Numerical study of helium jet injection into channel with sudden expansion

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Abstract. In the paper, results of the numerical study on the cross-flow helium jet injection into a channel with backward facing step (BFS) are presented. The simulations are performed under the conditions of high-enthalpy flow, which are similar to those of high speed flight. 2D and 3D numerical investigations were performed with ANSYS FLUENT 14.0. The objectives of the investigation are to study the flow structure in both 2D and 3D approaches and to find optimal conditions for air and helium mixing.

Keywords: supersonic flow; injection; mixing; numerical simulation.

1 INTRODUCTION

Jets introduced into a crossflow are commonly utilized in various engineering applications including injection of gaseous or liquid fuels into a cross air flow in a combustion chambers. Study of the problem is extremely challenging for CFD tools, since the flow structure is very complex due to multiple shock waves, large recirculation zones and high flow non-homogeneity. However, numerical investigations allow to understand different aspects of the problem, namely, the effect of the pressure of injected gas on the flow structure and parameters behind a backward-facing step; control of mixture parameters in the channel; reduction of pressure losses; etc.

In the paper results of the numerical study on helium injection into supersonic flow in a channel with backward facing step (BFS) are presented. The simulations are performed under the conditions of high-enthalpy flow, which are similar to those of high speed flight. The objectives of the investigation are to study the 2D and 3D flow structure and to find conditions for better air and helium mixing.

2 METHOD OF COMPUTATIONS AND RESULTS

2D and 3D numerical investigations were performed with ANSYS FLUENT 14.0 [1] with a RANS based approach closed by k-ω/SST model. Validation of the model and numerical algorithm was provided in terms of experimental data (Zukoski and Spaid, [2]), presenting helium jet injected transversally into supersonic air flow (P_∞=6.8 kPa, M_∞ = 2.61) through 0.27 mm width slot in a flat plate at M_j=1 and static pressure P_j=151 kPa and 287 kPa. Good agreement between the experimental and numerical data has been obtained (Fedorova et al., [3]).

Next, the numerical investigation for the helium jet injected into the primary air flow in the plane channel with BFS was carried out. The problem was solved in 2D and 3D approaches at M_∞=2.8, P_∞=0.11 MPa and total temperature T_0=2000 K. At the walls, “Cold wall” temperature conditions were applied. Jet parameters: P_j=1.72, M_j=1 and total temperature T_0=293 K. The jet was injected through a slot of 2 mm width (2D) or from a hole of 2 mm diameter (3D) with its center located 25 mm before the BFS (Fig.1). For the 3D problem, a section of 35 mm width containing only one injection hole was computed.

At the inlet section, the turbulent flow parameters at Mach 2.8 were set accounting for boundary layer presence on the top and bottom walls. On the solid walls, the no-slip velocity conditions and temperature of T_W=300 K were assigned. In 3D statement, the symmetry conditions were prescribed on the side walls of the computational domain. The outlet sections conditions were of pressure-outlet type for the both geometries. The main flow and jet parameters are provided in Table 1.

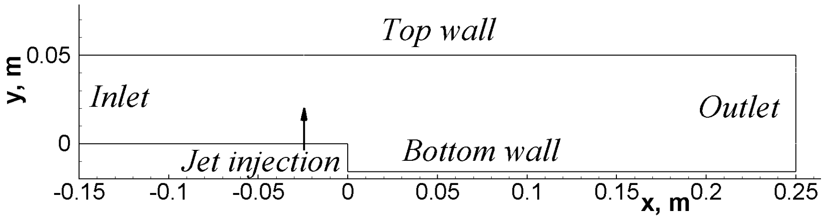

Figure 1: The 2D computational domains

Table 1: The main flow and jet parameters

Parameter	Channel flow	Jet flow
Mach number	2.8	1
Helium mass fraction	0	1
Static pressure, MPa	0.11	1.72
Total temperature, K	2000	293

In the 2D computations, relative dynamical pressure of the jet supply J = $(\rho U)_j/(\rho U)_0$ were equal to 2.35, 3.5 and 5 and the inclination angle of the jets varied from 30 ^{o} to 90^o. The influence of the injection angle on the flow structure is shown in Figure 2 for M_∞=2.8. The flowfield in the channel includes the separation zones S1 and S2, jet shock (JS), reflected shock (RS) and reattachment shock waves (RW, RW1, RW2). It was demonstrated that besides a substantial increase of jet penetration, growth of the jet axis slope results in the change of the channel flow parameters and the enhancement of mixing. It is necessary to pay attention to the large separation area appearance on the upper channel surface that can lead to the channel blockage owing to formation of the extensive separation area and normal shock wave ahead of BFS.

