2020

Influence of backward-facing step on the mixing efficiency of multi microjets at supersonic flow

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Abstract

© 2020 IAA The injection of the fuel is a highly important process for the enhancement of the scramjets. In this article, the presence of the backward-facing step on the mixing of the multi-fuel jets is expansively studied. The primary attention of this article is to scrutinize the flow feature of the fuel jet under the backward-facing step. The mixing mechanism of the fuel is also studied to compare this injection system with conventional methods. To do this, a 3-dimensional model is chosen to consider the real physic of the problem. Reynolds Average Navier-Stocks equations are solved with a computational fluid dynamic method to visualize the flow pattern of the fuel jet at the free stream Mach number of 4. SST turbulence model is also used for the calculation of the viscosity. Our results indicate that increasing the jet space from 4 to 10 times of jet diameter in the presence of the backward-facing step increases the mixing efficiency up to 20% in the downstream. Our findings depict that augmenting the number of fuel injectors from 4 to 8 augments the mixing rate up to 15% inside the combustor.

Disciplines

Engineering | Science and Technology Studies

Publication Details

Li, Z., Moradi, R., Marashi, S., Babazadeh, H. & Choubey, G. (2020). Influence of backward-facing step on the mixing efficiency of multi microjets at supersonic flow. Acta Astronautica, 175 37-44.

Influence of backward-facing step on the mixing efficiency of multi microjets at supersonic flow

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Abstract-The injection of the fuel is a highly important process for the enhancement of the scramjets. In this article, the presence of the backward-facing step on the mixing of the multi-fuel jets is expansively studied. The primary attention of this article is to scrutinize the flow feature of the fuel jet under the backward-facing step. The mixing mechanism of the fuel is also studied to compare this injection system with conventional methods. To do this, a 3-dimensional model is chosen to consider the real physic of the problem. Reynolds Average Navier-Stocks equations are solved with a computational fluid dynamic method to visualize the flow pattern of the fuel jet at the free stream Mach number of 4. SST turbulence model is also used for the calculation of the viscosity. Our results indicate that increasing the jet space from 4 to 10 times of jet diameter in the presence of the backward-facing step increases the mixing efficiency up to 20 % in the downstream. Our findings depict that augmenting the number of fuel injectors from 4 to 8 augments the mixing rate up to 15% inside the combustor.

Keywords: backward-facing step; combustion chamber; supersonic flow; numerical study; multi-micro jets

1. Introduction

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The advance in aerospace engineering is directly associated with the high-speed flight which is the old desire of the human [1, 2, and 3]. The invention of the ramjet was the big step to speed up the aerospace vehicles to sonic flight condition. The main simple concept of this engine helps the researchers to achieve supersonic combustion ramjet known as Scramjet. This advance was significant since the performance of this engine was reasonable for the flight with different operating conditions from subsonic to supersonic conditions [3, 4, 5, and 6]. This advantage is highly helpful to advance this engine in different aspects.

The main novelty of the scramjet engine is in the supersonic combustion condition while the speed of the freestream in the ramjet should be subsonic. Indeed, the speed of the free stream remains supersonic inside the combustor and this preserves the efficiency of the scramjet in high-speed flight [5, 7, 8, and 9]. This modification has some advantages/disadvantageous and they should carefully consider the design of the scramjet. Since the speed of the free stream is not reduced in the scramjet, the pressure drop of the free stream is much less than ramjet. However, the fuel mixing inside the combustor becomes harder due to the low duration time of the fuel within the combustor [9, 10, 11, and 12]. Since the main goal of the scramjet is to obtain a high-speed flight for the long-distance, efficient fuel mixing is essential for low fuel consumption. In fact, the advantage of the scramjet is a low fuel tank which reduces the weight of the high-speed vehicles [11, 13, 14, 15, 16 and 17].

To resolve the fuel mixing inside the combustor, some techniques have been introduced by different scholars and scientists [18, 19, 20, 21, 22, and 23]. The injection systems and geometry of the combustor is changed to enhance the fuel mixing and increase the fuel residence time for better fuel spreading. The transverse fuel injection system is the most conventional and simple technique for the distribution of the fuel in the combustor. This technique is widely studied with both computational and experimental approaches to reveal the main physic of the problem in various conditions [24, 25, 26, 27, 28 and 29]. In this method, the fuel jet is injected normal to the free stream and the interaction of the fuel with the main stream results in the fuel mixing. Although it seems that the method is simple and basic, the flow structure of the sonic jet in the presence of the supersonic crossflow is highly complex. Hence, it is extensively investigated by the researchers. The 3-D simulations of detonation onset in non-uniform gas mixtures formed resolving injectors and mixing zones were investigated by Smirnov et al. [30, 31]. To advance this technique, the single fuel jet is replaced with multi micro jets and this is extensively studied by researchers [32, 33, and 34]. In this modification, the interaction of the fuel jet with the main stream declines since the normal momentum of the fuel in the facing of the supersonic free stream is divided into multi jets. However, the arrangement of the fuel led to the formation of the multi vortices which improve the fuel mixing [35, 36, and 37].

