NUMERICAL FLOW VISUALISATION OF SIDE JET/CROSS FLOW INTERACTION

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ABSTRACT: The "lateral side jet technology" is commonly used for flight control of satellites and re-entry vehicles. Nowadays, it is applied to maneuver high-speed missiles flying in earth atmosphere. The flow field in the vicinity of such a lateral jet blown out into a supersonic cross-flow is extremely complex and up to now it has been very difficult to accurately predict the aerodynamic interaction phenomena, especially the total forces resulting from the jet thrust. Experimental and numerical investigations have been performed in the past by many researchers, who mainly have been interested in integrating the surface pressure to quantify the efficacy of the reaction control jet which is characterized using the force amplification factor K. Moreover, the present study is focussed on the analysis of the aerodynamic interaction processes running off in the side jet/cross flow interference region on a generic missile body. The region of observation is numerically simulated using the TAU-Code obtainable from the DLR, the German Aerospace Center, for solving the conservation equations of mass, of momentum by Reynolds-averaged Navier-Stokes equations and of energy. The Mach numbers investigated are M = 2.8 / 6 / 11.5 / 17.5 and atmospheric altitudes of H = 0 / 39 / 49 / 60 km. Real gas effects at high temperatures are as well considered. The simulations predict and visualize complex details of the side jet/cross flow interference and the aerodynamic mechanisms present in the interaction zone. They show how the side jet influences the cross flow like an obstacle producing a bow shock in front, an upstream facing over pressured recirculation and in the wake downstream an under pressured zone with horseshoe vortex separation.

1 Introduction

The present work describes the interaction between a lateral jet and the cross flow around a missile, designed for supersonic and hypersonic flight configurations. The numerical calculations are performed using the numerical finite-volume-method TAU [1] developed at the German Aerospace Center (DLR) in Germany. The aerodynamic interaction processes running off in the side jet/cross flow interference region are marked in Fig. 1 by a circle and are shown by streamline visualization on a generic missile body as well as by Mach number distribution in pseudo colours. The side jet is blown out from a nozzle, in Fig. 1 for example to the upper side in Mach number 2.8 cross flow, and interacts with the supersonic on flow which results in a lateral acting force.

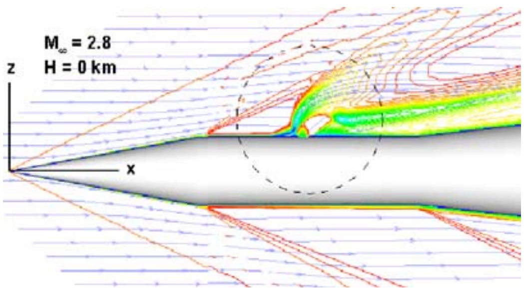

Fig. 1 Side jet/cross flow interaction

The side jet technology is mainly used for steering rockets as well as re-entry vehicles in the upper atmosphere. Recently, this technique is also used for the control of missiles, which fly in the lower atmosphere. Many publications are available since decades on the interaction phenomenon which is a very complex and non-linear fluid dynamics problem as described for example in the articles [2-9]. The main question to answer is concerned with the efficiency for vehicle steering especially to perform rapid maneuvers. A measure for the quality of a side jet steering tool is found in the amplification factor K which is therefore always on top of the investigations. But beyond, the current contribution is more interested to show the fluid mechanical mechanisms running off in the interaction zone by numerical visualizations to gain qualitative visual information on the flow field formation. But nevertheless quantitative results on the amplification factor K are also included in this study.

At high missile flight velocities in the lower atmosphere, the interaction between such a lateral jet and a super- or hypersonic cross flow leads to a bow shock in front of the side jet and a wake behind with imbedded vortices. This phenomenon was already discovered and investigated more than 40 years ago [2]. Measurements on the amplification factor, which is the ratio of the total normal force divided by the jet thrust, are given for example for a generic axial symmetric missile by Brandeis and Gill [3].

