a high steam temperature can correct this penalty. As a representative of the high-temperature gas turbine thermodynamic cycle, engine 2 is similar to engine 1, but the temperature is much higher. The same exploration

TABLE 5: Changes in segments fuel consumption for different strategies

Properties	Inject instantaneously [1]	Stored for cruise[2]	Power assistance only[3]
Change in T/O fuel*	-3.91%	-3.77%	-3.77%
Change in climb fuel*	-7.17%	-6.95%	-6.95%
Change in cruise fuel*	N/A	-0.65%	N/A
Change in 1h mission fuel*	-4.23%	-4.22%	-4.10%

* compared to conventional engine

[1] Power assistance, steam inject instantaneously

[2] Power assistance, steam inject during cruise

[3] Power injection only, no steam injection

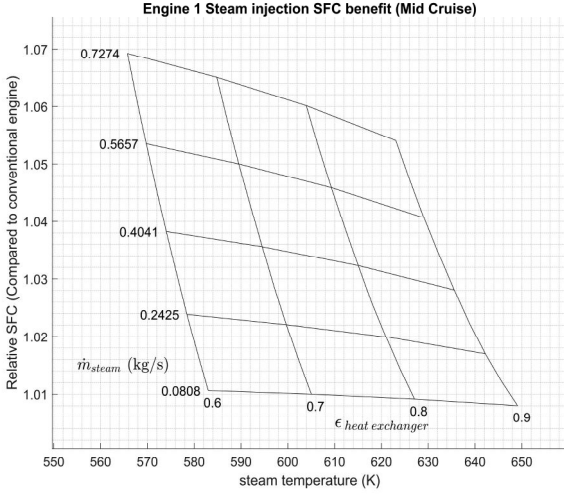


FIGURE 14: Steam injection's impact on Engine 1 (steam stored for cruise)

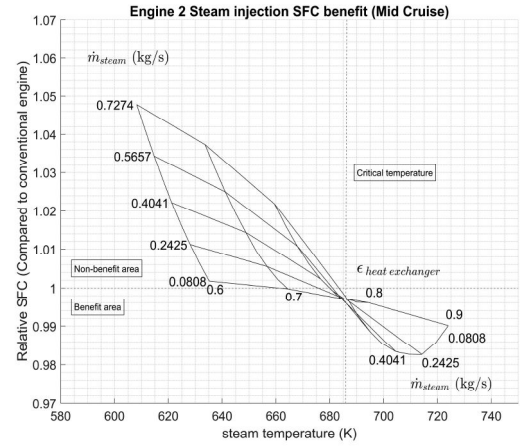


FIGURE 15: Steam injection's impact on Engine 2 (steam stored for cruise)

is conducted with engine 2 to discover the impact of the steam injection electrification strategy.

As fig.15 suggests, the steam injection shows a dramatic impact on engine 2 for the cruise segment. It is clear for engine two that the steam injection will again bring a penalty to the fuel consumption due to the loss of exhaust temperature. However, due to the high temperature in the thermodynamic cycle, the steam temperature is much higher in this case, and a critical point exists between the benefit and penalty areas.

High heat exchange effectiveness, resulting in the high steam temperature, makes it possible to beat the penalty that comes from exhaust temperature loss. But in most cases, the steam injection can only bring a penalty to the fuel consumption.

5.7 Steam injection in different flight segments

This phenomenon brings the next question, “for segments with higher temperatures, will the steam injection bring benefit?”. Two extra operation points have been simulated to address this question using engine 2 as an example, and the results are shown in the fig.16,17. For the Take-off segment, the steam injection is able to provide a promising benefit for fuel consumption due to the high temperature. On the other hand, at the top of the climb point, the critical point appears again, similar to the cruise