The film injection is also a valuable technique that tries to reduce the flow interaction via parallel injection of the fuel with the main stream. This model is not well since the mixing of the fuel with the free stream is not high. The application of the strut substantially helps this approach for efficient fuel mixing. The incidence of the strut results in the formation of the recirculation region where fuel could sufficiently mix with the supersonic incoming air [38, 39, and 40].

The cavity flame holder is also known as the efficient technique for the mixing of the high-speed flow with fuel jets. In this technique, the cavity is produced and the fuel jet is released inside the cavity where the velocity of the flow is much less than a free stream. Since fuel remains more in this region, it could sufficiently blend with the incoming air and its distribution in this region is more uniform [41, 42, and 43]. Besides, the temperature of the fuel is moderated in this region which is highly significant for the auto-ignition of the fuel. Due advantageous of this technique, it is highly used in the combustor and substantial studies have focused on this model. The application of the multi micro injectors rather than a single injector is more preferred since the fuel could mix and distribute homogeny through the cavity domain [44, 45, 46, and 47].

According to previous studies [48, 49, 50, and 51], the idea of the cavity could be enhanced since it offers low-speed regions with strengthening circulation which is helpful for the fuel mixing process. In this paper, the presence of the backward step is developed in the upstream of the multi micro jets. Figure 1 illustrates the full details of the proposed model for the efficient mixing of fuel inside the combustor of the scramjet. In fact, the attendance of the backward step manages the freestream interaction with the fuel jets to obtain the optimum location of the jet interaction. Besides, this mechanism allows the formation of the voracities which initiated from the velocity difference of the injectors and free stream at the bottom of the domain. The main jet interactions and generated shocks are schematically demonstrated in Fig. 1.

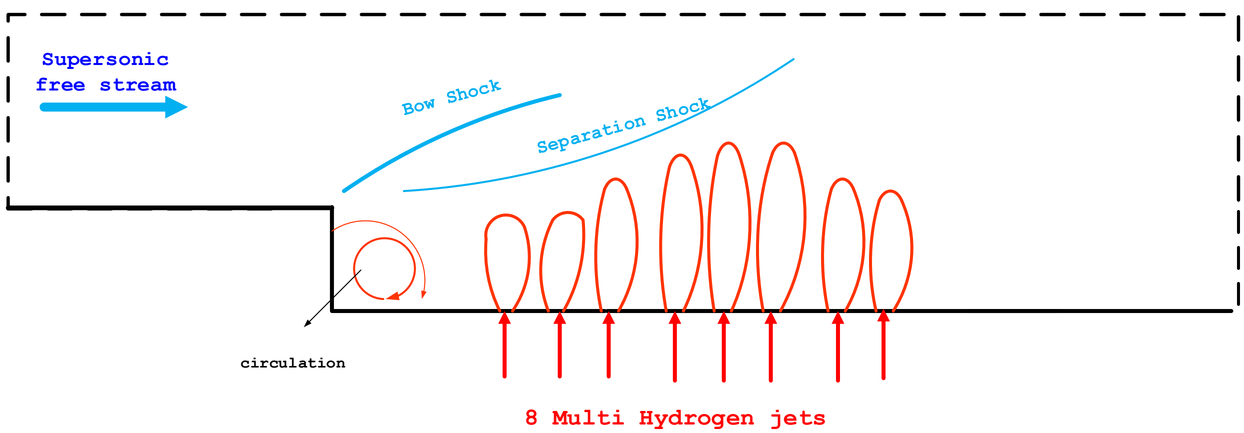


Fig.1 Schematic of backward-facing step in supersonic flow

In this computational investigation, the effects of the backward step on the fuel distribution of the eight micro jets are fully disclosed. The key attention of this work is to visualize the structure of the fuel jet in different step conditions. To do this, the computational method is applied to study the three-dimensional feature of the fuel jet interactions in the supersonic free stream of Mach=4.

Since the main nature of the vortex is three-dimensional, 3-D model is considered in our investigations to achieve more realistic results in our investigations. The influence of the jet space and jet total pressure on the fuel spreading are comprehensively investigated. The quantitative analyses on the fuel mixing in the downstream of the multi micro jet are also performed to achieve the optimum fuel distribution in this model.

2. Computational procedure and main governing equation

2.1.Governing equations

To simulate the compressible supersonic flow, the RANS equation is mostly used and it is coupled with the energy equation which is essential for the shock-capturing. Indeed, the formation of shock due to high velocity of the incoming air stream and step condition is evident. Hence, momentum and energy equations are simultaneously solved. In the selected equations, density of fluid is calculated via ideal gas model and heat capacity of the fluid is estimated via fluid mixture fractions. SST turbulence model is applied to calculate the viscosity in the model. This turbulence model is extensively used for the computational study of the compressible flow [52, 53, 54, 55, and 56]. To avoid repetition, readers are encourage to review our previous articles which fully describes the primary governing equations and main assumptions for the simulation of supersonic cross flow jet.