2 Side jet/ cross flow interaction problem

2.1 Jet topology

The jet interaction flow field is shown in principle in Fig. 2 for a supersonic cross flow with the separation shock in front of the bow wave and the wake region downstream. Considerable pressure forces are generated by the jet/cross-flow interaction due to shock wave/boundary layer interaction and boundary layer separation. The forces are set-up by: F_j (jet thrust), F_{i+} (over pressure in the separation zone upstream) and F_{i-} (under pressure in the wake downstream) forming the force amplification factor K as follows:

$$\frac{(F_{i+} - F_{i-}) + F_j}{F_j} = K \, .$$

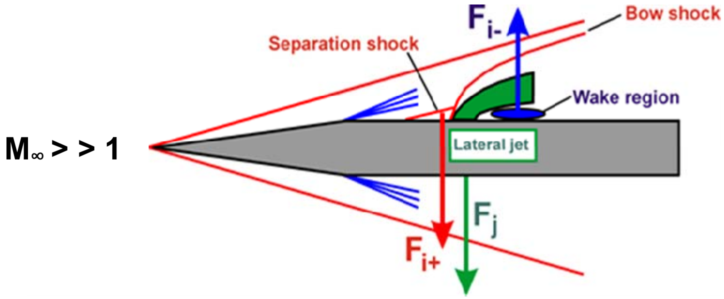

Fig. 2 Schematic design of the side jet/cross flow interaction

2.2 Numerical dimensions

Emphasis of the numerical study herein is put on the correct turbulence modeling with different turbulence models applied and variations mesh geometries with which accurate results may be produced for optimal numerical flow modeling. Extensive parameter variations gave predictions on the fluid dynamic interference including the efficiency of the side jet in super- and hypersonic flows at various atmospheric altitude conditions, concerning air pressure, air density and ambient temperature. A particular interest was directed to illuminate high temperature effects in hypersonic flows, as for example excitation of internal degrees of freedom and energy relaxation effects. For the flight parameters tested, by pressure integration around the missile surface, finally the efficacy of the side jet is characterized to achieve quantitative data on the amplification factor K.

Flow field visualizations and force information are necessary to clarify the interaction flow field formed on the concerned generic missile geometry by the blown out side jet interacting with the incoming cross flow. For that reason by means of CFD-calculations the effects induced by the control jet are visually highlighted and precise data for the lateral side jet thruster interaction at super- and hypersonic flight conditions are given. The numerical solutions are checked and validated by means of wind tunnel data obtained at DLR wind tunnels, see Adeli [10].

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This study reports on a parameter variation concerning the flight Mach number M and the flight altitude H as well as the jets pressure ratio p_{0j}/p_∞ given by the jets stagnation pressure p_{0j} divided by the on flow pressure p_∞. The investigations have been performed at the following flight conditions for Mach numbers and altitudes:

- flight Mach numbers M = 2.8 / 6 / 11.5 / 17.5,
- atmospheric altitudes H = 0 / 39 / 49 / 60 km,
- zero angle of attack.

The numerical flow solver TAU, is based on the

- conservation equations with friction and heat conduction,
- mmodelling of the viscosity and of heat conductivity,
- discretization schemes for space and time,
- turbulence modelling.

Several grid configurations have been tested as listed in Tab. 1 with the grids used, the number of knots and the number of prismatic cells normal to the wall. Fig. 3 visualizes the grid designs and arrangements for the grids A, B, C and D.

Grid (conical nose)	**number of knots N**	**Number of prismatic cells normal to the wall**
A: coarse	543062	16
B: fine	714910	16
C: fine adapted	758844	16
D: superfine	2589107	16