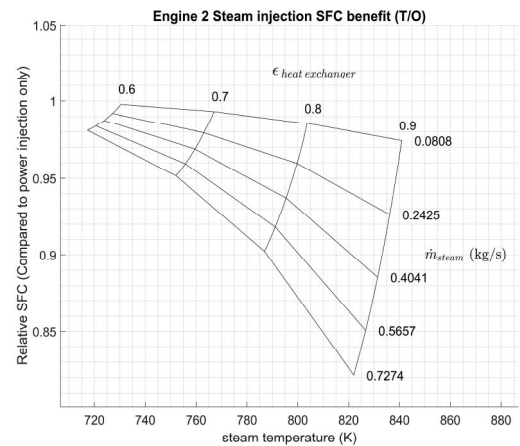


FIGURE 16: Steam injection's impact on Engine 2 (steam injected instantaneously)

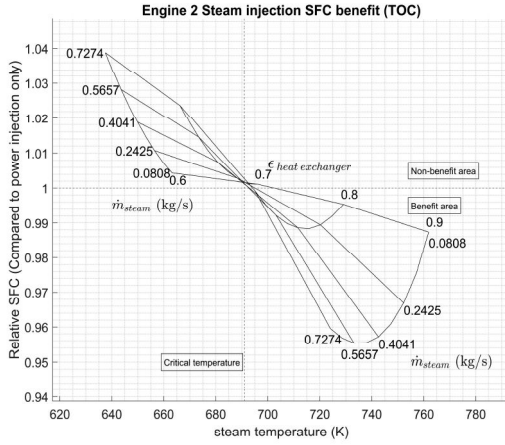


FIGURE 17: Steam injection's impact on Engine 2 (steam injected instantaneously)

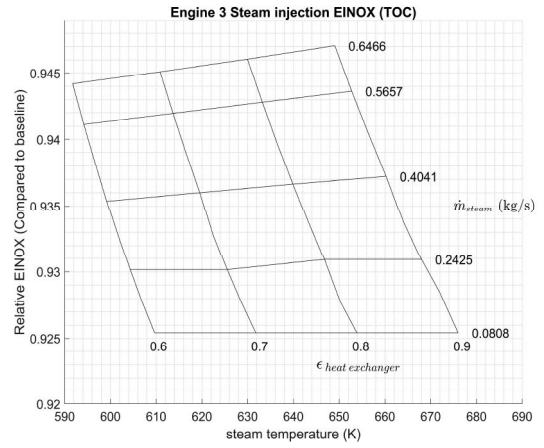


FIGURE 19: Engine 3 EINOX ratio(TOC)

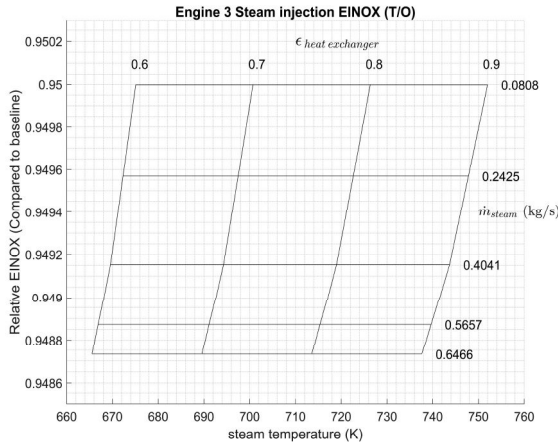


FIGURE 18: Engine 3 EINOX ratio(T/O)

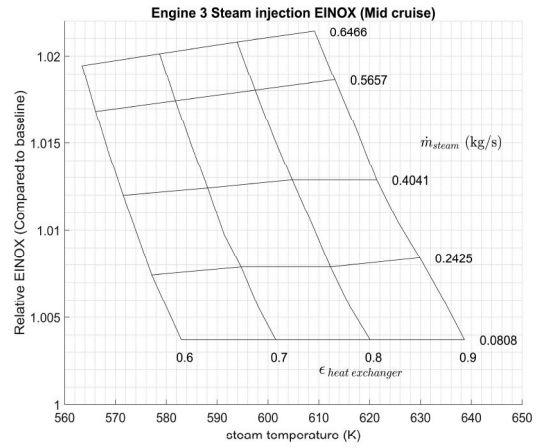


FIGURE 20: Engine 3 EINOX ratio(Mid cruise)

segment; a small mass flow and high heat exchange effectiveness are the right answers for steam injection to bring fuel consumption benefits.