2.2. Model description and applied boundary

Fig. 2 illustrates the size of our model with applied boundary conditions. As shown in the figure, the step height is 1 mm while its depth is equal to the radial of the injector. The length of the step is 20 mm from the inlet. The first jet space to the step is 5 mm in our model. The length and height of the domain are 100 mm and 10 mm, respectively. The diameter of the injector is 0.25 mm and the depth of the domain in the spanwise direction is 0.78 mm.

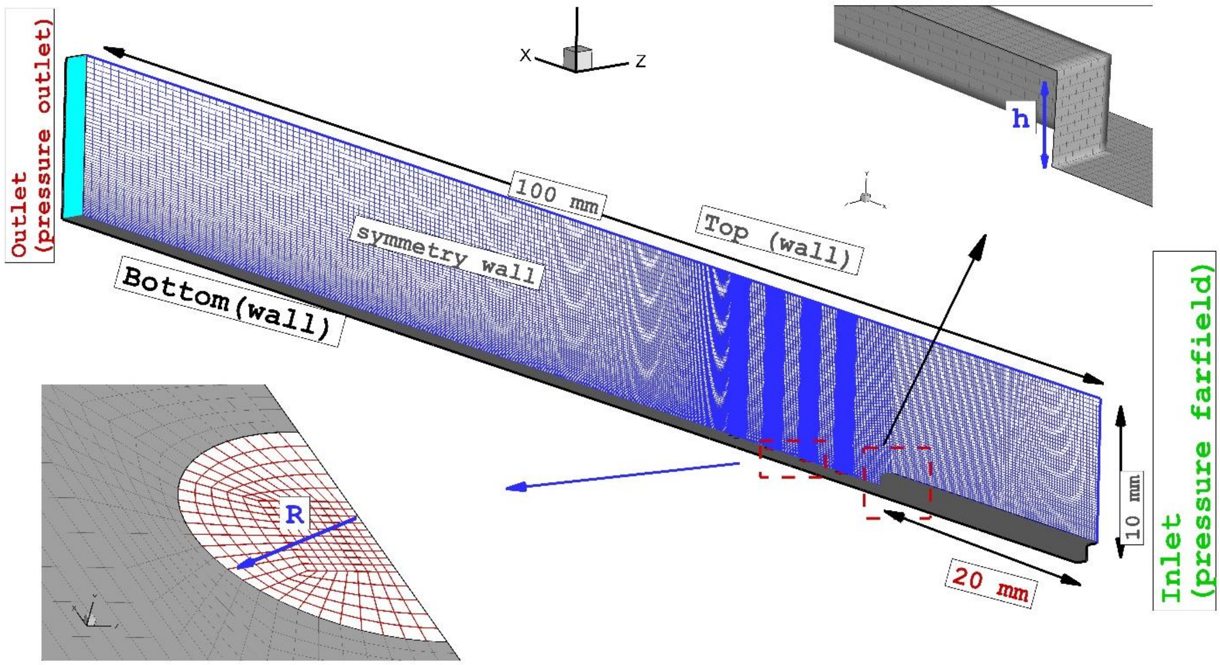


Fig. 2 size and geometry of upstream backward step

As illustrated in the figure, the wall boundary condition is applied on the top and bottom of the domain. The symmetry condition is applied to the front and lateral planes. Besides, the pressure far-field is applied for the inlet while the pressure outlet is selected for the outflow. For the injector, the pressure condition is applied according to the sonic condition. The inlet Mach number is 4 with atmospheric pressure and temperature of 1000 K. The fuel is injected in the sonic condition and its pressure is defined as the ratio of the total pressure of the freestream condition. In this study, the total pressure ratio (PR) of 0.1 is used as the main jet condition.

