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NUMERICAL INVESTIGATION OF POTENTIAL CAUSE OF INSTABILITIES IN A HYDROGEN MICROMIX INJECTOR ARRAY

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ABSTRACT

Hydrogen micromix combustion is a promising concept to reduce the environmental impact of both aero and land-based gas turbines by delivering carbon-free and ultra-low-NOx combustion. The high-reactivity and wide flammability limits of hydrogen in a micromix combustor can produce short and small diffusion flames at lean overall equivalence ratios.

There is limited published information on the instabilities of such hydrogen micromix combustors. Diffusion flames are less prone to flashback and autoignition problems than premixed flames as well as combustion dynamics issues. However, with the high laminar flame speed of hydrogen, lean fuel air ratio (FAR) and very compact flames, the risk of combustion dynamics for micromix flames should not be neglected. In addition, the multi-segment array arrangement of the injectors could result in both potential causes and possible solutions to the instabilities within the combustor.

This paper employs numerical simulations to investigate potential sources of instabilities in micromix flames by modelling an extended array of injectors, represented by either single or multiple injectors with appropriate boundary conditions at elevated pressure and temperature. Both RANS and LES simulations were performed and used to derive the Flame Transfer Function (FTF) of the micromix flames to inform lower order thermoacoustic modelling of micromix combustion. LES simulations indicate that the gain of the FTF is lower than predicted from the RANS simulations indicating a lower risk of high frequency thermoacoustic issues than suggested by RANS.

When LES simulations are conducted for certain representative configurations it is observed that there are persistent high-frequency instabilities due to the interaction of the flames. This phenomenon is not observed when only a single injector is modelled. LES simulations for two injectors are conducted with various geometries and radial boundary

conditions to identify the cause of the instabilities. It is concluded that the observed high-frequency instabilities are related to aerodynamic jet instabilities enhanced by both aerodynamic and acoustic feedback and key geometric features affecting the occurrence of the instabilities are identified. Only transient simulations such as LES are able to capture such effects and RANS simulations typically used in early stage design will not identify this issue.

Keywords: Hydrogen, Micromix Combustion, CFD, Combustion instabilities

NOMENCLATURE

Abbreviations

CFD	Computational Fluid Dynamics
FGM	Flamelet Generated Manifold
FTF	Flame Transfer Function
LES	Large Eddy Simulation
LH ₂	Liquid Hydrogen
OH	Hydroxyl radical
PDF	Probability Density Function
RANS	Reynolds-Averaged Navier Stokes
SST	Shear Stress Transport
WALE	Wall-Adapting Local Eddy-viscosity

Symbols

c	Speed of sound
C	Progress variable
f	Frequency
i	$\sqrt{-1}$
l	Length scale
m	Inlet mass flow
m_0	Mean mass flow
n	Flame response gain constant or an integer

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N	An integer: 1, 2, 3...
Q'	Fluctuating heat release
$\bar{Q}$	Mean heat release
t	time
u'	Fluctuating velocity (upstream of flame)
$\bar{u}$	Mean velocity (upstream of flame)
U_C	Phase speed of aerodynamic disturbances
$\Delta\tau$	Spread of time delays
ϕ'	Fluctuating equivalence ratio
$\bar{\phi}$	Mean equivalence ratio
τ	Time delay
ρ	Density
θ	Phase angle
ω	Angular frequency

INTRODUCTION

Due to the increasing concern over global warming and other environmental issues, highly ambitious emissions targets are being imposed on the civil aviation industry by legislation bodies [1]. Despite significant research efforts on advanced airframe and propulsion technologies, it has been reported [2, 3, 4] that these targets are unlikely to be met with carbon containing fuels. Liquid hydrogen (LH₂) has the potential to completely decarbonise civil aviation (both at mission and life cycle level) and significantly reduce the impact of aviation on the environment. Hydrogen will give a much cleaner exhaust compared to hydrocarbon fuels and could contribute to reduced radiative forcing and thus to lower global temperature-rise from aviation. The ongoing H2020 ENABLEH2 project [5], coordinated by Cranfield University, aims to revitalise the enthusiasm in LH₂ research for civil aviation and in doing so demonstrate that LH₂ and related enabling technologies are a feasible and sustainable solution for long term, environmentally friendly civil aviation.

Micromix combustion technology for aero engines was first studied by Aachen University [6, 7]. The concept utilises an array incorporating a large number of hydrogen flames. The much wider stability limits of hydrogen allow operation at very lean conditions. This allows reduced flame temperature hence reduced production of NO_x. In addition, the high molecular diffusivity and flame speed of hydrogen facilitates quicker mixing and lower residence time to further limit NO_x production. Hydrogen is injected as jets in cross flow via a circular orifice into the accelerated air exiting the air gate. This forms a non-premixed flame downstream reducing the risk of flashback and auto-ignition. The concept is shown in Figure 1.

The injectors are sufficiently small and the velocity of fuel and air are sufficiently high that the flames are miniaturised but highly intensified to ensure improved mixing and very fast reaction compared to conventional lean burn injectors. The additional benefits of the micromix concept includes the control of fuel scheduling within the injector arrays at various engine operating conditions, which could potentially not only tailor the temperature distribution at combustor exit and reduce that near the liner, but also reduce, at an early stage, the chances of

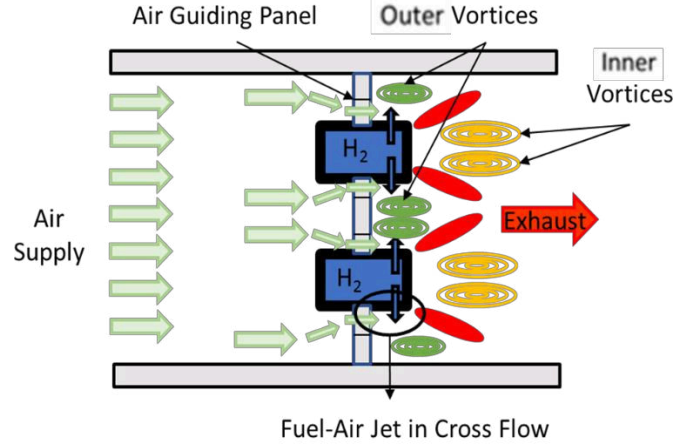


FIGURE 1: SCHEMA OF THE TYPICAL HYDROGEN MICROMIX FLOW FIELD

problems related to combustion thermoacoustics which often arises for lean combustion in particular.

All combustion systems have the potential to generate high amplitude pressure oscillations. These may be produced by a range of mechanisms including acoustic feedback, aerodynamic instability, aerodynamic-acoustic interactions, and the response of the flame to fluctuating inputs.

Aerodynamic instabilities such as vortex shedding, jet and shear layer instabilities do not normally create amplitudes high enough to be of concern, but these can be enhanced by acoustic feedback and/or interaction with the flame.

