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Influence of upstream strut on hydrogen fuel distribution inside the supersonic combustion chamber

Yu Jiang

M Barzegar

M Sheikholeslami

Houman Babazadeh

Ahmad Shafee

See next page for additional authors

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Abstract

© 2020 Hydrogen Energy Publications LLC The efficient fuel mixing in the combustion tank enhances the overall performance of scramjet. Current attempt examines the existence of the strut on the fuel mixing of the multi hydrogen jets at supersonic flow. The numerical approach was employed to visualize the 3D flow behind the strut with multi fuel-jets. The free-stream Mach is 2.2, and four multi jets released hydrogen inside the combustor with the sonic condition. The impact of jet arrangements and the total pressure ratio on the mixing effect of the strut is fully described. Our results indicate that fuel mixing and penetration improved due to the formation of the large subsonic region behind the strut. According to achieved results, the increasing jet space from 1Dj to 5Dj raises the overall mixing to 15% in our proposed model.

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Authors

Yu Jiang, M Barzegar, M Sheikholeslami, Houman Babazadeh, Ahmad Shafee, R Moradi, and Zhixiong Li

Influence of upstream strut on hydrogen fuel distribution inside the supersonic combustion chamber

Yu Jiang [a], M. Barzegar Gerdroodbary [b], M. Sheikholeslami [b,c], Houman Babazadeh [1,d,e], Ahmad Shafee [f], R. Moradi [g], Zhixiong Li [h,i]

[a] *School of Mechatronics Engineering, China University of Mining and Technology, Xuzhou 211006, China*

[b] *Department of Mechanical Engineering, Babol Noshirvani University of Technology, Babol, Islamic Republic of Iran*

[c] *Renewable energy systems and nanofluid applications in heat transfer Laboratory, Babol Noshirvani University of Technology, Babol, Iran*

[d] *Department for Management of Science and Technology Development, Ton Duc Thang University, Ho Chi Minh City, Vietnam*

[e] *Faculty of Environment and Labour Safety, Ton Duc Thang University, Ho Chi Minh City, Vietnam*

[f] *Institute of Research and Development, Duy Tan University, Da Nang 550000, Vietnam*

[g] *Department of Chemical Engineering, School of Engineering & Applied Science, Khazar University, Baku, Azerbaijan*

[h] *MJU-BNUT Department-Joint Research Center on Renewable Energy and Sustainable Marine Platforms, Engineering Research Center of Fujian University for Marine Intelligent Ship Equipment, Minjiang University, Fuzhou 350108, China*

[i] *School of Mechanical, Materials, Mechatronic and Biomedical Engineering, University of Wollongong, NSW 2522, Australia*

Abstract

The efficient fuel mixing in the combustion tank enhances the overall performance of scramjet. Current attempt examines the existence of the strut on the fuel mixing of the multi hydrogen jets at supersonic flow. The numerical approach was employed to visualize the 3D flow behind the strut with multi fuel-jets. The free-stream Mach is 2.2, and four multi jets released hydrogen inside the combustor with the sonic condition. The impact of jet arrangements and the total pressure ratio on the mixing effect of the strut is fully described. Our results indicate that fuel mixing and penetration improved due to the formation of the large subsonic region behind the strut. According to achieved results, the increasing jet space from 1Dj to 5Dj raises the overall mixing to 15 % in our proposed model.

Keywords: Scramjet; Cross flow jet; CFD; Hydrogen mixing; supersonic flow

1. Introduction

The significance of efficient supersonic engines has augmented for high-speed flights. The scramjet is now the most effective approach for access supersonic flight [1, 2, and 3]. The main difference of this engine with previous models, i.e., ramjet is its supersonic condition in the combustion chamber. This characteristic allows the incoming air stream to preserve its speed, and pressure loss decreases considerably [4, 5].

[1] Corresponding author:
Email address: houman.babazadeh.tdtu@gmail.com (Houman Babazadeh)

The performance of this supersonic engine is directly associated with the fuel injection technique. Therefore, the injection of fuel highly developed in the scramjet engine, and numerous methods of injection are examined to achieve a well-organized technique [6, 7, and 8]. Several injection systems and methods have been introduced according to the operating condition of the scramjet engine and flight speed [9, 10]. Cavity flameholder, strut injection, step injection, ramp injection, porthole cross injection, and film injection are investigated to disclose the main practical terms and conditions for advance of the scramjet unit.

In the film injection system, the fuel jet is released parallel to the free stream while the fuel injection is perpendicular to the free stream direction in porthole injection [11, 12, and 13]. In the former technique, the fuel mixing zone remains close to the bottom while the height of fuel penetration in the cross-jet system is more because of the jet direction to the mainstream. Meanwhile, the jet interaction with the free stream is considerably higher in the cross jet while it also decreases the mainstream flow momentum due to interactions of fuel [14, 15]. The main issue for the crossflow jet is a low resident time of the fuel inside the combustor, as well as its complex interaction with free airflow. Although this method has some issues, it is more proficient than other techniques.

