MIXING ENHANCEMENT BY SHOCK IMPINGEMENT IN A GENERIC SCRAMJET COMBUSTION CHAMBER

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Abstract. The present paper focuses on the mixing improvement in a generic supersonic combustion chamber for a fixed combustion chamber height with wall injection. On the one hand, internal shocks are employed to increase mixing and penetration, on the other hand injector design and spacing are investigated to achieve good penetration and mixing. With sonic hole injectors, a reduction of the injector spacing improves the mixing efficiency almost proportionally due to the reduced required massflow per injector. At very high aspect ratios, the relative penetration is reduced and the air in the upper part of the duct does not mix properly with the fuel. Penetration improvement due to the internal shock system, and tilted, supersonic inline injectors are presented to improve the mixing efficiency.

NOMENCLATURE

Symbols

\(A\) area
\(c\) mass fraction
\(D\) injector diameter
\(H_{cc}\) height combustion chamber
\(H\) duct height
\(L\) reference length
\(L_{cc}\) duct length
\(Ma\) Mach number
\(\dot{m}\) massflow
\(p\) pressure
\(p_0\) total pressure
\(q\) dynamic pressure
\(R\) gas constant
\(S\) injector spacing
\(T\) static temperature
\(u, v, w\) velocity in x, y, z direction
\(W\) duct width
1 INTRODUCTION

Employing scramjets (supersonic combustion ramjet) engine for hypersonic airbreathing vehicles requires an adequate design of the propulsion system such that the thrust produced over compensates the drag of the vehicle. The propulsion system itself with inlet, combustion chamber and expansion nozzle have a major contribution to the drag since the vehicle is designed around them. Especially the combustion chamber, due to the total pressure loss and wetted surface area, plays a major rule in the vehicle design. At supersonic combustion, the flow residence time in the combustion chamber is small and the fuel injection, mixing and combustion has to take place inside the combustion chamber. The combustion chamber length is defined by these effects. Achieving fast and homogenous mixing allows to reduce the combustion chamber length and by this also to reduce vehicle drag and structural mass and increase the performance of the vehicle\(^1\).

In the past, experimental investigations on the interaction and penetration of H\(_2\) injection have been performed and different injector inlet shapes have been considered to increase the mixing\(^2, 3\). The mixing enhancement of a shock or compression fan induced by a ramp or curved surface was investigated\(^4, 5\) numerically, according to this, the mixing efficiency can be improved significantly by the presence of a pressure increase.

Based on this idea, the present work focuses on an improved mixing efficiency due to the shock waves induced by a vertical H\(_2\) fuel injection in the combustion chamber, being
reflected at the upper and lower walls of the combustion chamber and interacting with the neighbouring injections. With this concept, the combustion chamber height and width effects the position of the internal shock system and by this, the mixing behaviour of the injected fuel.

The flow conditions for the present generic configuration are taken from typical combustion chambers being 2.5 for the Mach number, 1bar static pressure and 1300K static temperature. The combustion chamber dimensions are related to the fullscale combustion chamber of a future supersonic vehicle. The height of the combustion chamber is fixed at $H_{cc}=2H=0.3m$. Following the strategy with wall injection on both upper and lower combustion chamber wall, the computational domain employing symmetry conditions is reduced to $H=0.15m$ and a width depending on the injector spacing $S=2W$. Due to better comparison, the sizes are given dimensionless with the injector diameter being the reference length ($D=L$). Ducts with the cross section of $WxH=5x5$, $5x10$, $5x20$ and $5x30$ are investigated, compare Fig. 1. The injector diameter of $D=1$ and the width $W=5$ are kept constant to maintain the ratio of the diameter of the injected fuel jet in relation to the duct width for all cases. The desired equivalence ratio is 1, the fuel injection pressure has to be correlated with the inlet area of the computational domain being dependent on the injector spacing.

In order to estimate the performance of an injection system, the total pressure loss and the mixing efficiency are calculated. The air based mixing efficiency (ME) $\eta_m$ at a station of interest $x$ is defined as the ratio of the mass flux of oxygen that would react should the mixture be ignited to the mass flux of oxygen entering the duct:

$$\eta_m(x) = \int_{x} c_{O_2}^r \, d\dot{m} / \dot{m}_{O_2,x=0}$$

(1)

The mass fraction of the reaction oxygen is:

$$c_{O_2}^r = \min (c_{O_2}, c_{O_2}^S, c_{H_2}/c_{H_2}^S)$$

(2)

The stoichiometric mass fraction of hydrogen $c_{H_2}^S$ corresponds to 0.02876 and the stoichiometric mass fraction of oxygen $c_{O_2}^S$ to 0.22824.