Feedback generated oscillations are normally excited by a feedback loop between the combustion and an acoustic mode of the combustion system. This can be predicted during design by including all the relevant geometry and physics in a transient CFD model and observing whether unstable combustion occurs. However, this is computationally demanding [8] and not practical for early stages of design when many design iterations may need to be evaluated. An alternative approach is to use a computationally inexpensive low-order model which decouples the acoustic field and the flame response. The response of a flame or a burner to acoustic perturbations can be characterised by a flame transfer function (FTF) which can be used in a low-order model to establish the thermoacoustic stability of the design.

One approach is acoustic network modelling which represents the combustion system geometry as simple elements connected by acoustic transfer matrices [9]. The decoupling of the acoustic field in the combustor and the flame response represented by the FTF provides for a faster and inexpensive way to obtain the response of the flame to any design changes.

The FTF is most commonly defined as (see for example [10])

$$FTF(\omega) = \frac{Q'/\bar{Q}}{u'/\bar{u}} \quad (1)$$

where Q' and $\bar{Q}$ are the fluctuating heat release and mean heat release respectively and u' and $\bar{u}$ are fluctuating and mean velocity upstream of the flame respectively.

This may be determined analytically, experimentally or numerically by forcing a transient CFD model to give a known fluctuation velocity upstream of the flame and observing the effect on heat release.

This study was initially intended to compare the flame transfer function of a micromix injector determined using a combination of analytical models (using constants determined using RANS (steady state) CFD) with the more time-consuming method of using LES (transient) CFD.

When determining the FTF using transient CFD the model must not display feedback oscillations as the flame response becomes non-linear and the low amplitude FTF needed to predict the onset of oscillation cannot be determined. Non-representative combustion systems with the outlet boundaries defined as non-reflective are used to prevent acoustic feedback from the combustor to the flame. However, when initial models were run, very high amplitude pressure oscillations were observed.

In addition to the work on the FTF to characterise the flame with respect to conventional feedback driven thermoacoustic oscillations, our investigations into the unexpected high frequency high amplitude pressure oscillations are presented.

1. Numerical Simulation Setup

The design parameters of micromix injectors were previously introduced [11], as shown in Figure 2. In the current study, a high-momentum-flux-ratio design is investigated due to the reduced flame-flame interaction observed from CFD studies, which is considered as the main factor contributing to excessive NOx production.

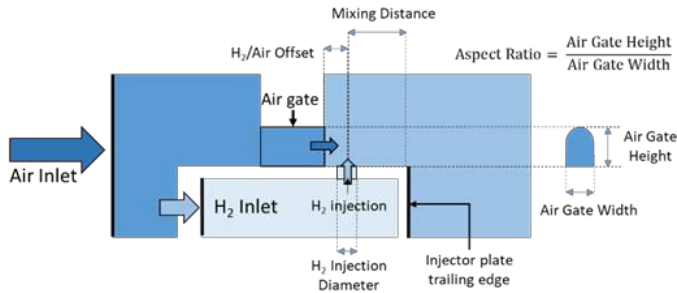


Figure 2: H₂ MICROMIX INJECTOR DESIGN PARAMETERS

The baseline geometry for this study consists of two such injectors, including two air gates and two hydrogen injection orifices as shown in Figure 3. For this high-momentum-flux-ratio design, the air gate exit area is 7.5mm², both the offset and the mixing distance are 2mm. The injector orifice diameter is 0.3mm. The radial and lateral spacing for the injectors are 5mm, hence the numerical domain has a 5x10mm cross-section area. The total domain length is 70mm, including 5mm upstream of air gate, 5mm air gate length and 60mm downstream of air gate exit.

The flow conditions are the same as those used in [11]. The air is fed into the domain upstream of the air gate with the inlet defined as a mass flow inlet of 3.865g/s. Downstream of the injection, in order to represent a very large injector array, the upper and lower sides are set to symmetry boundaries and the left and right sides are set to periodic boundaries. The outlet is defined as a pressure outlet. The operating pressure is set to 15 bar, the hydrogen and air inlet temperatures are set to 300K and 600K respectively and an equivalence ratio of 0.4 is selected.

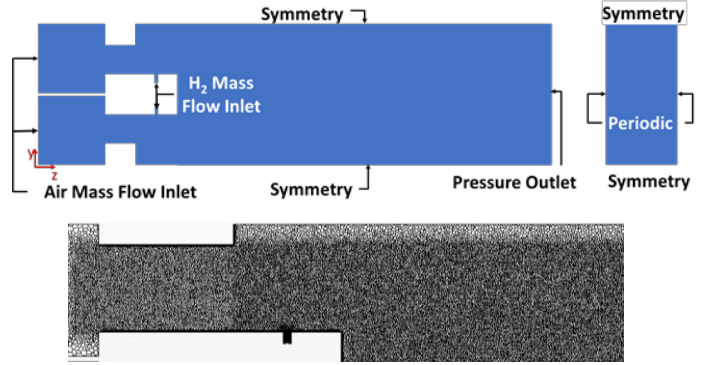


Figure 3: NUMERICAL DOMAIN AND IMPOSED BOUNDARY CONDITIONS (TOP) AND COMPUTATIONAL GRID (BOTTOM)

A grid independence study was conducted to determine the mesh size [12]. Local refinement of the mesh is employed at regions of interest to achieve sufficient resolution for the LES studies. Within the anticipated flame region, a cell size of 0.06mm with 10 prism layers in the vicinity of the wall so that y^+ is kept below 2 for walls adjacent to the fuel injection and combustion. The mesh size upstream of the air gate and downstream of the flames are set to 0.3mm.

Commercial software Star-CCM+ was used for both RANS and LES studies. The fluid is considered as a compressible ideal gas considering the relatively high jet velocity. For the RANS cases, the k-omega SST turbulence model is employed as the shear stress transport (SST) formulation allowing for integration down to the wall, resulting in a more accurate near wall treatment. For the LES cases, a Wall-Adapting Local Eddy-viscosity (WALE) sub-grid scale model with all y^+ wall treatment is used. A non-reflecting pressure boundary condition is used at outlet for the LES case to avoid any feedback waves from the domain exit. The LES time step is 0.3μs to ensure the Courant number is close to 1 within the flame region based on estimation of the average velocity from RANS simulations. There are 15 sub-iterations per time step so that all residuals fall at least 3 orders of magnitude within the time step.

The Flamelet Generated Manifold (FGM) with diffusion flamelets approach was employed for modelling hydrogen combustion and turbulence-chemistry interaction. This model assumes that the chemical reaction process occurs much faster than the integral time scale of the turbulent flow. If the smallest scale of eddies does not significantly impact on the chemical reactions, the turbulent flame can be considered as a differential set of laminar flames. The chemistry is defined by mixture

fraction and progress variable so that the temperature, enthalpy and species concentration can be pre-tabulated. A Probability Density Function (PDF) is used to mimic the effect of turbulence on chemistry. For the RANS study, the diffusion characteristics of hydrogen-air mixture is modified by changing the turbulent Schmidt number from the default value of 0.7 to 0.2, to accommodate the much higher mass diffusivity of hydrogen compared to hydrocarbon fuels. Further justification on the validity of using FGM and relevant model constants for micromix combustion is included in [13]. For LES, the turbulent diffusion is controlled by the locally resolved turbulence and the same turbulent Schmidt number was used at the sub-grid scale. The FGM model assumes a unity Lewis number for flamelet table generation. A 9-species 25-steps mechanism [14] is used for hydrogen reactions. This is shown to produce similar level accuracy compared to larger sized mechanisms [15].