The application of the CFD method considerably helps scientists to develop this technique in diverse situations [16, 17, and 18]. In fact, the interface of the hydrogen jet with high Mach hardly discernible in the experimental schlieren technique and shock formation analysis is also required to study and discover the main characteristics of the fuel jet flow. The computational approach reveals more details on fuel penetration and distribution with low cost [19, 20]. Due to these advantages, most of the new idea is initially developed and examined via CFD method to reveal its effects and then, experimental examinations are conducted to ensure about the CFD results [21, 22].

The computational simulations of Pudsey et al. [23, 24] reveals significant results on the mixing performance of the multi cross-jets. Their comparison shows that the multi-jet fuel injection is superior to a single jet with equal fuel mass flow rate. The application of multi-jets for the mixing of the fuel was widely investigated in different fuel jet configurations such as cavity flameholder, strut, and backward step condition [25, 26, 27, and 28]. According to these studies, the fuel distribution and mixing zone are larger and homogeny. These records also indicate that the position and direction of the multi jets could significantly enhance the performance of this arrangement. Meanwhile, a combination of different techniques, i.e., shock generator and upstream sinusoidal surface also improves the mixing zone inside the combustor. It is also found that the strut technique enhances the mixing of the fuel jet via the preparation of the low-pressure subsonic region behind the strut.

Since multi-jet configuration offers an efficient mixing zone with a stable condition, the application of the strut in upstream of multi-jet arrangements could enlarge the mixing zone and fuel penetration inside the combustion chamber. According to this, Fig. 1 presents the configuration of the suggested model for the injection of the four multi-jets at supersonic flow. In this model, the strut is applied in the upstream of the multi-jets, and this induces compression shock, which deflects the free stream.

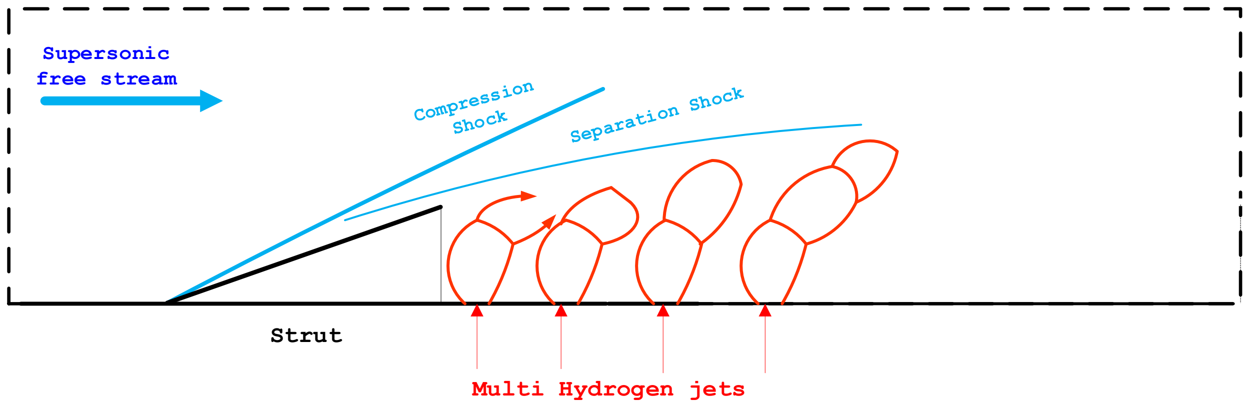

Fig. 1 Current suggested model for better mixing

As shown in Fig. 1, fuel jet expands in the downstream, and this permits the jet to scatter in the upward direction. In this exploration, computational simulations are done to unveil the existence of strut in left side of the multi fuel-jets at supersonic crossflow. In this configuration, the power of fuel jet pressure and jet space on the mixing efficiency of the fuel jet is fully investigated. The flow organization of the jet in the existence of the upstream strut is demonstrated via 3-D computational simulations. The mixing zone and fuel spreading are also described in these articles.

2. Main equations and Computational approach

The simulation of the supersonic compressible flow inside the combustion chamber was done in the previous research articles [29-36]. RANS equations have been selected for the modeling of the multi hydrogen jet at the supersonic air stream. The energy equation is also solved concurrently due to the existence of the shock in our selected model [37-42]. Since hydrogen gas is injected in crossflow air stream, the species transport equation is also considered for the second gas (hydrogen). Besides, the jet interaction results in the formation of the wake, and fluctuation of the velocity is not stable in our model; the SST approach was employed for the computational modelling of the suggested model. This model is used for the highly compressible flow with a sever velocity gradient, such as supersonic internal flow [43-51]. The 2^{nd} -order upwind technique was also employed for the discretization of the main governing equations.