Tab. 1: Grids generated

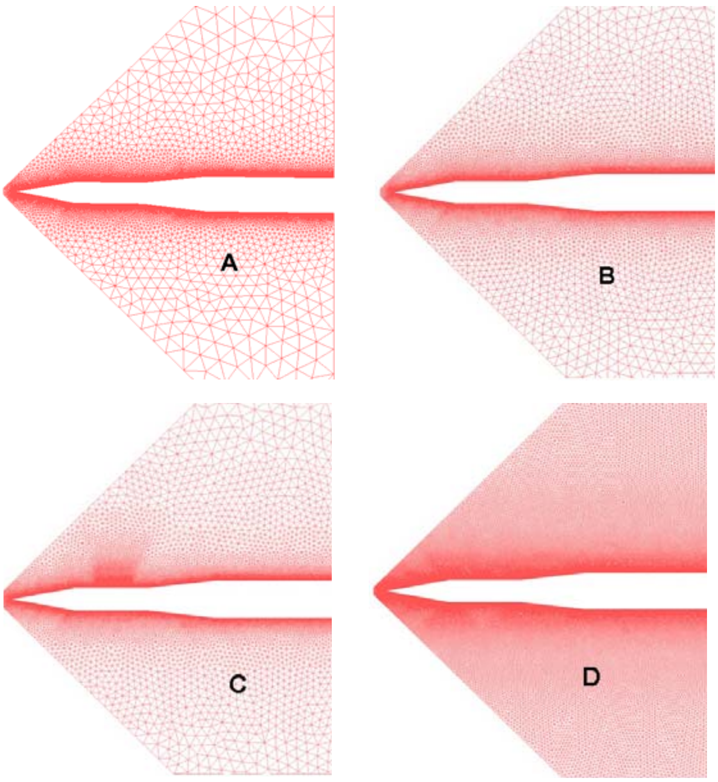

Fig. 3 Visual view of grids generated

3 Numerical results

3.1 Grid adaption

The procedure of grid refinement and grid adaptation resulted in the outcomes shown in Fig. 4 with the variation of the force amplification factor K versus 1/N and the flight data included in Fig. 4 for M = 2.8. The K-factor increases with grid enhancement, i.e. increasing number of knots N and becomes practically constant for grid C and D. This K-behaviour shows the range of grid appliance for having reasonable and precise numerical results available. Mesh A delivers K ≅ 0.2, mesh B calculates K ≅ 0.29 and mesh C as well as D give K ≅ 0.35 which is practically the K-value for N → ∞.

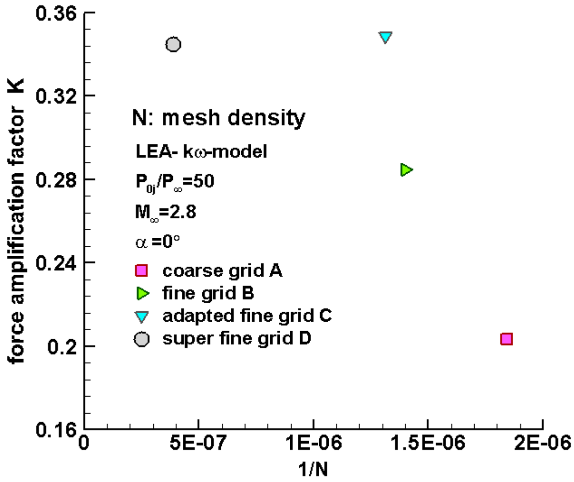

Fig. 4 Verification by mesh refinement

3.2 Side jet/cross flow interaction visualizations

In Fig. 5 the visualization with streamlines depicts together with the pressure distribution (c_p-coefficient) in Fig. 6 along the jet's centerline very clearly the flow field formation. The side jet acts as an obstacle and initiate in supersonic cross flow a bow shock surrounding the jet's out blowing gas. In front of the bow wave the pressure increase in the recirculation zone and in the rear a depression is present. The numbering (1-11) correlates the pressure distribution in Fig. 6 to the locations on the missile body in Fig. 5.