2. FTF Derivation Approaches

As mentioned in the Introduction there are various ways of obtaining a flame transfer function using CFD. The FTF can be obtained using both steady (RANS) and unsteady approaches. Tay-Wo-Chong et al. [16] compare FTFs for premixed flames derived from unsteady CFD using both LES and uRANS (unsteady RANS) approaches with experimental data. LES shows better agreement with experimental data especially in describing the distribution of heat release. Based on this and the fact that LES, in principle, more accurately describes unsteady processes, LES was chosen for this study. Experimental determination of the FTF is planned to confirm that this approach is equally applicable to micromix combustion.

Only steady state information can be determined using RANS CFD models. To determine the FTF an analytical model relating “steady” information to the acoustic characteristics of the flame is needed. The first such model (the n - τ model) was proposed by Crocco [17] which related the FTF to a characteristic time delay, τ . This was developed further by Sattelmeyer [18] and Eckstein [19] to include both the mean flame time delay τ and the spread of time delays $\Delta\tau$. This modified n - τ model provides an analytical expression for FTF in terms of time delay (τ) and spread of time delay ($\Delta\tau$) [10]. It is based on the assumption that heat release fluctuations are the main acoustic driver and that they are driven by equivalence ratio fluctuations which are in turn driven by velocity fluctuations.

$$\frac{Q'}{Q} \propto \frac{\phi'}{\bar{\phi}} \propto \frac{u'}{\bar{u}} \quad (2)$$

where ϕ' and $\bar{\phi}$ are fluctuating and mean equivalence ratio respectively.

Thus, the characteristic time delay (τ) and spread of time delay ($\Delta\tau$) are the times from fuel injection (thus the onset of equivalence ratio fluctuations) to combustion. The FTF may then be given by [10]

$$FTF(\omega) = n \frac{\sin \omega \Delta\tau}{\omega \Delta\tau} e^{-i\omega\tau} \quad (3)$$

where n is a constant representing the gain of the flame response, τ is a characteristic time delay for the flame, $\Delta\tau$ is the spread of time delays and ω is the angular frequency.

In this study, the time delay is approximated as the mean residence time between the plane of fuel injection to the location of the flame front. The parameter is found using the Lagrangian Multi phase model in star-CCM+. A residence time between two locations for each injected particle can be computed using this model. A distribution of all the injected particles can be obtained and mean and standard deviation provide the mean flame time delay and the spread of time delay respectively.

The location of flame front is defined as the location of highest heat release within the flame. In order to define this region, progress variable C which defines the progress of the combustion reaction and production of the hydroxyl radical (OH) which is analogous to heat release are used. From the data generated by the FGM model, production of OH can be described as a function of progress variable for a range of mixture fraction curves. The value of c corresponding to the maximum value of OH represents the region in the flame where heat release is maximum.

As mentioned previously, when determining the FTF using an LES model it is important that there are no large amplitude oscillations which will result in non-linear behaviour of the flame. When the baseline model described in Section 1 was run, very high amplitude oscillations occurred meaning that it could not be used to determine the FTF. A single injector configuration was created by spitting the baseline configuration (Figure 3 along the centreline (Figure 4). This configuration did not produce high amplitude pressure oscillations and could be used for the analysis.

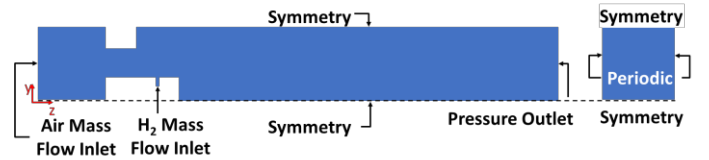


Figure 4: NUMERICAL DOMAIN AND IMPOSED BOUNDARY CONDITIONS (SINGLE INJECTOR CONFIGURATION)

Since the LES turbulence model provides time varying flow fields, the FTF can be found by measuring the response of heat release fluctuations to forced inlet mass flow rate perturbations. The forcing conditions are imposed on the mass flow rate since the boundary condition may be considered less acoustically reflective than the velocity boundary condition, however reflection of acoustic waves will still occur as discussed in Section 6.

When determining the FTF, the forced mass flow rate perturbation results in a velocity perturbation upstream of the injector which results in an equivalence ratio fluctuation at the injector. The forcing condition can be imposed in two ways: the multifrequency forcing technique which considers multiple forcing frequencies in a single input signal thereby reducing the number of simulations required to obtain the transfer function over a range of frequencies and single frequency forcing which

allows the determination of the FTF at a single frequency. In this study, both techniques are used.

Cranfield University is currently building a test rig to investigate combustion behaviour of micromix systems, including measurement of the FTF. The rig will be capable of measuring the FTF up to 2kHz, thus a range of frequencies up to this limit is chosen for investigation. The multi-frequency forcing input is a signal consisting of five frequencies (449Hz, 859Hz, 1249Hz, 1553Hz, 1951Hz) spread throughout the range 0 to 2kHz and the single frequency analysis is performed at the first two of these frequencies (449Hz and 859Hz) to provide a direct comparison between the two techniques. The frequencies are chosen to be integer values to minimise the chance of coincidence of harmonics affecting the results.

The forcing amplitude for both techniques is 20% of the mean inlet mass flow rate at each frequency to characterize the linear region of the thermoacoustic behaviour. The imposed mass flow rate profile at the inlet is represented by:

$$m = m_o(1 + A \sum \sin(2\pi f_n t + \theta_n)) \quad (4)$$

where m is total mass flow, m_o is mean mass flow, A is a constant (0.2), f is frequency, t is time, θ is phase angle and n is an integer.

In this case the mass flow forcing of 20% of mean results in a velocity amplitude between 6 and 10% of the mean velocity at each frequency point. The difference between velocity amplitude for single and multiple frequency cases are less than 10%.

The response of heat release fluctuation to the inlet forcing is monitored in terms of fluctuations in OH. The temporal evolutions of OH and velocity perturbation are normalised with respective mean values and the data is converted to the frequency domain. The flame transfer function can be obtained by finding the gain and phase relationships at the forced frequencies. The magnitude of the FTF is given by:

$$|FTF_n| = \frac{|OH|_n}{|u|_n} \quad (5)$$

and the phase of the FTF is given by:

$$\widehat{FTF}_n = \widehat{OH}_n - \widehat{u}_n \quad (6)$$

where $|OH|_n$ and $\widehat{OH}_n$ are the magnitude and phase of the normalised OH fluctuations at the n^{th} frequency respectively and $|u|_n$ and $\widehat{u}_n$ are the magnitude and phase of the normalised velocity fluctuations at the n^{th} frequency respectively

3. Comparison of RANS and LES Derived Flame Transfer Functions

The mean time delay obtained from the analysis based on a RANS simulation (Schmidt number 0.2) is 0.12ms and the spread of time delays is 0.078ms. Using Equation 3 results in the FTF shown (red line) in Figure 5. Results of both single frequency and multiple frequency forcing are also shown in Figure 5. It should be noted that the low gain seen at the three highest frequencies (1249Hz, 1553Hz, 1951Hz) results a low

level of OH emission and the results may be affected by noise. The gain values will be an upper limit of the actual gain and the phase values should be treated with caution.