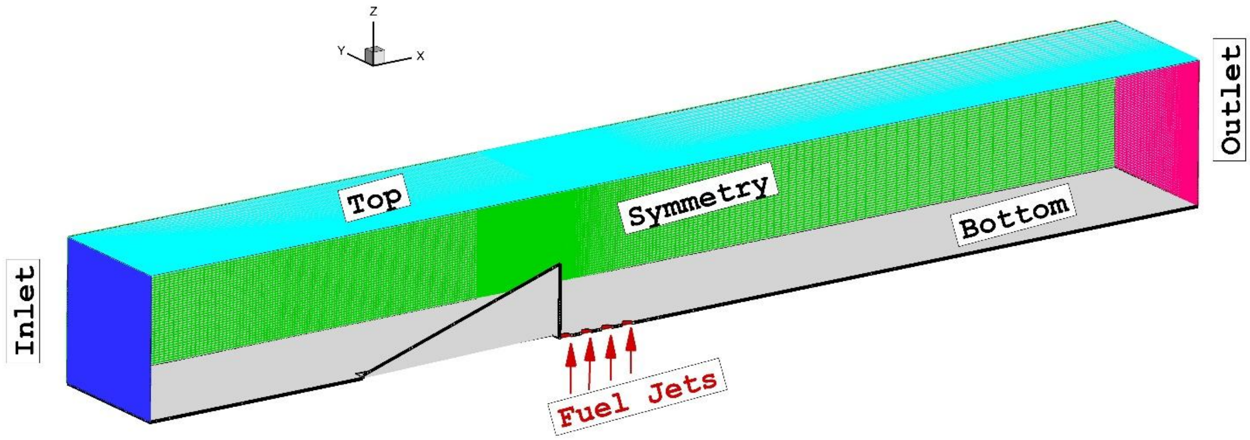

Fig. 2 Description of domain and boundaries

For the computational study of the selected model, the applied strut model by Freeborn et al. [52] are chosen for our computational investigations. As shown in Fig. 2, the supersonic air stream is applied with Ma=2 at the inlet, and the jet injector is located behind the strut. As demonstrated in this figure, 4 multi-jets with d=0.5 mm is chosen as an equivalent of a single jet with d=1mm. The height and length of the strut is defined to obtain the strut angle of 30^o. The pressure of the jets is determined as the ratio of the free stream total pressure. In current research, two total pressure ratios of PR=0.27 and PR=0.5 are investigated. Two gaps of the jets 1Dj and 5Dj are chosen for this research, where Dj is the diameter of the fuel injectors. The hydrogen is injected with sonic velocity through the nozzles. The symmetry condition is applied in both sides of the model since half of the domain is chosen for the reduction of the computational time.

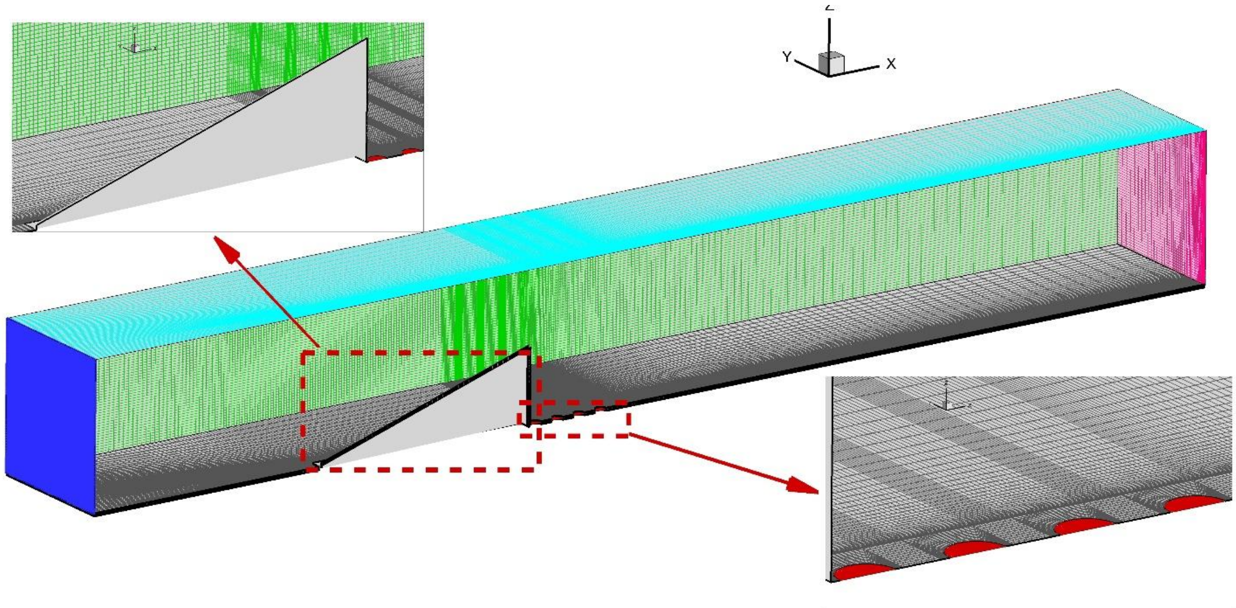

Fig. 3 Produced structure grid

The grid production for the selected model is also performed as the main step for the CFD modeling. As demonstrated in Fig 3, the high-quality hexahedral structured grid is produced for our selected model. For the grid production, the size of mesh is low at injectors since the velocity of the fuel is high, and the jet interactions with the free stream are substantial. In fact, the gradient of the pressure and velocity in the back of the strut is excessively high, and this requires a sufficient grid with a reasonable aspect ratio to evade any numerical errors and round off. Besides, four meshes are produced to approve the grid independence of the achieved outputs. Table 1 presents the average hydrogen mass fraction at the plane 40 mm downstream of the strut. It is found that increasing grid cells more than a fine grid with 3632000 cells does not change the value of hydrogen concentration in the selected plane downstream of multi-fuel jets.