The total pressure loss (TPL) due to viscous forces, flow separation, mixing and shock waves is defined as:

$$\Pi(x) = 1 - p_{0,rec}(x)$$

(3)
With the pressure recovery being:

\[ p_{0,\text{rec}}(x) = \frac{\int_{0}^{x} \rho u p_0 \, dA}{\int_{0}^{\infty} \rho u p_0 \, dA} \]  \hspace{1cm} (4)

2 NUMERICAL MODELLING

The CFD solutions are achieved with the unstructured DLR TAU-Code that has been validated in the past for different configurations at super- and hypersonic flow conditions, including extensive studies for wall jet injection\(^7\), \(^8\). The time-accurate three-dimensional Navier-Stokes equations are marched for steady or unsteady conditions by an explicit three stage Runge-Kutta scheme or an implicit LUSGS scheme. Different standard upwind solver such as Van-Leer, AUSM and AUSMDV and gas modelling formulations for perfect gas, thermo-chemical equilibrium and nonequilibrium are available. State of the art acceleration techniques such as local time stepping, residual smoothing and multigrid are implemented. The present calculations have been performed using a nonreacting mixture model for two perfect gases. Diffusion is modelled via the Schmidt-number, hydrogen and air are modelled as perfect gases employing an additional equation for the 2nd species.

All computations are performed with laminar wall boundary conditions in order to separate the large scale mixing and diffusion from the influence of the turbulence. Since most fullscale models foresee boundary layer bleeds at the combustion chamber entrance, this assumption is reasonable. The generic duct in front of the injector is short so that even turbulent calculations do not have a major effect on the global mixing due to the small boundary layer thickness. Employing thick boundary layers in the range of 2-3 injector diameters at penetrations of 5-6 diameters improves the mixing strongly\(^9\), but are not typical for a scramjet combustion chamber and are not considered here. The hybrid grids are generated with 24 to 32 prism cells in the boundary layer and have been locally adapted several times.

3 RESULTS

The following results are presented for dimensionless duct dimensions from 5x5 until 5x30. The calculations were performed with a reference length \(L=1\text{cm}\), targeting a duct height of a fullscale application of 30 cm including injection from both walls. Scalability will be addressed in the following section. For better comparison, the x-axis will be scaled in injector diameters \(x/L\), the injector diameter being equal the length scale \((D=L=1\text{cm})\).

The quadratic duct with a dimension of 5x5 \((p=9\text{bar})\), identical injector spacing and duct height is taken as a reference case. In a first step, the flowfield was calculated as a jet being injected through a flat plate without the bounding box of the combustion chamber (Fig. 2). The presence of a separation region in front of the injector can be seen. The injected hydrogen leads to a vortical flow downstream the injector hole, enhanced by the horseshoe vortex originating from upstream the injector hole. This leads to a good spreading in the vertical duct direction, but not in spanwise direction.
The flowfield topology including the combustion chamber symmetry walls is shown in Fig. 3. The bow shock is on the one hand reflected at the upper symmetry plane and the wall, on the other hand at the spanwise symmetry plane. The reflected shocks affect the injected hydrogen flow. The hydrogen is deflected down by the bow shock which was reflected at the top symmetry plane. The reflection at the side planes deflect the hydrogen flow towards higher penetration. The effects on the mixing efficiency (ME) are included in Fig. 4. The larger flow separation in front of the injector, being partly filled with hydrogen, improves the mixing efficiency even in front of the injector plane. Between $x/L=6$ (impingement of top shock) and 14 (impingement of side shock), $ME$ increases at a slightly higher rate as for the farfield reference solution. The top shock deforms the hydrogen from a cylindrical to a spanwise elliptical shape. At $x/L=14$, the side shock impinges, spreading the flow and deflecting it towards a lateral elliptical shape which increases the growth rate of the $ME$. At $x/L=20$ (or $x/H=4$ duct heights), the $ME$ is increased from 9 to 13.5%. The total pressure loss (TPL) is increased from 18.5 to 21.5% due to the reflected shock system.