Through the exploration stated, it can be concluded that the steam injection electrification strategy has certain limitations for gas turbine cycle designs. Steam injection is not suitable for high-specific thrust gas turbine cycle designs because the superheat processing would bring a significant penalty to fuel consumption and compromise its benefit.

5.8 The NOx emissions

This research recognizes one of the most important factors that the electrification and steam injection will bring on is the NOx emissions, this research used the NOx calculation correlation developed by Kyprianidis to capture the EINOx production rate between the electrified engine and the baseline engine is demonstrated in the fig. 18-20.

The electrified engine, due to the power injection, will run at a relatively lower power rating than the baseline engine during the

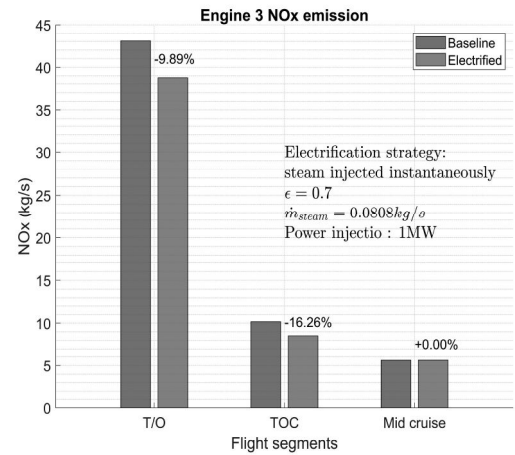


FIGURE 21: Engine 3 steam injected instantaneously NOx emission

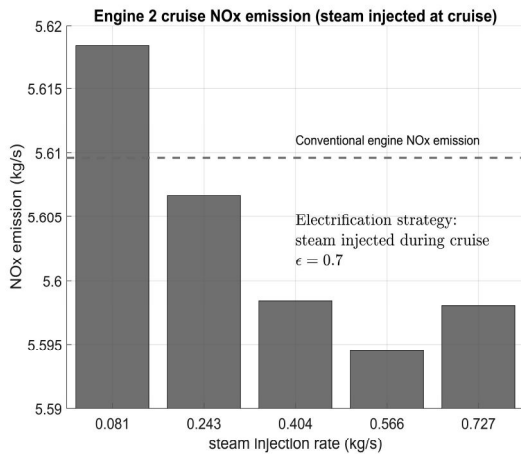


FIGURE 22: Engine 3 steam injected during cruise NOx emission

T/O and climb. Thus the pressure at the entry of the combustor will be lower and the EINOx emission will be reduced. Furthermore, the research calculated and presented the NOx emission production rate in the fig. 21 to demonstrate the NOx production of the baseline engine and a typical electrified engine. The fig. 21 presents a typical electrification case with 0.0808kg/s steam injection and power injection, equipped with a HEX that has heat exchanger effectiveness of 0.7. The result suggests the steam injection can cut up to 9.89% NOx at T/O, 16.26% at TOC.

On the other side, it is worth pointing out that though the EINOx during the mid-cruise shows an increase, due to the fuel benefit from steam injection, the increased EINOx will be compromised by the reduced fuel flow in some cases as fig. 22.

6. CONCLUSION

This research modelled and comprehensively assessed the civil turbofan engine electrification using the fuel cell and steam injection electrification strategy. The assessment reveals the characteristics and features of the impact of steam injection on gas turbine electrification in terms of fuel consumption and reaches to the conclusions:

- Steam injection electrification strategy has a complicated impact on the turbofan engine. It has the potential to enhance the benefit provided by the power assistance, but there are certain constraints to the gas turbine's thermodynamic cycle design.
- The steam mass flow and steam temperature are the two critical factors that affect the impact of steam injection; both of these two parameters stand in an equally important position. Considering the total mass of water produced from the fuel cell depends on the fuel cell size and usage period, there is no reason that the high mass flow approach would bring more benefits to fuel consumption.
- The steam temperature, on the other hand, is the proper approach to the steam injection. By enhancing the heat exchange effectiveness of the heat exchanger or deploying the steam

injection in a higher-temperature engine cycle, the steam injection can save more fuel by redirecting more heat from the exhaust to the combustor.