Table 1. Grid independency

	Num. of cells	Average Hydrogen mass fraction
Coarse grid	1932000	0.214
Medium grid	2844000	0.223

Fine grid	3632000	0.228
Very fine grid	4222000	0.231

The free stream velocity and pressure are chosen as initial conditions for our computational investigations. The CFL number is 0.1 for the first iterations, and then it increases up to 1.5 when the residual of the velocity and pressure converge to low values. The convergence is obtained when the average hydrogen concentration becomes stable in at least two planes in downstream of the jet.

3. Results and Discussion

3.1. Testing the accuracy

Testing the accuracy of computational technique and achieved outputs is vital for numerical investigations. Therefore, the penetration rate of the single fuel jet is compared with other empirical data of Povinelli, Rogers, and McClinton [28, 29]. According to comparison, the deviation of our numerical fuel jet penetration is within the range of other experimental studies, and it confirms that our CFD method is reliable and usable.

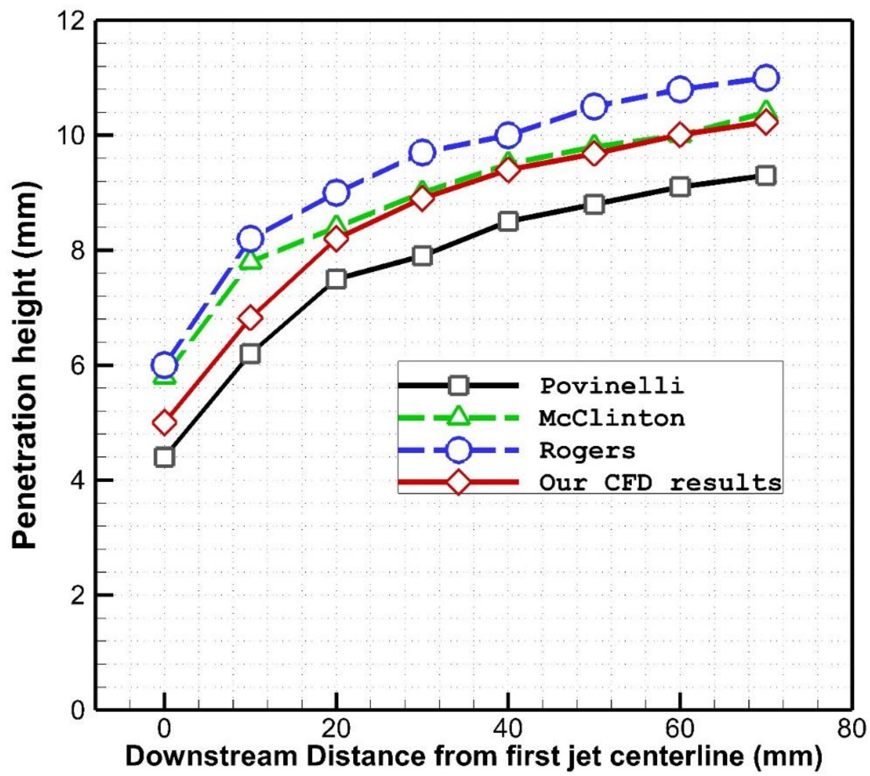

Fig. 4 Validations

3.2. Flow Analysis

Figure 5 demonstrates the 3-D flow style of the multi hydrogen jets in the existence of the upstream strut at $M_\infty>1$. The figure demonstrates fuel jet distribution and structures the two jet pressure ratio of 0.27 and 0.5. The 3-D contour clearly demonstrates that the jet moves upward in the back of strut until the edge of the strut. As the hydrogen jet encounters the free stream flow, the fuel jets turn downstream. In the low jet pressure of 0.27, the fuel jet directs downstream because PR is not high, and its interaction with the free stream is limited. As the jet pressure is increased to 0.5, the vortex feature within the jet augments, and this intensifies the jet interactions with the free stream in the top edge of the strut. Hence, the flow stream becomes swirl in this region, and the mixing zone expands efficiently in downstream.