3.1 Grid refinement study and scalability

In order to address the numerical dissipation due to grid resolution a grid refinement study was performed. This allows defining the required mesh resolution to predict the physical mixing effects in the flowfield. The results for the 5x5 ($p=9$bar) duct are shown in Fig. 5. The total pressure loss is predicted well after the $2^{rd}$ grid adaptation. Considering the mixing efficiency 5 adaptations are needed to reach mesh convergence. The total number of nodes is increased from the initial mesh (70,000) up to 400,000 points after the $5^{th}$ adaptation. The numerical dissipation leads to unphysically high mixing efficiencies at low grid resolutions. The solution on the initial mesh therefore over predicts the mixing by a factor of almost 3.

<table>
<thead>
<tr>
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<th>point number</th>
</tr>
</thead>
<tbody>
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<td>initial</td>
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</tr>
<tr>
<td>adaptation 1</td>
<td>109,000</td>
</tr>
<tr>
<td>adaptation 2</td>
<td>179,000</td>
</tr>
<tr>
<td>adaptation 3</td>
<td>307,000</td>
</tr>
<tr>
<td>adaptation 4</td>
<td>355,000</td>
</tr>
<tr>
<td>adaptation 5</td>
<td>400,000</td>
</tr>
</tbody>
</table>

Table 1: Number of grid points for grid refinement study

The scalability of the results to other duct dimensions was further on investigated. Due to the small boundary layer thickness these viscous effects are mainly present away from the mixing region and therefore do not affect it significantly. Scaling a 5x5 or a 5x30 duct to a targeted height of 15 changes the resulting mixing efficiencies by less than 0.5%. The changes in total pressure loss are negligible in the mixing region, minor changes occur close to the injector, included later in Fig. 11 (5x30 duct, $p=56$bar).
3.2 Injector spacing variation

Reducing the injector spacing results in a higher aspect ratio of the duct. For the following investigations, the spanwise dimension (W=5) and the injector diameter (D=1) were kept constant, whereas the height was increased (H=10 to 30). The equivalence ratio was kept constant, which results in a higher pressure of the injected hydrogen. Results for the 5x10 duct contains Fig. 6. The side reflection of the bowshock impinges first the hydrogen flow, the top reflected shock second (Fig. 6). After the top reflection, the flow is almost aligned parallel with the duct. Both increase the mixing from 9 (farfield, without shock reflections) to 13% (with reflections) at x/L=20, which corresponds to x/H=2 (Fig. 7). The hydrogen being left at this plane has a shape more comparable with the duct, the relative spanwise and lateral extension is better than with the 5x5 duct. This helps further mixing downstream the duct. The total pressure loss is increased from 18 to 20%.

For the 5x20 duct (p=38bar), the computational domain was only extended to x/H=1.07. With increased pressure and higher penetration, the influence of the separation zone in front of the injector vanishes since less fuel enters the separation. Downstream the injector, two side reflections of the bowshock impinge on the fuel before the top reflection (Fig. 8). After the first side shock impingement (x/L=10) the fuel is divided into an upper and a lower regions with maximum concentration which increases the mixing, see also Fig. 9. A slight expansion reduces the mixing after x/L=20, before at x/L=28 the second side reflection impinges and increases the mixing once again. At the exit plane (x/H=1.07) ME reaches 13%, the TPL 22%. The relative maximum penetration depth reaches slightly more than 50% of the duct height. The increased injector pressure partly compensates the total pressure loss in the flowfield, which refers to the total pressure at the duct inflow, compare equation (4). Therefore, the total pressure loss becomes negative in the vicinity of the injector plane.

The most extremely case being investigated was the 5x30 duct (p=56bar) corresponding to an injector spacing being 1/6th of the 5x5 duct, see fig. 10. Due to the high aspect ratio, the relative penetration reaches less than 50% at the exit plane (x/L=60; x/H=2). The TPL is 23%, ME is 17% (Fig. 11). The flow is getting unsteady resulting in a slightly wavy structure of the hydrogen concentration. Three side reflections impinge before the top reflection reaches the injected fuel.

It can be stated, that all investigated cases (different injector spacings) reach comparable mixing efficiencies at the same downstream positions taking the injector diameter as reference value (x/L). But, for a fullscale combustion chamber, the absolute required length at fixed height H is important. Taking x/H as a reference it can be stated that the smaller the injector spacing (with smaller absolute injection diameter) the higher the mixing efficiency at the same x/H position. Injectors with smaller spacings have to inject deeper, leading to a better surface to volume ratio of the injected fuel which is the main effect regarding the improved mixing.