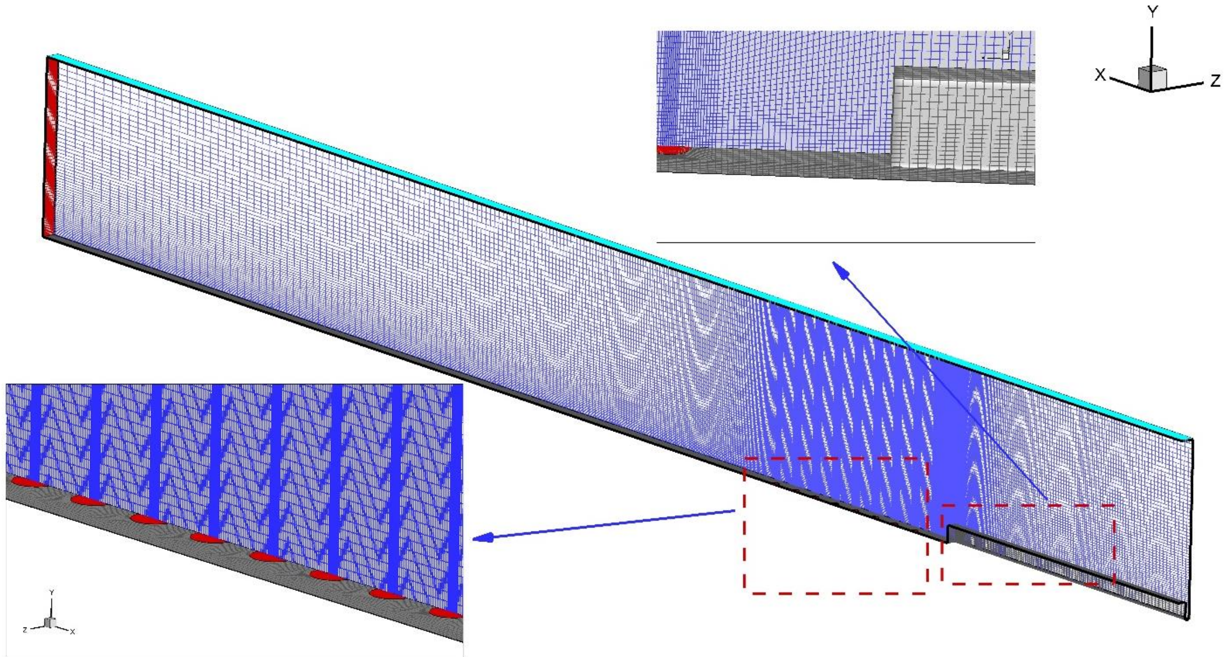


Fig. 3 detail of applied grid

2.3. Grid production

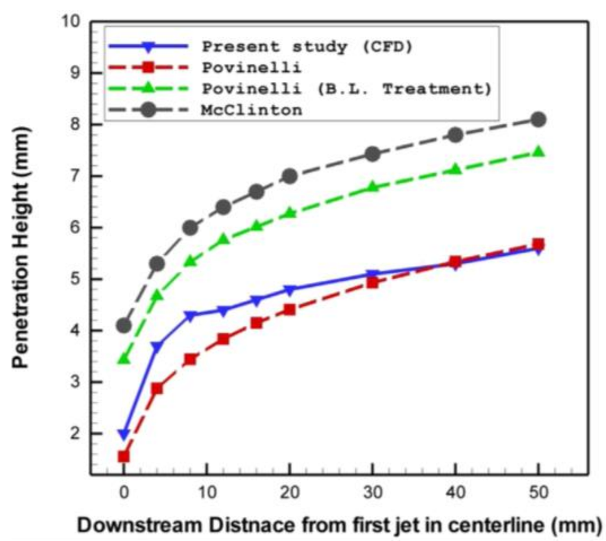
The grid generation is highly significant to reduce errors and avoid discrepancies from the real results. In this work, four different grids are examined to confirm the mesh independency of the obtained results. The number of the grid elements for this model was 842000, 1220000, 1648000 and 2422000 cells. The comparison of the obtained results shows that the grid with 1648000 cells is the most efficient one which has proper resolution for the capture of the shock interactions in our model. Besides, the Y+ value on the first row of the grid is calculated for these grids and it is lower than 1 for the selected grid. It shows that the grid resolution in the vicinity of the bottom and jet is high enough. **Figure 3** illustrates the details of the selected grid with close-up views. The numerical simulations is expected to provide sufficient data for accumulation of errors estimates. Smirnov et al. [55, 56] showed that the error itself depends on accuracy of algorithm and grid, and on the number of integration steps.

3. Results and Discussion

3.1.Validation

For the evaluation of the correctness of the numerical simulations, the comparison of the obtained results with experimental data is essential. In this model, no experimental data is accessible. To overcome this, the result of the single cross jet flow with an experimental model is widely examined by different groups and researchers. One of the significant factors for the fuel distribution in the combustor is the penetration height where the mass fraction of the fuel is more than 0.5 %. In this work, the height of penetration is calculated on the plane with 5 mm interval in downstream of the multi jets. Figure 4 plots the change of the single cross flow jet with other experimental data. The comparison of the results shows that the obtained values are within the range of the experimental data with acceptable deviation. Besides, the results of our simulation are verified with computational data of Pudsey et al. [57] in **Fig. 5.** In this figure, the mass fraction of the four micro hydrogen jets is compared in the downstream (20 mm from the first jet). It is noticed that our data is close to the results of Pudsey et al. [57] for the multi-fuel jet model.

a)



b)