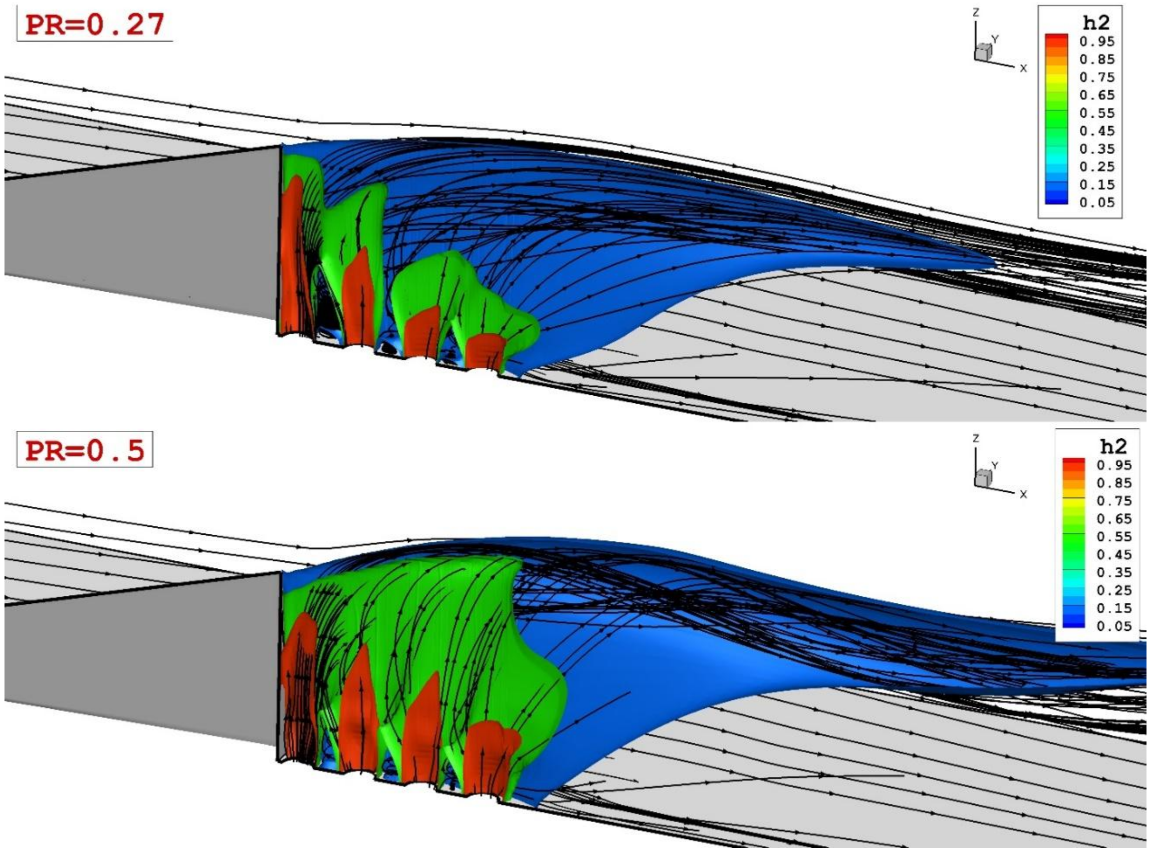

Fig. 5 Showing the difference of multi-fuel jet in the existence of the upstream strut in two jet pressure of 0.27 and 0.5

To notice the effects of strut, the contour of the multi-fuel jets without strut was demonstrated in Fig. 6. The comparison of the fuel jet at a jet pressure of PR=0.27 for model with/without strut confirms that jet height in the existence of the strut is highly more than conventional multi cross-jets, and mentioned characteristic would leads to high mixing rate in the downstream. The structure of the jet stream for strut model demonstrates that the power of the vortices augments in the gap of the jets and this increase the span wise distribution of the fuel jet.

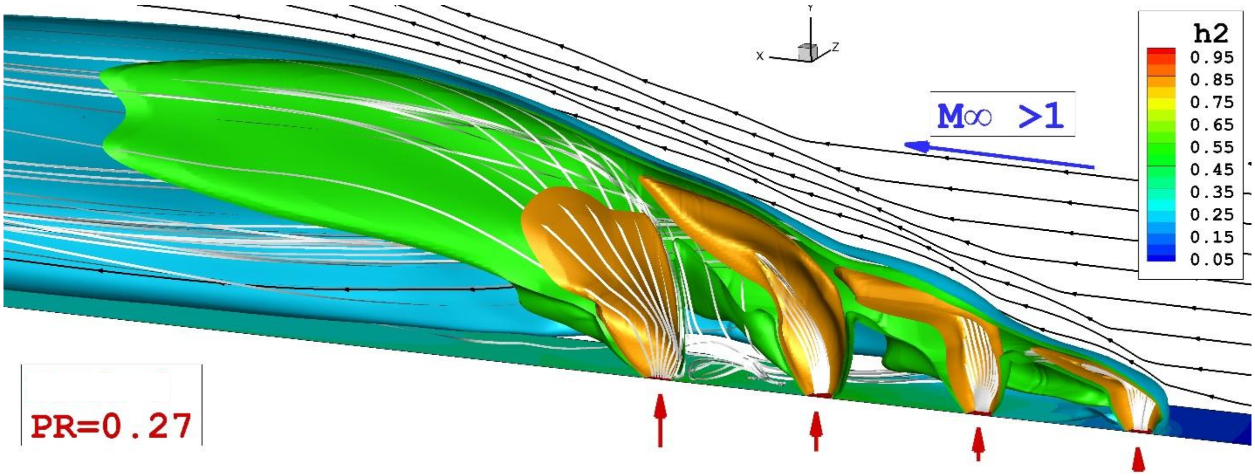

Fig. 6 Concentration of hydrogen when $M_{\infty}>1$

Fig. 7 compares the mixing zone on the jet plane for these two jet pressures ratios of 0.27 and 0.5. It is clear that mixing zone behind the strut does not change substantially. Indeed, the mixing region becomes more enriched due to the high mass fuel rate. It is found that fuel concentration increases behind the strut by elevation of the fuel jet total pressure.