3.3 Injector shape modification

In order to investigate the effect of injector shape modifications on the total pressure loss and the mixing efficiency a streamwise and a spanwise slot were investigated. The slot width
is 0.5D, the length 1.68D, resulting in the same injector area as for the D=1 hole injector. For the 5x5 duct, the results for ME and TPL of a streamwise and spanwise injector are shown in Fig. 12.

The streamwise injector has approximately the same TPL as the hole injector, whereas the mixing efficiency due to the shock impingement is only improved from 9 to 10.5%. Due to the thinner injector, the shocks impinge later and are not that strong compared with the hole injector. The injector shape itself does not have an impact on the mixing, the reference solution with farfield conditions has the same ME as the hole injector (9%, compare Fig. 4).

The flowfield of the spanwise slot injection case is getting strongly unsteady due to a moving separation in front of the injector (Fig. 13). With a certain frequency, hydrogen is entering the separation or is penetrated fully into the main flow. This can be seen also at the ME in Fig. 12, which is in front of the injector already 1.5%. By this, large scale high hydrogen concentration regions moving downstream are generated which improve the mixing. This moving separation causes the bow shock to oscillate, and, for the case including the shock reflections, the reflections impinging the fuel enhance the unsteadiness of the flow. The TPL is not increased significantly due to this, as can be seen at a certain point in time of the unsteady calculation in Fig. 12 (TPL 20±1.5%). The mixing efficiency is significantly improved due to the unsteadiness of the shock and separation system from 9.5±1% to 16±2%.

A steady state solution is observed both for stream- and spanwise injection into the 5x10 duct (Fig. 14 and 15). Due to the higher injection pressure, the separation in front of the injector does not play a significant role since the main flow affects the injected fuel less which penetrates deeper into the duct. With the streamwise slot, there is a small, strong horseshoe vortex present which dominates the mixing of the fuel. The impinging shocks have only a minor effect on the ME (increase with 0.5% to 8.5%, see Fig. 16) which is lower than with the round hole injector type. For the spanwise slot, ME without the shocks is quite poor (6%). The reason is a weak horseshoe vortex, which does not lead to a strong vertical flow downstream the injector hole. The injected fuel stays in a compact flow with a weak vortex structure. Employing the symmetry planes with the impinging shocks and slight flowfield differences in the injector area improves the ME to 8%. TPL are in the range of 18 to 21%. The streamwise injector shows slightly smaller losses.

According to the previous results, the main effect of the significantly improved mixing efficiency of the 5x5 duct (spanwise slot) is the unsteadiness of the flow due to the lower injection pressure and not the injector shape. Also according to experimental data, the injector shape shows only little effect on the global mixing behavior.

### 3.4 Investigation of axially extended combustion chambers

Until now, the mixing behavior the vicinity of the injector was investigated. For the practical injection into a combustion chamber, the mixing of fuel and air along the chamber is essential, since the mixing mainly drives the combustion process. The combustion of stoichiometrically mixed fuel and air takes place within approximately 10 centimeters; therefore the mixing process itself defines mainly the required combustion chamber length. Calculations have been performed for the 5x5, 5x20 and 5x30 duct, all having a length of 12H
A. Mack, J. Steelant

(1.8m length for a duct height of 2H=0.3m). The grids contain 1-1.5\times10^6 points. The grid resolutions are taken from the end of the short ducts and are kept approximately constant until the exit plane.

The solution for the 5x5 in Fig. 17 shows, that the flow is getting strongly unsteady, which improves the mixing significantly. The ME is higher than with the short duct, the grid resolutions are comparable. The TPL reaches 28% at the duct exit.

The flowfield topology for the 5x20 duct is shown in Fig. 18. The shock system has an impact on the flow topology further downstream. The side reflections vanish further downstream, the top/wall reflections dominate the flowfield. The penetration is significantly improved, the injected flow reaches almost the upper symmetry plane. The results for ME and TPL of the 5x20 duct (Fig. 19) show good agreement with the previous solution for the short duct (included from Fig. 7). Therefore the grid resolution can be considered as sufficient also for the long duct. The flow is slightly unsteady, ME reaches 48% at the exit plane with an almost linear increase towards the end. The TPL reaches 27%.