- Considering the facts stated for steam mass flow and steam temperature, it can be concluded that the steam injection is more suitable for injecting instantaneously with the water production than storing for the cruise segment. The engine has a higher temperature, which can superheat the steam to a higher temperature. Meanwhile, this research has proved that high mass flow steam injection would bring no extra benefit for fuel consumption.

- The electrification would have a significant impact on the emission production of the engine. The electrification strategy can cut the NOx emission by a significant amount. The steam injection during the cruise segment, on the other side, results in some uncertainty. Compared between the two steam distribution strategies, the steam injection during T/O and climb would clearly bring more emission benefit compared with the strategy of storing the steam and injecting it during the cruise.

When considering the deployment of steam injection to a specific engine, it is important to understand two questions: "Is the engine cycle design suitable for deploying steam injection?" "Which segment is best for injecting the steam".

- The superheat processing of the steam, which has been proven to be the most important factor in steam injection, would cause a loss of the core exhaust temperature. Considering the gas turbine produces a part of the thrust from the exhaust, this would lead to a loss of the thrust and require more fuel burn in the combustion chamber to correct. This loss would penalise the steam injection and compromise the benefits of fuel consumption.
- The loss of core thrust is more significant in the high specific thrust engine cycle design, which relies more on the core thrust compared to the low ST engine. The steam injection has a critical point, which divides the benefit area from the penalty area. When the loss caused by the steam injection is more than the benefit it brings, there would be no reason to deploy the steam injection because it brings a penalty to the fuel consumption.
- For an engine with relatively high specific thrust, similar to engine 2, it is important to understand that steam injection is not suitable for all flying segments. The steam is preferable to be distributed during the take-off and early climb, and when the steam injection crosses the critical point, it should be cut off.
- The steam injection is suitable for high temperature, low specific thrust engines, representing the future high thermal efficiency and high transfer efficiency engine design roadmap. Based on the reasons above, the research believes that steam injection has the potential in the future engine cycle design.

7. FUTURE RESEARCH INSIGHT

The hybrid-electric aircraft propulsion and turbofan engine electrification has raised a significant research interest in the past

decade and major institutions and research projects have revealed its potentiality and development. In the previous research, it has been established clearly that one of the biggest concerns and constraints on the development of hybrid-electric architecture is the technological development of batteries. The weight of the battery limits the system's degree of hybridisation, causing the electrification's benefit to be limited. Also, the power assistance to the compressor would bring a penalty to the engine's efficiency by moving the engine's operating point from where it is designed to be. This is why an electrification strategy is needed, to enhance engine efficiency.

This research demonstrates a hybrid-electric propulsion strategy by using an alternative power source, a PEM fuel cell, to take the place of the battery compared to other conventional hybrid-electric architecture. Furthermore, this research highlights the by-product of water, using the concept of steam injection to enhance the gas turbine's efficiency by redirecting the waste heat from the core exhaust to the combustor. This concept is favourable for future gas turbine development. As the trend of turbofan engine development suggests, the future turbofan engine will likely target higher BPR and lower ST. The core exhaust temperature will increase with the BPR and the engine will rely less on the core exhaust to provide thrust. These are favourable for steam injection as this research has already demonstrated.

On the other side, the future turbofan engine is likely to develop a higher OPR to enhance its thermal efficiency. This development will bring certain drawbacks to the steam injection because the steam injection will need more power to pressurize, matching the combustor inlet pressure. Also, the development of PEM fuel cells will have a dramatic impact in terms of water production rate. With the increased stack efficiency in the future, the water production rate would decrease, leading to a decreased total steam available. This development will lead to a decreased total energy recovered from the exhaust, thus degrading the benefit.

Although this research focuses on the electrification's impact on the gas turbine and its performance, it is worth noting that the potentiality of such electrification requires more study on the system view. This research has demonstrated the complications of the steam injection system, and it is important to emphasise that such a complicated system requires a highly integrated system design. The system's function and size require a system design feasibility study and assessment. The complicated and highly integrated system requires a thorough risk and failure assessment, including the potential failure and backup plan. Also, the design of the propulsion system requires the gas turbine to provide sufficient power in the case of electrification system failure.

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