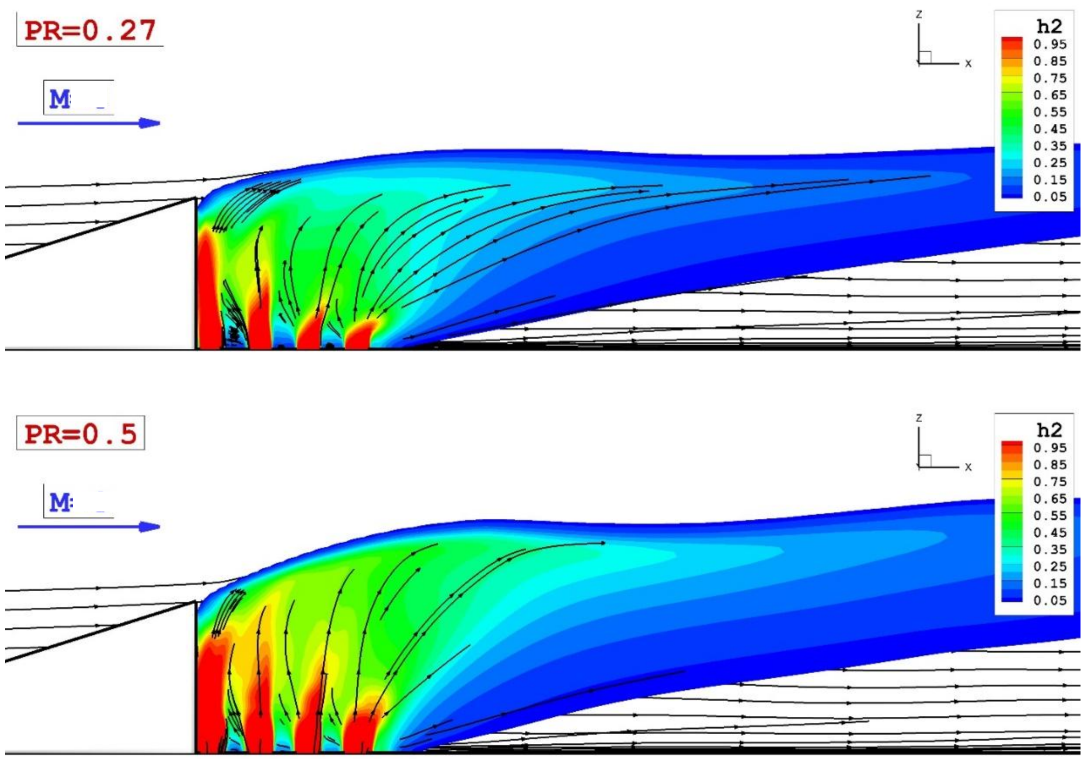

Fig. 7 Fuel mixing zone in the jet plane

3.3. Jet space effects

Since the jet spaces could enhance the mixing efficiency in our model, Fig. 8 depicted the Mach contour on the model with jet spaces of 1Dj and 5Dj. The streamline patterns are also demonstrated in this figure to compares the main difference between these two models. The results of Mach contour confirms that the subsonic region is produced in the space of the jets. As the jet spaces is increased to 5Dj, this subsonic region expands, and small vortices are generated in these spaces. Besides, strength of the vortices increases in high gap distance.