Finally, the computation of the 5x30 (56bar) duct are shown in Fig. 20. The results for the ME of the long duct are slightly above the ones of the short one, which is a result of the grid resolution. Due to the high aspect ratio of the duct the resolution in spanwise direction is slightly lower. At the exit plane, the ME reaches 48%. Although the 5x30 injection indicated a better mixing in the vicinity of the injector than the 5x20 duct, this effect vanishes with increasing length. Due to the high aspect ratio, the global mixing of the air in the upper part of the duct with the fuel rich mixture in the lower part is reduced. The 3D effects of the flow are reduced and the relative penetration of the fuel is lower as has been shown with the short duct. This reduces the TPL, which is 25% at the exit plane. The flow shows minor unsteadiness.

As shown in the previous results, the shock system affects the flow topology significantly. All side reflection of the bowshock, which are mainly present in the front part of the duct, redirect the flow upwards. For the long ducts, 3 to 4 top reflections take place inside the duct. The downwards oriented ones redirect the flow downwards, the upwards oriented ones upwards. If the side reflections manage to increase the flow angle such that the first top reflection aligns it with the duct axis, all further shocks will increase the penetration. This increases the overall penetration significantly, as can be seen with the 5x20 duct (not shown here for the other ducts). The maximum penetration in front of the first impinging top reflection is 0.6H which is increased due to the shocks until 0.87H at the duct exit. Optimizing the injector spacing therefore leads to an improved mixing. Better penetration can be achieved due to the shock system which results together with better cross section mixing capabilities (aspect ratio of duct) in higher mixing efficiencies.

3.5 Penetration improvement

The results of the long ducts illustrate, that the highest possible penetration should be achieved in order to get the air flow in the upper part of the channel mixed with the fuel. This creates large scale vortex structures, which over compensates disadvantages of the injector mixing capability. The penetration behavior can be describes in the following form, found in good agreement by different authors$^2,7$ for flat plate experimental data:
\[
\frac{y}{D} = \alpha \left( \frac{q_j}{q_{\infty}} \right)^\beta + \left( \frac{x}{D} \right)^\gamma
\]  
(5)

with \( \alpha = 2.5-3.5, \beta = 0.4-0.55, \gamma = 0-0.4. \)

Since the combustion chamber is not infinite and the shock system will affect the flowfield from around the downstream position \( x/L=H \) being 10 to 20 injector diameters, penetration will be reduced to that range. Therefore, the second term in (5) can be neglected by adjusting the coefficient \( \beta \) slightly. Employing \( \beta = 0.5, \) the dynamic pressure and the massflow:

\[
2 \cdot q = \rho \cdot u^2 = \kappa \cdot p \cdot Ma^2
\]  
(6)

\[
\dot{m} = A \cdot \rho \cdot u = D^2 \cdot \frac{\pi}{4} \cdot \kappa^\frac{1}{4} \cdot p \cdot \rho \cdot Ma^2
\]  
(7)

The penetration depth can be rewritten as:

\[
y = \frac{\alpha}{\sqrt[q_{\infty}]{q_j}} \sqrt[2]{\frac{2 \cdot \kappa_j \left( \frac{R_j}{T_j} \right)^{\frac{1}{4}} \kappa_j}{\pi}} \cdot \sqrt[4]{Ma_j}
\]  
(8)

- Penetration is independent from the injector diameter
- There is a minor increase in penetration due to the temperature of the injected gas (term 3 in (4)), which is usually fixed due to technical reasons
- The penetration increases with the square root of the massflow (term 2 in (8)), which is determined by equivalence ratio and injector spacing. Small spacings require low massflow rates which reduces the penetration
- Increasing the injection Mach number increases the penetration (term 4 in (8)), was also shown by Billig\(^2\)
- Finally, the penetration is inversely proportional to the square root of the free stream dynamic pressure (term 1 in (8)). Since there is a bow shock present, the gas faces the pressure behind the bowshock, which can be reduced by tilting the injector axis\(^10\) in streamwise direction. Setting multiple injectors inline will result in the same effect, the downstream located injector face a lower pressure due to the expansion behind the upstream ones\(^11\)

For the following investigations, a supersonic \( Ma=3 \) injection at an angle of \( 60^\circ \) was chosen. The calculations for the 5x10 duct were performed employing the streamwise slot. For this configurations, the penetration indicated by the maximum hydrogen concentration in the symmetry plane in increased from 0.61H to 0.81H by almost one third (Fig. 21). The mixing close to the injection in not significantly affected by these modifications of the injector, the ME is comparable with the results from the round hole injector. Regarding the TPL, the higher total pressure (static pressure 7.2 bar, total pressure 265bar) partially compensates the losses generated by the shock system (Fig. 22).