It can be seen that the magnitude (gain) of the FTF derived from single frequency forcing is higher than the multi-frequency forcing in both cases, but the trend of decreasing frequency is the same. Similarly, with the phase the 449Hz results are almost identical, but there is a difference at 859Hz, however the decreasing phase representing a time delay is seen in both cases.

The multi-frequency results except at 1553Hz show good agreement with the RANS prediction, suggesting that the RANS approach gives a good indication of the characteristic time delay. However, the gain falls much more rapidly in the LES results, suggesting a greater spread of time delays than that determined by the RANS approach. As LES captures time variations in the flow field that are not captured in RANS a greater spread of delays is not surprising.

To give an indication of the possible differences between the RANS and LES approaches n and $\Delta\tau$ were varied in Equation 3 to produce a closer representation of the LES data. The result is shown in Figure 5 (blue dashed line) where n is 1.5 and $\Delta\tau$ is 0.4ms. This is not intended to be a formal fit to the data but aids the visualisation of the differences. This suggests that the low frequency gain may be higher than that predicted using the usual value of $n=1$ in $n-\tau$ FTF models. It also suggests a possible explanation for the apparently outlying phase at 1553Hz due to the phase shift that occurs because of the interaction of multiple time delays in the flame.

It should be noted that the derivation of Equation 3 assumes a top hat distribution of time delays with a spread of $\pm\Delta\tau$ about

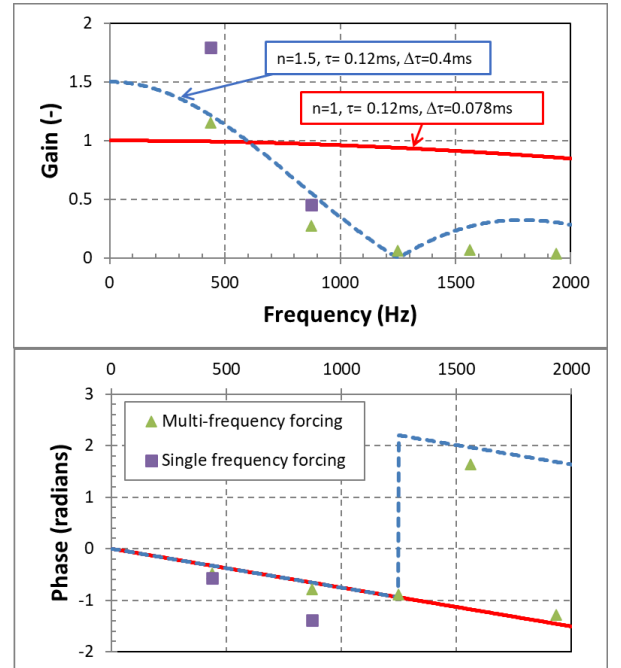


Figure 5: COMPARISON OF RANS AND LES DERIVED FTFs (Solid red line represents RANS result, symbols represent LES results, Blue dashed line represents indicative fit to LES results)

the mean value. A $\Delta\tau$ of greater than half the mean value implies negative time delays. Thus, the time delay of 0.4ms used in Figure 5 is not physically realistic as it implies negative time delays. This suggest that the relatively simple formulation used in Equation 3 is inadequate in this case. It does, however, capture the form of the observed results and may provide the basis for an improved formulation.

4. Jet Instabilities

The observed instabilities are clearly not associated with acoustic modes of the combustor and usual thermoacoustic feedback oscillations as a non-reflective boundary has been defined at the combustor outlet and no significant pressure oscillation are observed in the combustor. Alternative causes for the observed instabilities are considered. It is well known that pressure oscillations can be generated in flow systems and a number of correlations have been developed to characterise instability frequencies. [20, 21, 22] due to features such as shear layer instabilities and vortex formation. These instabilities are generally relatively low amplitude, but can be enhanced by interaction with other features of the system

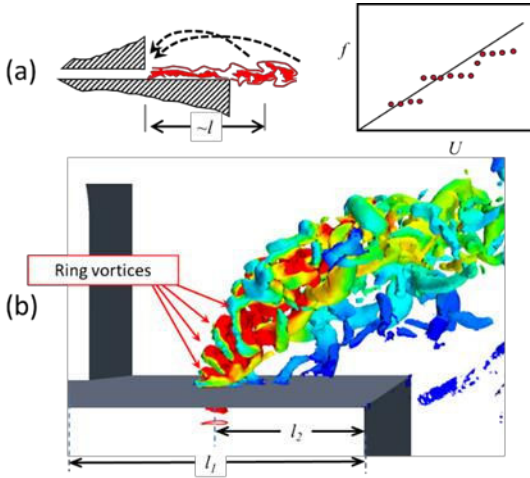


Figure 6: (a) STREAMWISE LENGTH SCALES AND TYPICAL VARIATION OF FREQUENCY (f) VS. VELOCITY (U) (after Rockwell [21]). (b) CHARACTERISTIC FLOW IN MICROMIX COMBUSTION

Rockwell [21] identified a range of geometries that could lead to such enhancement, one example is given in Figure 6(a). This interaction generates the ladder like frequency behaviour shown. It can be seen (Figure 6) that this configuration has features in common with the micromix injector. Flow disturbances from the air gate may propagate to the downstream edge of the injector plate (distance l_1) or alternatively flow disturbances from the fuel injection may propagate to the edge of the injector plate (distance l_2). Thus, it is possible that geometric features of the injector are enhancing flow instabilities generated at the air gate or the fuel injection jet.

Rockwell [21] reported that the frequency of the enhanced oscillations could be determined from:

$$\frac{l}{U_c} + \frac{l}{c} = \frac{N}{f} \quad (7)$$

where l = Length scale, U_c = the phase speed of the disturbance, c = speed of sound, N is an integer (1, 2, 3...) and f is the frequency

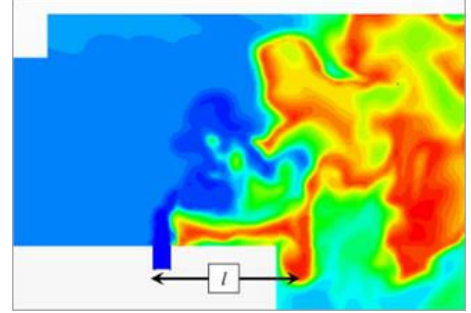


Figure 7: TEMPERATURE CONTOURS SHOWING CHARACTERISTIC INTERACTION LENGTH FOR OBSERVED MICROMIX JET INSTABILITIES

Examination of data from the simulations clearly shows the potential for such interactions and Figure 7 shows temperature contours following the form of flow depicted in Figure 6(a). The characteristic length, l , shown is the length from just upstream of the jet as the upstream base of the jet is key in determining the modes of the jet. Regan and Mahesh [23] refer to a zone in this area as the “wavemaker”. The characteristic length, l , also includes the flow feature at the downstream end of the injector plate as suggested by Figure 6(a).