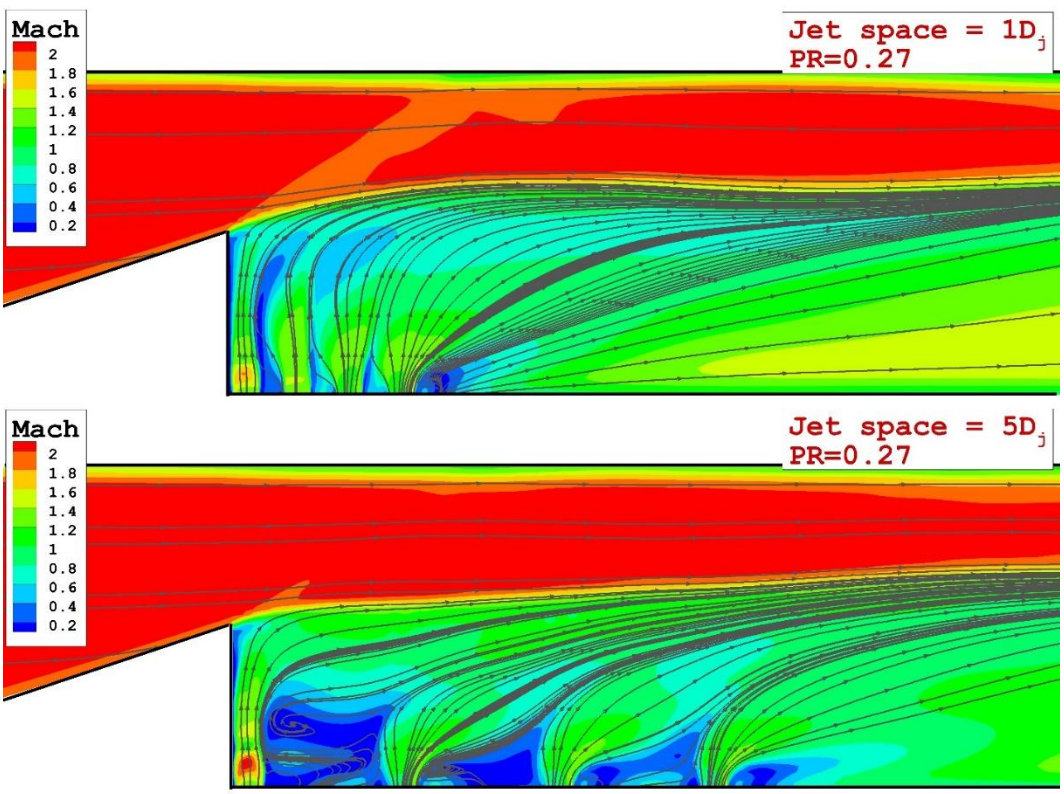

Fig. 8 effects of jet spaces on the Mach contour of multi-fuel jets

The temperature distribution on a jet plane for these two models is exhibited in Fig. 9. The achieved outputs indicate that the fuel jet expansion results in the reduction of the temperature through the region, while the temperature inside the gap is high due to the formation of vortices. Increasing the gap space enlarges the temperature region.

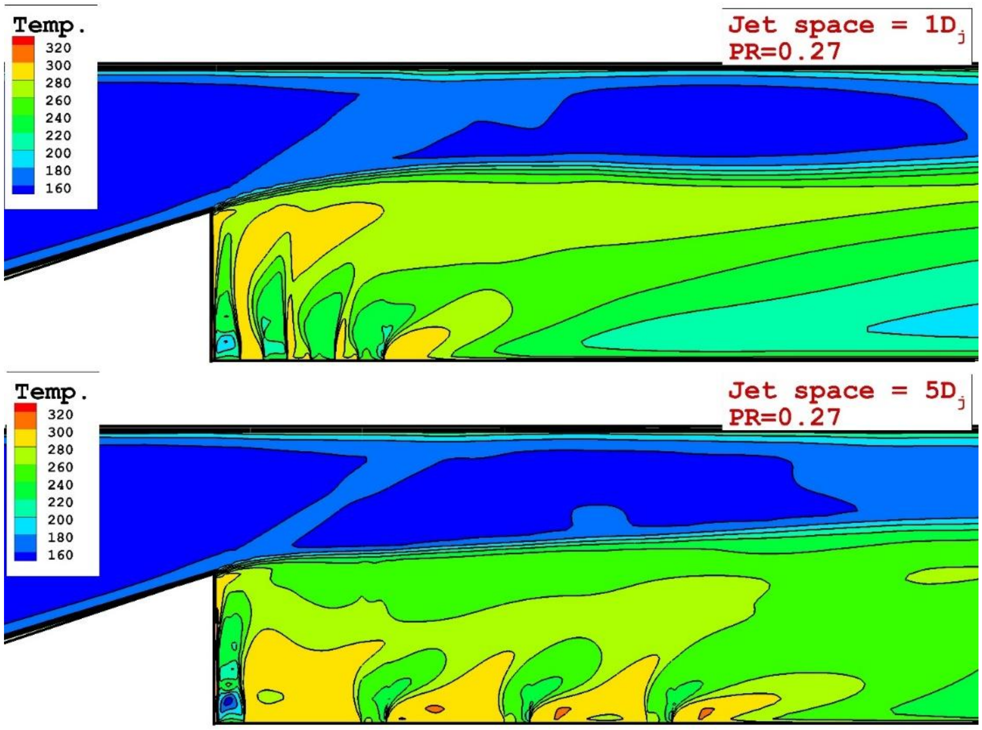

Fig. 9 Effects of jet spaces on the temperature distribution behind the strut

3.4. Mixing efficiency of multi-jet with strut

The primary goal for the usage of the strut in the upstream is to increase the mixing performance of the fuel jets within the tank. The formula for the calculation of the mixing was presented by Lee [53] and it is presented as follows:

$$\eta_{mix} = \iint Y_{H_2}^{r} \rho u \, dz dy \Big/ \iint Y_{H_2} \rho u \, dz dy \tag{1}$$

where

$$Y_{H_2}^{r} = \begin{cases} Y_{H_2}, Y_{H_2} \le Y_{H_2}^{st} \\ Y_{H_2}^{st} (\frac{1 - Y_{H_2}}{1 - Y_{H_2}^{st}}), Y_{H_2} > Y_{H_2}^{st} \end{cases} \tag{2}$$

with $Y_{H_2}^{st}$ introduced as the stoichiometric hydrogen fraction. The mixing performance of the model with two PR is illustrated in Fig. 10. It is proved that the mixing increases up to 50% in the initial jets while the mixing performance in the downstream is the same for a model with/without strut. Indeed, the main influence of the strut is in the vicinity of strut due to the formation of the wake behind the strut.