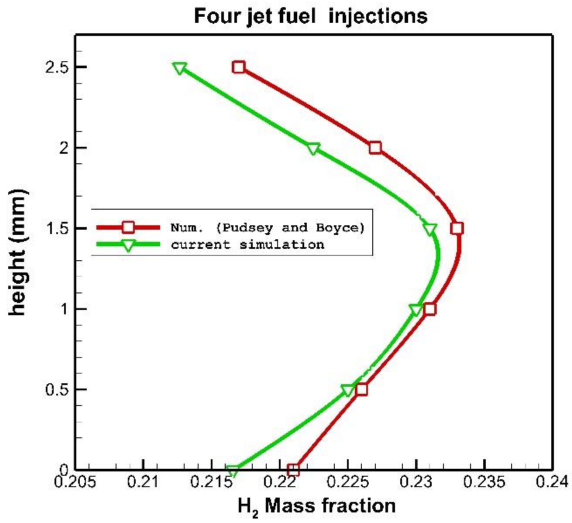


Fig 5. A) Validation B) Verification

3.2. Flow feature

In this study, 3-D model is selected to disclose the main flow feature of multi jets in presence of upstream step. **Figure 6** illustrates the 3-D contour of the 8 micro jets with PR=0.1 when upstream backward step is applied. According to our previous studies, it is found that the jet space is highly effective on the fuel mixing inside the combustor. Hence, the results of fuel distribution for three jet spacings of 4Dj, 7 Dj and 10 Dj are presented in this figure.

In the case with a jet spacing of 4Dj, the presence of the step directs the supersonic main stream to the top of the jet. The presence of the backward step results in the formation of a circulation region in the distance of the firs jet and step. As demonstrated in the 3-D contour, the core of the fuel jet gradually extended and three last jets have the most core height. In fact, the strong barrier forms in the upstream of the first jet and this obstructs the penetration of the free stream into the fuel injectors.