The enhancement frequency for the baseline configuration may be evaluated by determining l from Figure 7 and using Equation 7. The results are given in Table 1 together with the enhancement frequencies for the for Reduced Mixing Distance configuration (see Section 5.4).

Table 1: PREDICTED ENHANCEMENT FREQUENCIES

N	1	2	3
Frequency for Baseline configuration (kHz)	11.5	23.0	34.5
Frequency for Reduced Mixing Distance configuration (kHz)	17.8	35.5	53.3

The 23.0kHz result is very close to the observed frequency in the baseline configuration (23.8kHz) and it is thus possible that this is a key feature in the enhancement of the instabilities. However, a periodic aerodynamic feature at an appropriate frequency also needs to be identified.

For jets in cross flow Ruiz et al [22] identified six main classes of vortices: ring-vortices, the counter-rotating vortex-pair, V-shaped vortices, the horse-shoe vortex, hair-pin vortices at the wall, and far-field vortices. He also identified the characteristic Strouhal numbers associated with such jets. Features on the upstream (windward) side of the jet were found to have Strouhal numbers (based on jet diameter and bulk jet velocity) of 0.2, 0.4, 0.6 and 0.8. Features on the downstream

(leeward) side of the jet had Strouhal numbers of 0.15, 0.3, and 0.6. This is also consistent with the classic range of frequencies for a free jet [20] which suggests a preferred mode with a Strouhal number of 0.4.

Examination of the frequency of formation of the ring vortices Figure 6(b) at the upstream base of the jet indicates a frequency of formation of 175 to 180kHz consistent with a Strouhal number of 0.2 as suggested by Ruiz et al [22] as the lowest frequency on the upstream side.

This is far higher than the frequency (~23kHz) of the high amplitude oscillations. Thus, direct one to one interaction of features such as the ring vortices with the geometric features of the injectors is not the source of the issue.

However, it is possible that sub-harmonic interaction occurs with acoustic interaction occurring periodically with only every N vortices. This will be discussed further in the next section.

5. LES on Single and Multiple Injectors

5.1 Cold flow simulation

A non-combusting simulation was run to investigate whether any intrinsic flow instabilities were interacting with combustion to cause the observed high amplitude oscillations. Pressure was monitored at a range of locations on an axial plane through the centre of the jet as indicated in Figure 8. These locations were chosen to capture general features, but particularly aimed at specific effects as follows:

- Locations 1 to 3: features related to the air gate
- Locations 4 to 6: features relating to the main fuel jet
- Locations 7 and 8: features related to the jet and boundary layer
- Location 9: features relating to flow over the injector plate trailing edge.

It was found that pressure spectra at locations 1 to 3 were similar to each other, as were locations 4 to 6 and locations 7 and 8. Location 9 showed no additional features to those seen at locations 7 and 8.

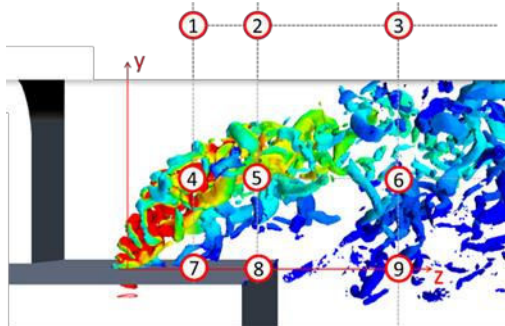


Figure 8: MONITORING LOCATIONS FOR COLD FLOW STUDY

Figure 9 shows spectra for locations 1, 5 and 9 as representative of the key frequencies. It can be seen that there are peaks at 1.8, 10.5 and 14.5kHz in all spectra.

Location 1, representing the flow from the air-gate outside the fuel jet also has a high frequency peak at 66kHz with less

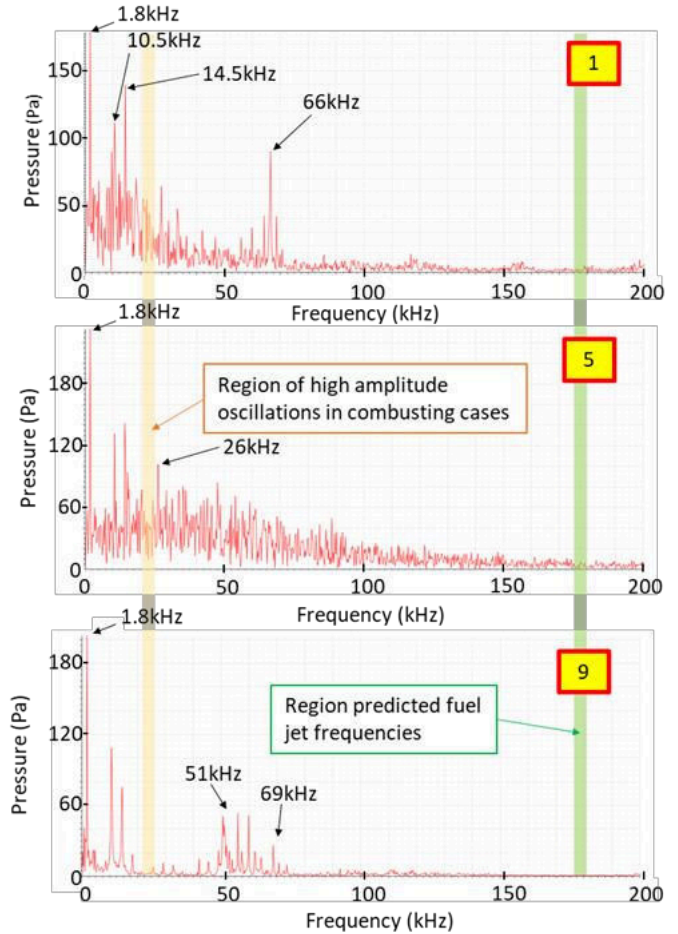


Figure 9: PRESSURE SPECTRA SEEN AT LOCATIONS 1, 5 AND 9 (NON-COMBUSTING CASE)

apparent side bands. Location 5 within the fuel jet shows no other strong features, but a minor peak at 26kHz can be seen. This is close to the range of frequencies of the high amplitude oscillations seen in the combusting cases indicated in orange in the plot. Location 9 representing flow from the trailing edge of the injector plate has a number of small high frequency peaks in the range 51 to 69kHz. None of the spectra show strong features in the range of frequencies seen in the combusting cases, and there are no features close to the predicted jet characteristics based on a Strouhal number of 0.2 (indicated in green in Figure 9). However, the rate of formation of the ring vortices was assessed and was found to be approximately 220kHz, higher than the predicted frequency (175kHz) shown in Figure 9 or that seen in the combustion case. It is also above the range frequencies analysed.