As described before, the idea of the inline injector is to achieve a high penetration but also
taking advantage of the low massflow per injector hole to achieve good mixing. The geometry was taken according to an available design, 11, 12 injectors are aligned inline with a length over diameter ratio of 48. The overall area of the 12 injectors is the same as for the D=1 round hole injector resulting in a D=0.29 injector diameter. The injection angle is 60°, Mach number 3.0. Results of hydrogen injection into a 5x20 duct are shown in Fig. 23. The further downstream located injector holes penetrate much deeper into the duct, leading to a penetration almost proportional to the x/L position. The flow exiting the injectors stays at an angle of almost 60° until the maximum local penetration is reached. The impinging side shocks do not have a major effect on the penetration since the flow angle is already high. Behind the last injector, penetration is reduced and the flow is aligned with the duct axis due to the impinging bow shock reflection. The penetration reaches 0.9H. The hydrogen concentration distribution at the exit plane indicates good mixing, the fuel is spread along almost the whole duct height. (static pressure 14.4 bar, total pressure 530bar) The flowfield downstream the first shock impingement is comparable with a strut injection. It shows a homogenous hydrogen distribution with a very weak large scale vortex. Due to the small injector holes, the ME reaches 17% at x/H=2 (Fig. 24). Above x/L=1.3 ME is higher than with the hole injection into the 5x20 duct. The TPL is 17% at the x/L=2 plane.

<table>
<thead>
<tr>
<th>type:duct/injector</th>
<th>z/H at c(H₂)max</th>
<th>z/H at c(H₂)=0.02</th>
<th>Position of top bow-shock impingement on injected flow</th>
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</thead>
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<tr>
<td>5x5 hole</td>
<td>x/H=1</td>
<td>x/H=2</td>
<td>x/H=1</td>
</tr>
<tr>
<td>5x10 hole</td>
<td>0.52</td>
<td>0.57</td>
<td>0.68</td>
</tr>
<tr>
<td>5x10 slot streamwise</td>
<td>0.59</td>
<td>0.64</td>
<td>0.66</td>
</tr>
<tr>
<td>5x10 slot streamwise</td>
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<td>0.46</td>
<td>0.61</td>
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<tr>
<td>5x20 hole</td>
<td>0.45</td>
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</tr>
<tr>
<td>5x20 12 in-line, Ma=3, 60°</td>
<td>0.74</td>
<td>0.86</td>
<td>0.79</td>
</tr>
</tbody>
</table>

Table 2 : Penetration characterisation for different injectors and duct types (x/H≤2.3)

In table 2, some results of the dimensionless penetration are shown for different injector designs, conditions and duct dimensions. Increasing the aspect ratio of the duct cross section (5x5, 5x10, 5x20) reduces the penetration. The 5x5 duct reaches its maximum penetration later than at x/H=2 (compare also Fig. 2 and 3) and suffers from the early shock impingement which should be taken into account comparing the data in table 2. With the higher ducts, the bow shock reflected on the upper symmetry plane impinges later which increases the penetration. The streamwise slot reduces the penetration by 10%, whereas increasing the injection Mach number and tilting the flow increases the penetration significantly. The 12 inline injectors show the highest overall penetration, which is mainly limited by the impinging reflecting bow shock.
3.5 Flow conditions

The flow condition at the duct entry is \( \text{Ma}=2.5 \), static pressure 1bar, static temperature 1300K. Table 3 contains the flow conditions of the jet for all configurations, the static temperature of the injected hydrogen flow is 300K.