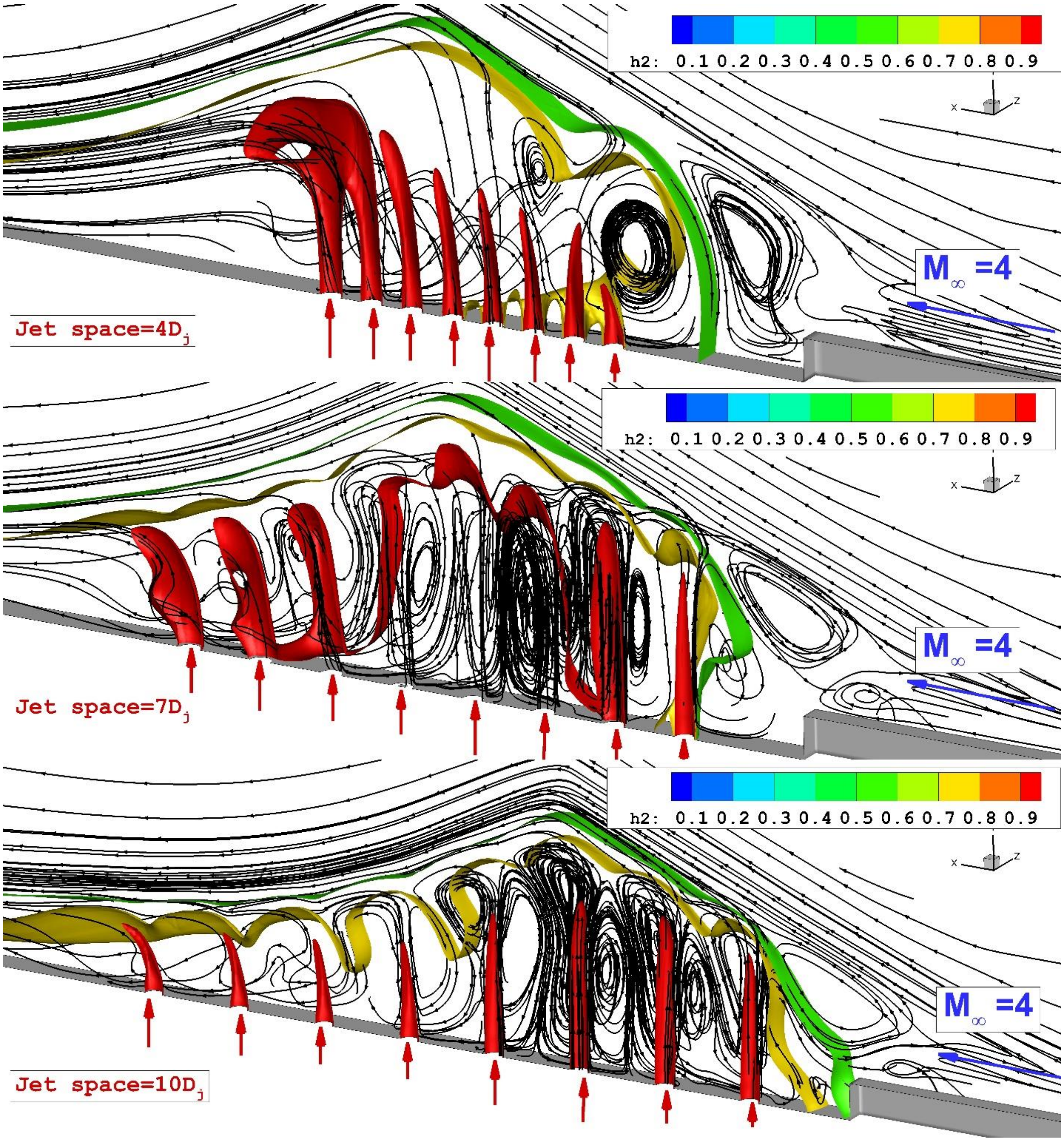


Fig. 6 comparison of the multi fuel jets with different jet spacings in presence of upstream backward step

As the jet space is increased to 7Dj, the creeping flow which moves along the bottom surface could penetrate within the jets and results in the vortices. This augments the spanwise distribution of the fuel inside the domain. When the jet space becomes 10 Dj, these vortices are amplified and the spiral structure of the last jets is clearly noticed. Besides, the strength of the vortices reduces the concentration of the fuel in the last jets and enhance the mixing with the main stream.

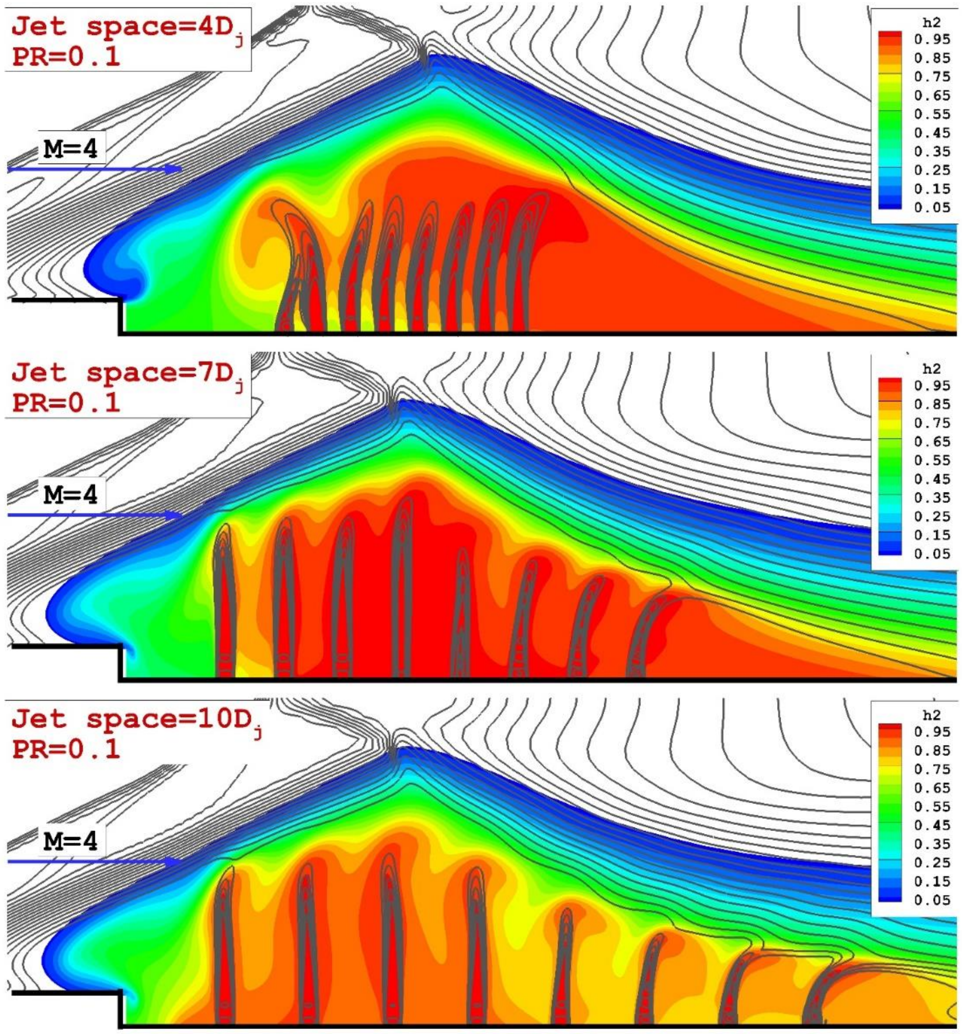


Fig. 7 temperature contour on the jet plane

To evaluate the impact of the step condition, the temperature distribution on the jet plane is demonstrated in **Fig. 7**. Since the main interaction of the jet and main stream occurs in the jet plane, the temperature contour and streamline could reveal information data about the fuel jet structure. As shown in **Fig. 7**, two distinctive circulations are produced in the upstream of the jet. When the jet space is increased, the strength and size of these two circulation decrease. In fact, the normal momentum of the jet in the vicinity of the first jet weakens and this allows the main stream to moves within the jets. Since the main stream interacts with a top wall in the middle of the jets, the temperature increases at the top of the jets. In the case with jet space of 10Dj, just one circulation is observed in the upstream of the first jet.