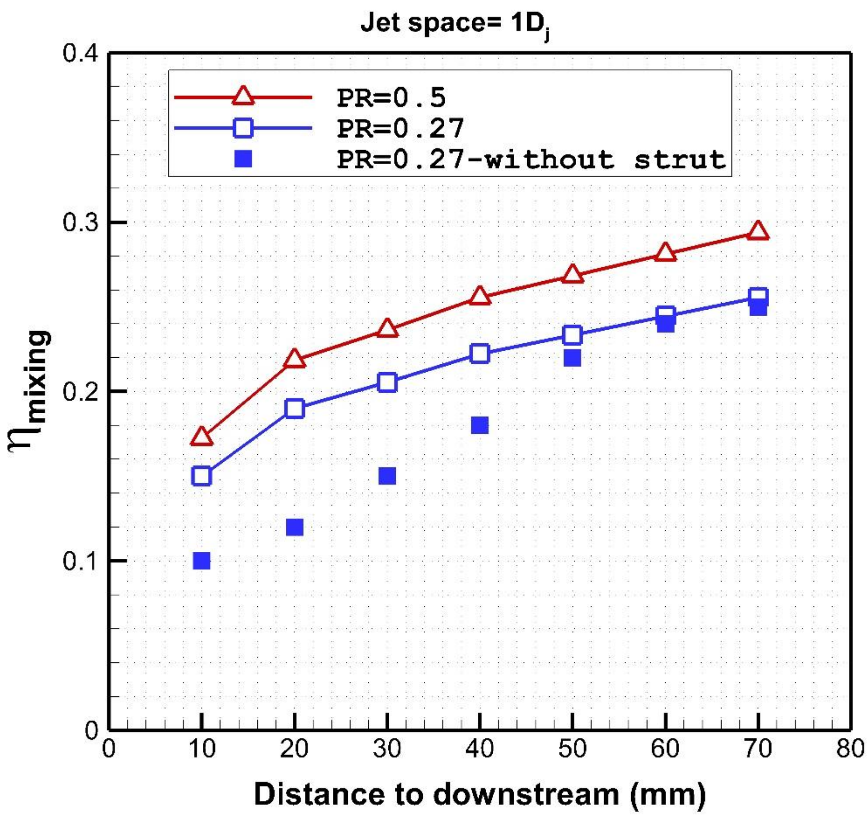

Fig. 10 Comparison of the fuel mixing in right side of jet

Fig. 11 depicts the mixing efficiency for the two-gap spaces of 1Dj and 5Dj at PR=0.27. The comparison of these two gaps demonstrates that augmenting the jet space declines the mixing performance in the arounf of the strut. However, the fuel mixing augments in the downstream due to the intensification of vortices within the gap. As shown in the figure, the mixing efficiency decreases up to 19% at 10 mm downstream of the first jet while mixing efficiency raises more than 22 % in the far distance (70 mm in downstream of the first fuel jet).

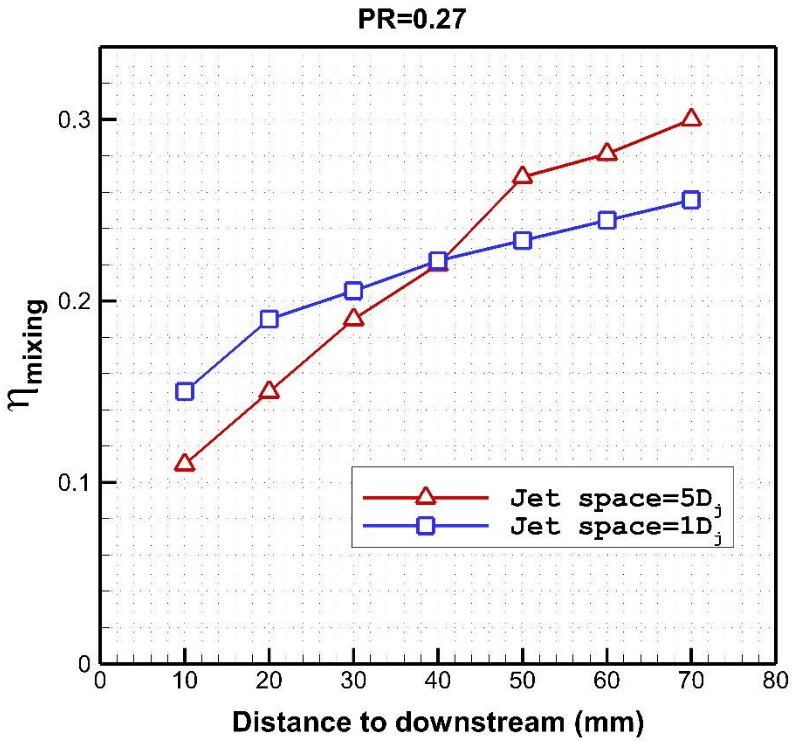

Fig. 11 Effects of jet spaces on fuel mixing in right side of multi jets with strut

4. Conclusion

Current paper presents the role of the strut on the upstream of the multi fuel-jets at the supersonic air stream. To do this, CFD tool was employed to simulate the hydrogen jet stream when free stream air with Mach=2 flows inside the domain. The influences of the jet pressure and jet space on the fuel diffusion in downstream are comprehensively investigated. Current article applied the CFD approach for the analysis of the jet feature in the existence of the upstream strut. The Mach contour and mixing zone are compared in the downstream of the multi jets. Our outputs indicated the following results:

- The presence of upstream strut enhances the normal diffusion of the fuel. In fact, the wake behind the strut allows the jets to penetrate in the upward direction.
- Jet pressure does not change the mixing zone since the most portion of the fuel could spread in an upward direction.
- The influence of the jet spaces reveals that the increasing jet space from 1Dj to 5Dj raises the overall mixing of the hydrogen jet to 15 % in our proposed model.

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