<table>
<thead>
<tr>
<th>configuration</th>
<th>( \text{Ma} [-] )</th>
<th>( \phi[^\circ] )</th>
<th>( p_e ) [bar]</th>
<th>( p_0 ) [bar]</th>
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<tr>
<td>5x5 (hole &amp; slots)</td>
<td>1</td>
<td>90</td>
<td>9.4</td>
<td>17.8</td>
</tr>
<tr>
<td>5x10 (hole &amp; slots)</td>
<td>1</td>
<td>90</td>
<td>18.8</td>
<td>35.6</td>
</tr>
<tr>
<td>5x20</td>
<td>1</td>
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<tr>
<td>5x30</td>
<td>1</td>
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<tr>
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<td>7.2</td>
<td>265</td>
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<tr>
<td>5x20 12 inline supersonic</td>
<td>3</td>
<td>60</td>
<td>14.4</td>
<td>530</td>
</tr>
</tbody>
</table>

Table 3: Injector flow conditions

4 CONCLUSIONS

The present investigations show, that the injector configuration and the injector spacing, which is related to the combustion chamber cross section sizes, has an major impact on the flow topology, the shock pattern and as a result on the mixing efficiencies. For sonic hole injectors, the mixing efficiency is increasing almost inversely proportional with the injector spacing due to the reduced massflow per injector, whereas the injector shape does not play an important role. Larger injector spacings lead to higher penetration and, depending on the injector shape, to unsteady flow with improved mixing efficiencies. For all hole injector systems, the mixing can be improved significantly by the presence of the reflected bowshocks in the combustion chamber and unsteadiness. If the bow shocks reflected on the side symmetry planes are impinging before the top symmetry reflection, penetration is improved which increases the overall mixing. Too small injector spacings reduce the local mixing improvement in the vicinity of the injector further downstream due to reduced 3D flow effects. The unmixed air flow in the upper part of the duct mixes slower in the high aspect ratio duct. This problem can be overcome with supersonic injection at a certain tilting angle or an inline injector design, which increase the penetration significantly. Especially the inline injector combines high penetration with good mixing efficiencies due to the small injector mass flow per injector hole.

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REFERENCES


FIGURES

Fig. 1: Cross sections of the generic ducts with wall injection from both sides

Fig. 2: Flow topology for flat plate hole injection, $p_0=17.8$bar, w/o symmetry planes

Fig. 3: Flow topology for 5x5 duct, hole injection, $p_0=17.8$bar, with symmetry planes
Fig. 4: Mixing efficiency and total pressure loss for $p_0=17.8$ bar (5x5 duct)

Fig. 5: Grid convergence study for 5x5 duct, $p_0=17.8$ bar.

Fig. 6: Flow topology for 5x10 duct, hole injection, $p_0=35.6$ bar

Fig. 7: Mixing efficiency and total pressure loss for $p_0=35.6$ bar
Fig. 8: Flow topology for 5x20 duct, hole injection, \( p_0 = 71.2 \text{bar} \)

Fig. 9: Mixing efficiency and total pressure loss for \( p_0 = 71.2 \text{bar} \)

Fig. 10: Flow topology for 5x30 duct, hole injection, \( p_0 = 107 \text{bar} \)

Fig. 11: Mixing efficiency and total pressure loss (\( p_0 = 107 \text{bar} \); \( H = 0.3 \) and 0.15m)
Fig. 12: Mixing efficiency and total pressure loss for slot injectors ($p_0=17.8$bar)

Fig. 13: Flow topology for 5x5 duct, spanwise slot injection, $p_0=17.8$bar

Fig. 14: Flow topology for 5x10 duct, streamwise slot injection, $p_0=35.6$bar

Fig. 15: Flow topology for 5x10 duct, spanwise hole injection, $p_0=35.6$bar
Fig. 16: Mixing efficiency and total pressure loss for slot injectors ($p_0=35.6$bar)

Fig. 17: Mixing efficiency and total pressure loss for 5x5 duct ($L_{cc}=12H$, $p_0=17.8$bar)

Fig. 18: Flowfield topology of 5x20 duct ($L_{cc}=12H$) with hole injection ($p_0=71.2$bar)
Fig. 19: Mixing efficiency and total pressure loss for 5x20 duct (Lcc=12H, p0=71.2bar)

Fig. 20: Mixing efficiency and total pressure loss for 5x30 duct (Lcc=12H, p0=107bar)

Fig. 21: Flow topology for 5x10 duct, supersonic slot injection (streamwise, Ma=3, 60°)

Fig. 22: Mixing efficiency and total pressure loss for Ma=3 slot injection
Fig. 23: Flow topology for 5x20 duct, 12 supersonic inline injectors (Ma=3, 60°)

Fig. 24: Mixing efficiency and total pressure loss for 12 inline injectors