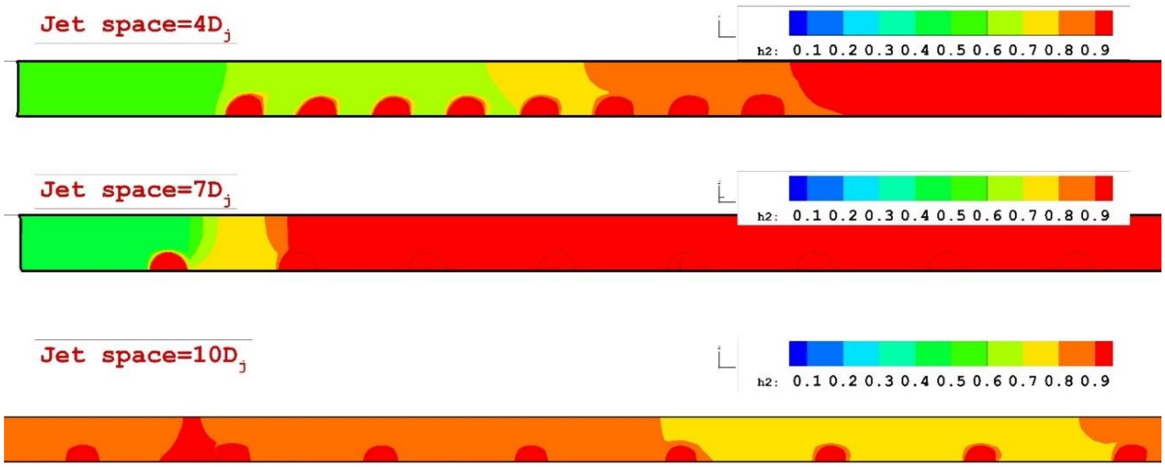


Fig. 8 The distribution of hydrogen mass fraction on the bottom of the surface

Figure 8 illustrates the hydrogen mass fraction on the bottom of the domain for three jet spaces at PR=0.1. The H_2 concentration on the bottom surface clearly increases when the jet space is increased. Indeed, this is due to strengthening of the vortex structure which recirculates the fuel in the spanwise direction. Hence, fuel concentration increases at the bottom of the surface.

3.3. Fuel Mixing

The mixing performance of the fuel should be compared quantitatively to evaluate the effects of the jet space in our problem. **Figure 9** plots the mixing efficiency of the hydrogen jet for the three jet spaces at the downstream of the injectors at PR=0.1. According to our findings, the lowest mixing efficiency in the vicinity of the injector is associated with model with jet space of 4Dj. In fact, the mass flow rate of the fuel is lower in this case and this is the main reason for this outcome. As the jet space is increased, the vortices among the jet are intensified and the mixing value increases. **Figure 9** confirms that the mixing performance of the case with 10 Dj is more than other models when the distance to the first jet is more than 30 mm. In this work, non-reacting flow mixing efficiency is considered. In fact, all mixing parameters and characteristics would be different in reacting flows.