These cold flow investigations have not identified a potential cause of the high amplitude pressure oscillations seen in the combusting case.

5.2 Baseline configuration and feed options

For the “baseline” geometry, the fuel to two hydrogen orifices is fed from the same feeding arm, as in Figure 3. Due to the feature of the infinite array configuration, the alternative to

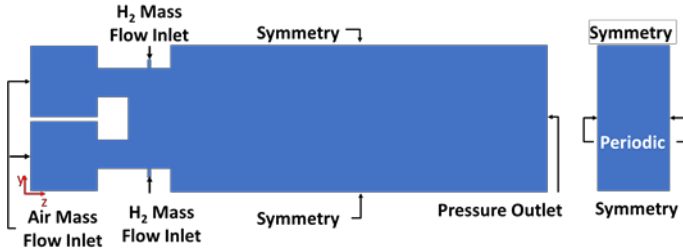


Figure 10: STANDARD GEOMETRY OPPOSITE H₂ FEED

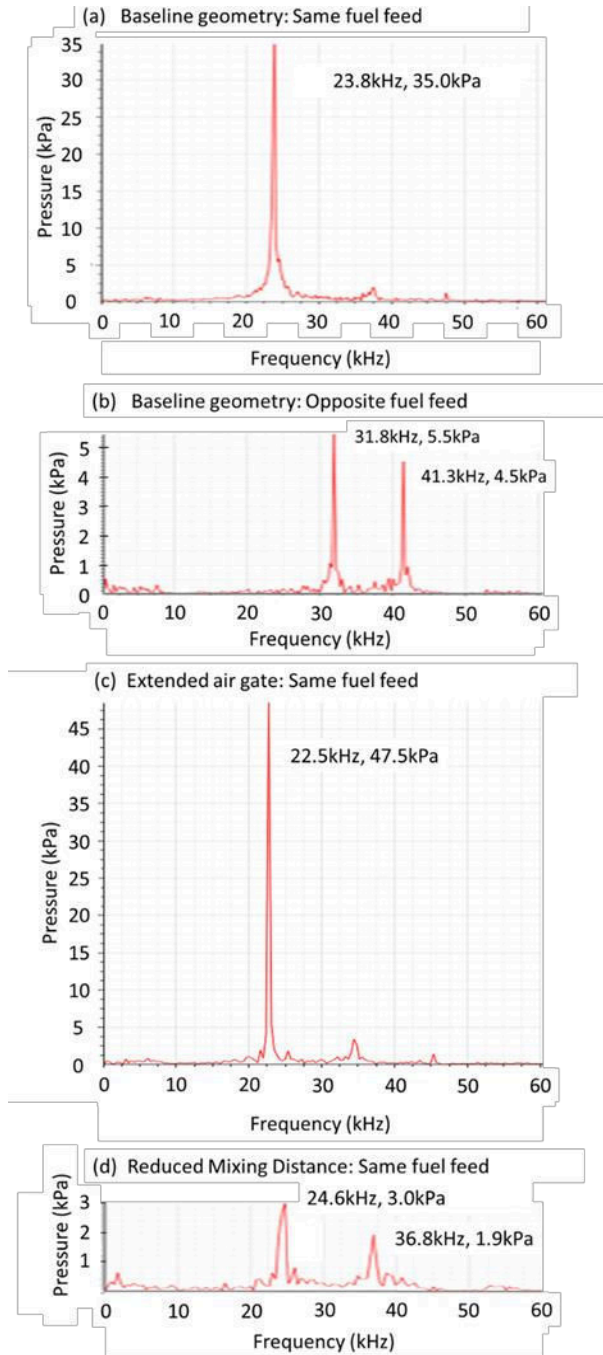


Figure 11: PRESSURE SPECTRA MEASURED IN THE AIR GATES FOR THE FOUR COMBUSTING CASES

model the pair is to model the two injectors with opposite feed, such as the geometry shown in Figure 10. In this case, as the top and bottom of the boundary is also symmetric, the upper and lower half of the injector trailing edge is no longer physically connected, instead they are mirrored. Thus, both acoustic and aerodynamic features at the trailing edge of the injector plate may be affected by this change.

Typical spectra for the two configurations are seen in Figure 11(a) and (b). The high amplitude fluctuation observed in the same feed configuration is not seen in the opposite feed configuration. The highest peak amplitude is reduced by 85%. It can also be seen that the single peak frequency (23.8kHz) observed in the baseline case has shifted to two peak frequencies at 31.8kHz and 41.5kHz, with amplitudes significantly lower.

The single injector and opposite fuel feed configurations both show relatively low levels of oscillations, allowing time averaged quantities to be compared representing steady state conditions. Time-averaged temperature and OH contours from the LES models of the two configurations are presented in Figure 12. As shown by the red lines, for the high temperature and high OH concentration zones, there are only minor differences between the temperature and OH distributions along the axial direction. The flame length, and the position of the flame front are not significantly affected. Although the amplitude of pressure oscillation in the two injector configuration is relatively higher, the impact is not significant. This shows that the single injector model is able to capture the effect of injector interaction on the flame shape and average heat release. This is sufficient for most analysis that is needed for optimising the design such as studying combustion efficiency and emissions and for the FTF determination in Section 3. Whereas the multi-dimensional propagation of acoustic waves and aerodynamic interactions, particularly at the trailing edge of the injector plate, can only be captured in multi-injector simulations.

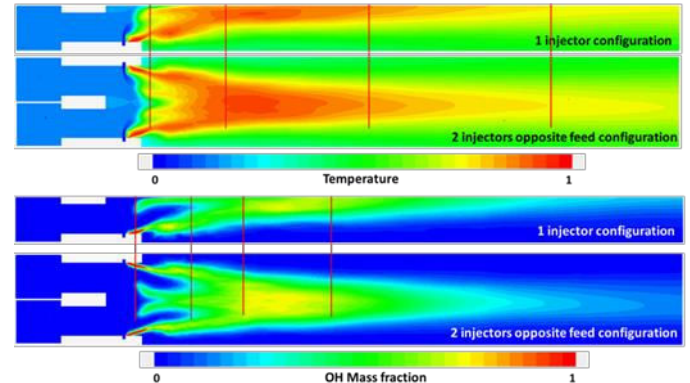


Figure 12: TIME AVERAGE TEMPERATURE AND OH FOR LES CASES (NON-DIMENSIONALISED)

5.3 Extended air gate

In the baseline configuration cyclic high amplitude pressure oscillations alternating within the two air gates were seen (see Figure 14). This suggests that the acoustic waves travelling between the inlet and hydrogen jet injection through air gate may

be a contributing factor to the instability observed. It is worth mentioning that in STAR-CCM+, it is not possible to consider anechoic inlet boundary conditions, therefore the pressure wave travelling towards upstream from the jet will be reflected. In the case that the instability is purely generated by the flow features upstream of the jet injection, such as vortices caused by flow contraction and expansion adjacent to the air gate, the dominant frequency is likely to shift if the length of the air gate varies. This will be considered as more numerically than physically induced resulting from the reflective inlet boundary condition.