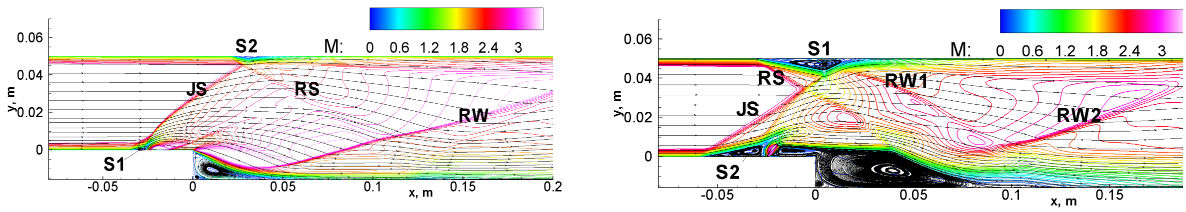

Figure 2: Mach contours and streamlines at different helium injection angles: left: α=30° and right α=60°

3D computations with normal injection were carried out under flow conditions similar to the 2D case. Analysis of the x shear stresses at the bottom wall (Fig. 3) showed that negative values corresponding to the boundary layer separation are observed in two small regions before and after the jet and also in the base region after the BFS. The shape of the reattachment line in the base region is not straight, and the size of the separation at the central line is smaller. In contrast to the 2D case, no helium appears in the recirculation zone after the BFS since the jet goes above the recirculation domain. In Fig. 4, the experimental findings were compared to the results obtained by numerical schemes of first and second order of accuracy within the 3D approach. Picture shows that the first order computations significantly underpredict the base pressure minimum and the maximum, associated with the jet shock reflected from the top wall. For the second order computations, satisfactory agreement of the numerical and experimental data on the pressure distribution was obtained.

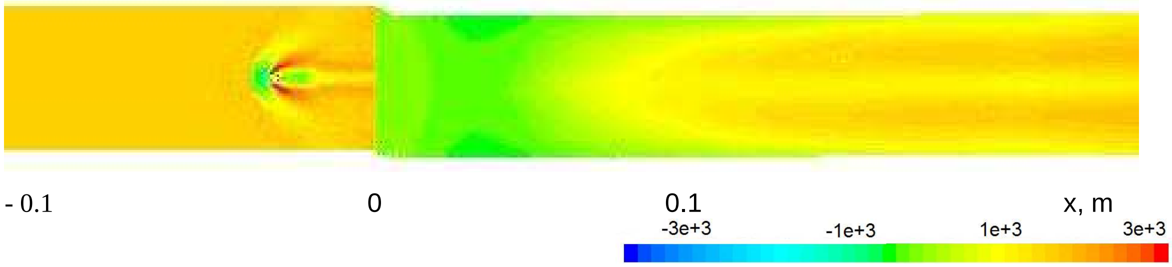

Figure 3: Shear stresses at the bottom wall of the model.

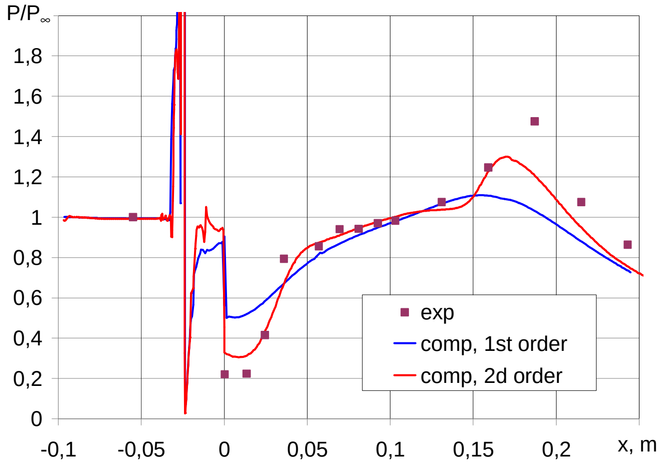

Figure 4: Experimental and computed pressure distributions along the central line on the bottom wall.

At next step, in order to improve the mixing of helium and air, oscillating sine-like static pressure conditions with frequences of about 3.3 and 6.6 kHz were applied at the jet injection position. Jet static pressure amplitude Pj was varying by 25 % of the mean value. Steady-state solution was used as initial condition. Figs. 5 and 6 show a consequence of the helium mass fraction fields and the velocity fields, respectively, for different iterations during the last sine period of the computation. The velocity fields clearly reveal the complex nature of the flow. On the lower wall upstream of the jet, there is a big separation zone causing a shock wave. On the opposite wall, this shock wave gives rise to another smaller separation zone which in turn results in a shock wave at the boundary layer reattachment point. This phenomenon can be observed several times in the flow field.