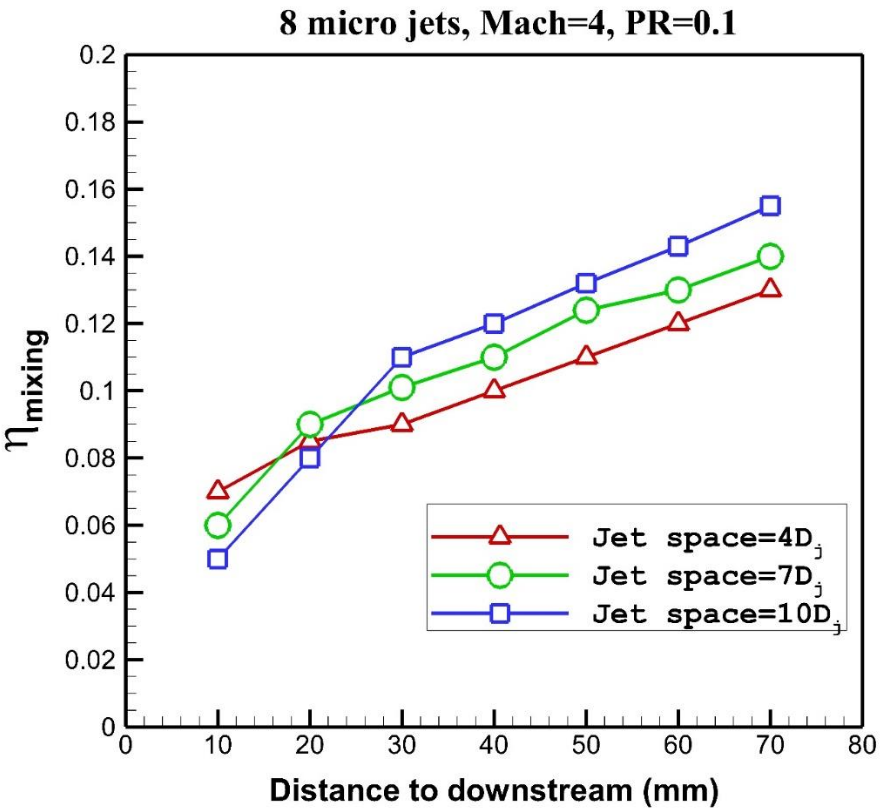


Fig. 9 Mixing efficiency for different jet space at model with upstream backward-step

In the evaluation of the multi jets, the optimum number of the jet is significant. To compare the impact of the number of injectors on the mixing efficiency, **Figure 10** presents the variation of the ratio of the mixing efficiency to fuel mass flow rate for the 4 and 8 micro jets at PR=0.1. It is noticed that the performance of the 8 micro jets is highly better than four multi jets at the same jet pressure. This is mainly due to amplification of the vortex structure when the number of the jet increases.

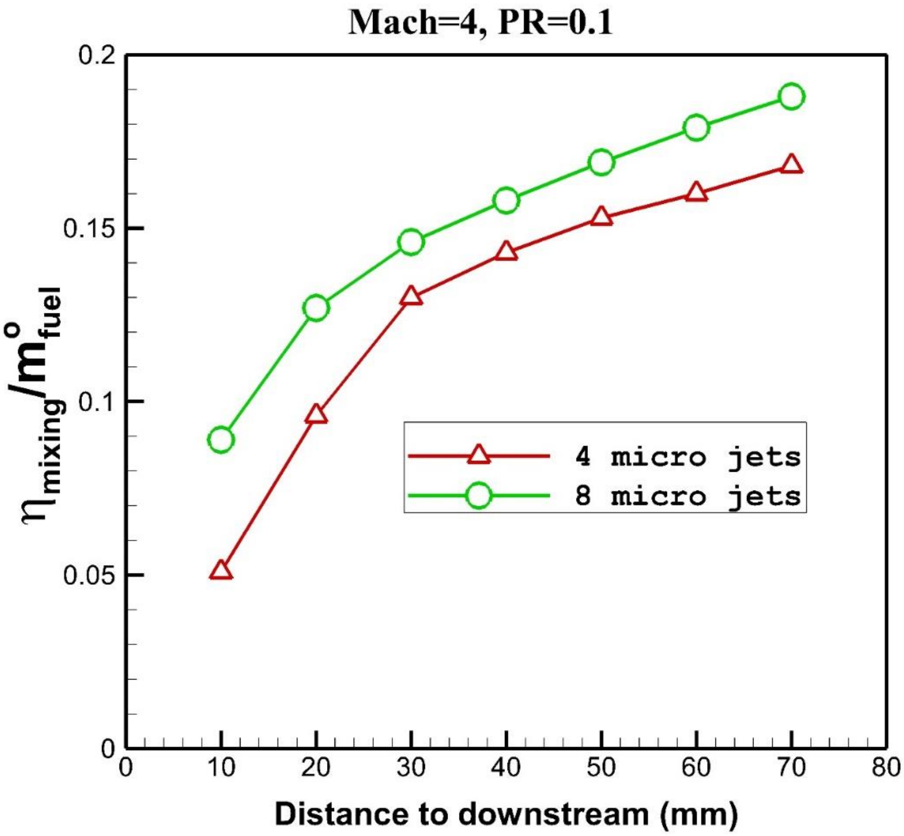


Fig. 10 comparison of the mixing ratio of 4 and 8 micro jets

4. Conclusion

In this study, the structure of the multi-fuel jet in the presence of the upstream backward step is fully studied. Three-dimensional model of the problem is chosen to ensure than real condition is applied. Reynolds Average Navier-Stocks equations are solved for the simulation of the high-speed compressible flow with an injection of the multi cross jets. The impact of jet space of the hydrogen jet on the fuel jet feature is comprehensively examined. Our investigations demonstrate that the presence of the backward step moderates the free stream interactions with fuel jets. Moreover, the formation of the spanwise vortices is strengthened in step condition. Our results show that increasing the fuel jet space significantly improves the fuel mixing in the far downstream. Also, the fuel mixing of the eight multi jets is more than the case with equivalent four jets. Comparison of four and eight micro jets indicates that mixing factor of four micro jets approximately 27% higher that equivalent four micro jets. It is also found that mixing efficiency increases about 31 % as the jet pressure distance is increased from 4 Dj to 10 Dj.

Acknowledgement: This research is partially supported by NSFC (No. 51979261), Australia Research Council (No. DE190100931), and Fujian Province Natural Science Foundation (No. 2018J01506)

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