An LES model with a modified air gate geometry is performed in order to investigate this possibility. The air gate is extended from 5mm to 6mm in the axial direction. This configuration also produced high amplitude oscillation (Figure 11(c)), with 36% higher amplitude than the base case (Figure 11(a)) and a small ($\sim 5\%$) reduction in peak frequency.

5.4 Reduced mixing distance

The propagation time from the fuel injection to the trailing edge of the injector plate may also have an impact on both acoustic and aerodynamic behaviour of the system. This is investigated by reducing the mixing distance from 2mm for the baseline case to 1mm. The characteristic length of the jet-trailing edge interaction is therefore changed accordingly.

Figure 11(d) shows that there is a significant reduction (90%) of pressure oscillation amplitude compared to the baseline case (Figure 11(a)), but the difference in peak frequency is less than 1kHz. A second lower amplitude peak is seen at 36.8kHz. This implies that the instability is no longer enhanced to the same extent by the feedback from the trailing edge because of the change in characteristic length.

6. Discussion on the Causes of the Observed Pressure Oscillations

Both baseline and extended air gate configurations show high amplitude oscillations at similar frequencies (Figure 11). As it shows the highest level of oscillations the extended air gate configuration is considered first (Figure 13). The left hand plots in Figure 13 clearly show the progression of pressure through the instability cycle. In all cases the pressure in the upper air gate is in antiphase with the pressure in the lower one. The height of the pair of injectors is 10mm which is close to half a wavelength in air at the supply conditions (10.9mm) and considering the half sine wave (A) shown in the upper plot it is tempting to conclude that this is of significance. However, the two injectors are not connected by an air path at supply temperature and the location of the half sine wave shown is in the combustion zone where the temperature (see right hand plot) and thus speed of sound will be significantly higher and thus the wavelength will not match.

Similarly, considering waves in the horizontal direction, the length from the upstream (left-hand) end of the domain to the downstream end of the injector plate is 15mm similar to a $\frac{3}{4}$ -wavelength (16.4mm) at supply conditions, or the length of the injector plate is 10mm, similar to a $\frac{1}{2}$ -wavelength. The pressure distribution in most of the injectors shows a $\frac{3}{4}$ -wave-like variation as in B in the upper plot. The left-hand surface of the

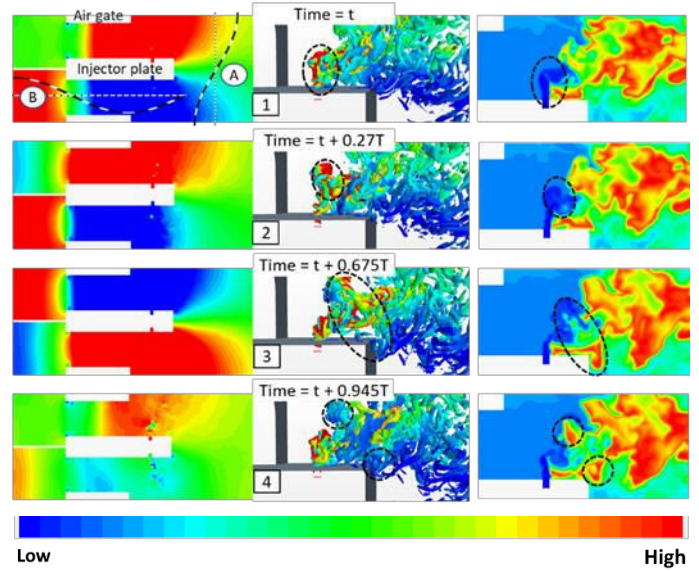


Figure 13: LES RESULTS FOR EXTENDED AIR GATE, STEPPING FROM TOP TO BOTTOM THROUGH AN INSTABILITY CYCLE OF PERIOD T . (Left: PRESSURE CONTOURS IN A PAIR OF INJECTORS. Middle: FLOW STRUCTURE IN UPPER INJECTOR. Right: TEMPERATURE CONTOURS IN UPPER INJECTOR)

plot represents the air inlet and is defined in the model as a mass-flow inlet. If a velocity boundary condition had been defined this would have been totally reflective as no velocity fluctuations would be possible.

However, with a mass flow boundary condition, the mass flow is constant and velocity variations are restricted to those due to pressure variations, this will tend to force this surface to approximate a velocity node (i.e. to approximate to a reflective surface, but not be totally reflective). This would also be consistent with the pressure antinode at B in Figure 13. However, this is not seen in all plots and is far less apparent in the results for the standard air gate (Figure 14) which, while showing pressure at this surface in antiphase with that at the exit of the air gate, pressure magnitudes are much lower at the inlet surface. This suggests that reflections from the inlet may contribute to the pressure distribution seen, but $\frac{3}{4}$ -wave modes in this region are not the primary issue.

Considering the potential half wave pattern along the length of the injector plate: both the extended air gate and the standard air gate configurations appear to display a quarter wave pattern along the length of the injector plate with pressure nodes close to both the upstream and downstream ends of the injector plate, but it is more obvious in the standard air gate configuration (Figure 14 Upper left-hand plot, A and B). (It should be noted that the standard air gate has a shorter injector plate (9mm) and the observed frequency is higher, consistent with this.). This will result in an acoustic velocity distribution of the form as shown at C in Figure 14. This will cause significant acoustic velocity amplitudes at the fuel jet D. This is likely to be a factor in the generation of the observed high amplitude oscillations. It is possible that this half-wave mode has been excited by a

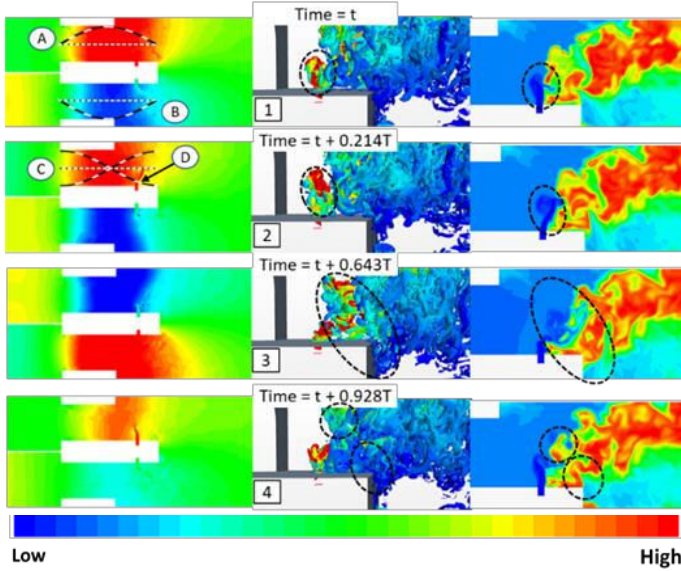


Figure 14: LES RESULTS BASELINE CONFIGURATION STEPPING FROM TOP TO BOTTOM THROUGH AN INSTABILITY CYCLE OF PERIOD T . (Left: PRESSURE CONTOURS IN A PAIR OF INJECTORS. Middle: FLOW STRUCTURE IN UPPER INJECTOR. Right: TEMPERATURE CONTOURS IN UPPER INJECTOR)

conventional feedback mechanism due to the interaction between incoming velocity fluctuations and the heat release from the flame and as the oscillations grow, the observed flow effects are induced by the acoustic wave. However, the gain for the FTF typically reduces with increasing frequency as indicated in Figure 5. The FTF determined by LES has a very low gain (0.04) at the highest frequency evaluated (1.9kHz) and this would be expected to fall further as frequency increases, thus conventional flame feedback is unlikely to be the primary cause of the oscillations and more complex interactions are indicated.