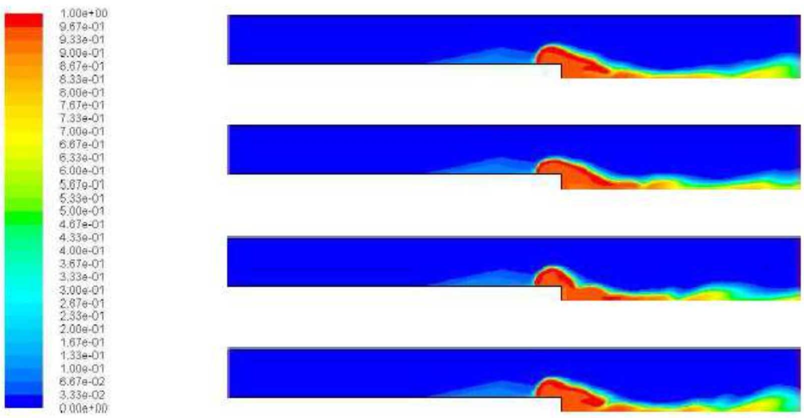

Figure 5: Mass fraction of Helium for 6666 Hz 25 % amplitude case at 1500, 1600, 1700 and 1800 iterations.

It is interesting to note, that there is only very little change in the upstream size of the jet separation zone, whereas the downstream influence of the unsteady boundary conditions can be seen clearly. Meantime, the jet penetration depth increases with the pressure increasing. Furthermore, the unsteady injection influences the helium distribution within the flow field in comparison to the steady state case. Helium is propagated farther away from the wall outside the boundary layer and in the recirculation area upstream of the step a better mixing occurs, though it should be kept in mind that this positive effect on mixing might only be relevant for the two dimensional case.

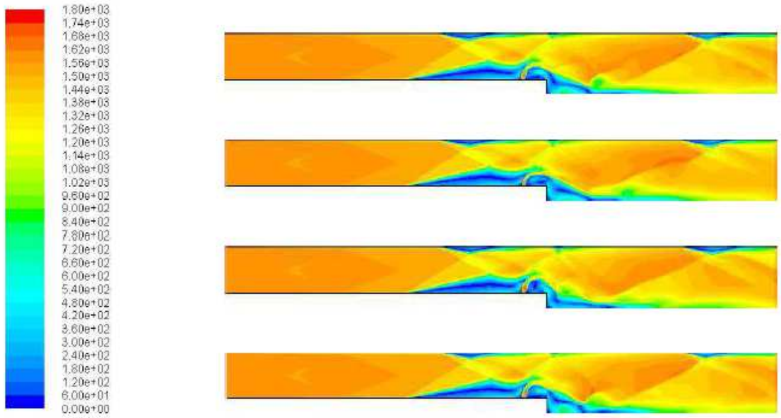

Figure 6: Velocity field for 6666 Hz 25 % amplitude case at 1500, 1600, 1700 and 1800 iterations, 0 - 1800 m/s.

Future work will include the implementation of pulsating jet pressure conditions to the 3D problem.

3 CONCLUSIONS

- 2D and 3D computational analysis has been performed for the problem of Helium jet injection into the supersonic (M_∞=2.8) airstream in a channel with sudden expansion;
- A detailed flow structure is obtained and analyzed for the 2D case. It is shown that the jet injection angle increase leads to higher jet penetration depth and mixing improvement between the main and jet flows, but, on the other hand, to greater total pressure losses;
- The strong influence of the approximation order of the computational method is shown. The lower order approximation schemes underpredict the size of the separation zones and overpredict the base pressure level;
- Results of 3D computations are compared to the experimental data on pressure distributions along the center line on the bottom wall. Satisfactory agreement of the numerical and experimental data is attained;
- Significant 3D effects are revealed in the computations for the case of the round jet hole. The main difference with the 2D case is the lower intensity of the interaction of the primary (air) and secondary flows due to the primary flow spreading around the jet;
- Applying the oscillating sine-like static pressure conditions for the jet injection can provide better mixing in the flow;
- Computational results are intended for clearer understanding of the mixing processes taking place in combustion chambers of scramjets.

ACKNOWLEDGEMENTS

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