As discussed in Section 4, there is the potential for feedback from the trailing edge of the injector plate to the upstream edge of the fuel nozzle. This can be seen in the centre and right-hand images in Figure 13 and 14. The upper image shows the fuel jet initially almost vertical (circled) indicating a reduction in the air flow velocity in the low velocity part of the acoustic cycle. This results in several ring vortices coalescing into a larger structure as seen (circled) in the second image down. In the corresponding right hand image, the dark blue in the structure (circled) shows low temperature, thus the structure contains unburnt fuel. The third set of images down shows the structure developing and combustion starting in it (indicated by the green coloration in the upper part of the circled region in the right-hand image). The expansion due to the combustion and the positive velocity part of the acoustic cycle cause the flows along the upper edge of the injector plate to be directed down and towards the right causing a corresponding structure to form at the trailing edge of the injector plate (i.e. the red structure forming in the lower part of the circled region). The lower plot shows these two structures developing and convecting downstream. It can be seen that at this point the base of the jet is vertical and the process is starting

to repeat. Examination of the data indicates that typically eight ring vortices coalesce to form these structures. For the extended air gate case the observed ring vortex formation frequency of approximately 175 to 180kHz would result in interaction as $1/8^{\text{th}}$ subharmonic at frequencies of approximately 21.9 to 22.5kHz consistent with the observed instability frequency of 22.5kHz and the observation that eight ring vortices coalesce to form each structure

This is also consistent with the proposal in Section 4 that the instability is linked to feedback from the leading edge at the frequencies shown in Table 1 which shows an enhancement frequency of 23kHz ($N=2$). For the configuration with a reduced mixing distance, Table 1 indicates predicted enhancement frequencies of 17.8 and 35.5kHz. Thus, enhancement at $\sim 23\text{kHz}$ is not expected and the high amplitude pressure oscillations do not occur (Figure 11(d)), confirming that this feedback mechanism is an important feature in the generation of these oscillations.

It is important to note that the oscillations occur in antiphase in adjacent injectors and the behaviour at the trailing edge of the injector is critical in generating this behaviour. Figure 15 shows a pair of air gates as the paired structure forms in the upper air gate (expanded from Figure 13). It can be seen that the cool structure at A is paired with a similar hot structure at B in the upper air gate. As B moves down over the trailing edge of the injector plate the corresponding structure in the lower air gate (C) moves down below the lower edge of the injector plate and ingests some cooler fluid (green at the centre). The paired structure at D is hot (red) due to combustion of the fuel. The antiphase behaviour of the structure ensures the antiphase behaviour of the acoustic pressures within the air gates.

This explains why the single injector arrangement does not display high amplitude oscillations as the use of a symmetry boundary on the centreline of the injector plate does not allow this antiphase aerodynamic behaviour to occur. Similarly, for the case with two injectors with opposite fuel feed (as Figure 12). This strongly suggests that the instability is linked to feedback from the trailing edge of the injector plate of the form shown in Figure 6(a) involving sub-harmonic interaction with the

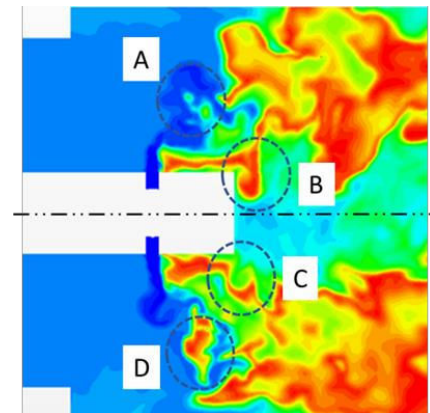


Figure 15: EXTENDED AIR GATE CONFIGURATION: TEMPERATURE CONTOURS SHOWING PAIRED STRUCTURES IN ANTIPHASE IN UPPER AND LOWER AIR GATES

upstream formation of the ring vortices. This is likely to be significantly enhanced by a half wave resonance along the length of the injector plate.

Thus, to reduce the risk of such instabilities in practical injectors the design of the injector should consider the relationship between the convection time (related to the phase speed of convected disturbances) from the fuel nozzle to the trailing edge of the injector plate and the period of a $\frac{1}{2}$ -wave acoustic mode along the injector plate. Attention should also be paid to the dynamic characteristics of the fuel jet, such as the formation of ring vortices, and the possibility of sub-harmonic interactions.

CONCLUSIONS

The phase of the FTF determined by RANS and LES is consistent showing that the RANS approach gives a good estimate of characteristic time delay of the flame.

The LES determination of the FTF using multiple frequency forcing produces higher gain than that produced with single frequency forcing, suggesting non-linear effects reduce the gain in the multiple frequency case. However, both approaches show a clear reduction in gain as the frequency increases. The reduction in gain is much more pronounced than that suggested by the RANS approach. This indicates that the RANS approach may be useful in early stage design, particularly at low frequencies, but will be very conservative at higher frequencies.

Experimental determination of the FTF is planned to confirm these findings.

The LES simulation shows that there is potential for large-amplitude high-frequency pressure oscillations to occur in micromix combustion systems and the phenomenon is affected by injector design and interaction between adjacent injectors.

Care is required in setting up LES simulation to ensure the radial boundary conditions do not prevent realistic aerodynamic and acoustic behaviour in the radial direction.

Design of injectors should consider the potential for feedback from the trailing edge of the injector plate to the fuel jet and the potential for coupling with axial acoustic modes of the air gate.

This phenomenon has been shown to occur in LES simulations but has not yet been reported in practice. This requires careful experimental investigation to confirm whether this behaviour occurs in practice.

Construction of an experimental rig to perform hydrogen micromix combustion testing including emissions evaluation and FTF measurement is currently underway. Investigations into this high frequency instability will be undertaken. This will be supported by numerical simulation of the test configuration to determine whether high frequency instabilities are predicted with the real radial boundary conditions and more detailed upstream geometry.

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Numerical investigation of potential cause of instabilities in a hydrogen micromix injector array

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