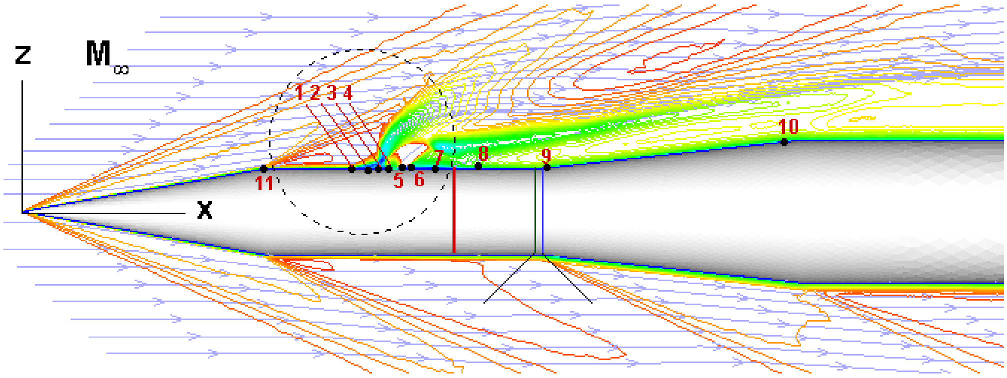

Fig. 5 Streamlines around the generic missile

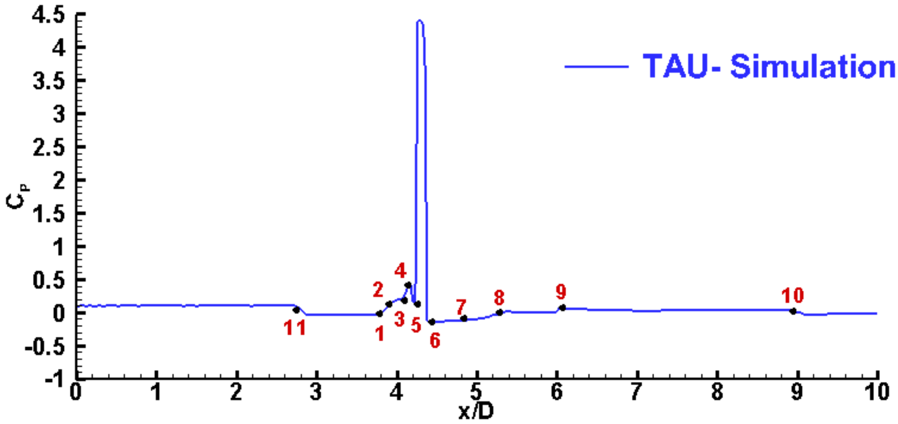

Fig. 6 Pressure distribution along the jets centreline (D = missile body diameter)

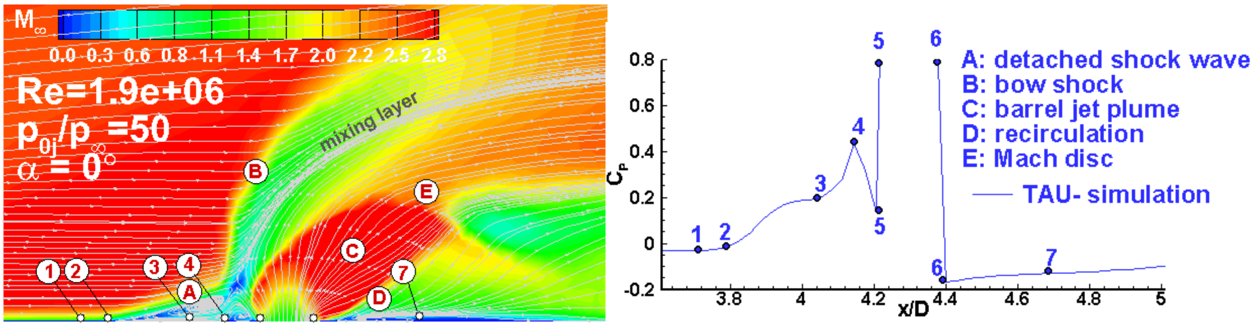

Fig. 7 Enlarged interaction region: jet interference topology (left) and pressure distribution (right)

An enlarged view of the jet interaction region is given in Fig. 7, visualized with the Mach number pattern and the distribution of the c_p-coefficient. The numbering (1-7), same locations as in Figs. 5 and 6, and the characters (A-E) mark in detail the flow field formation with: (A): detached shock wave, (B): bow shock, (C): barrel shock plume, (D): recirculation region and (E): Mach disc.

Mach number distributions are visualized in Fig. 8 up to Mach number 17.5 including real gas effects at high temperatures. They obviously show at 0° attack angle that the jet interference strongly depends on the cross flow Mach number. The aerodynamic mechanisms present in the interaction zone are numerically visualized and the simulations illustrate clearly the complex details of the side jet/cross flow interaction. They show how the side jet influences the cross flow like an obstacle producing a bow shock in front, an upstream facing over pressured recirculation zone and in the wake downstream an under pressured zone with horseshoe vortex separation which is obviously visualized in Fig. 11.

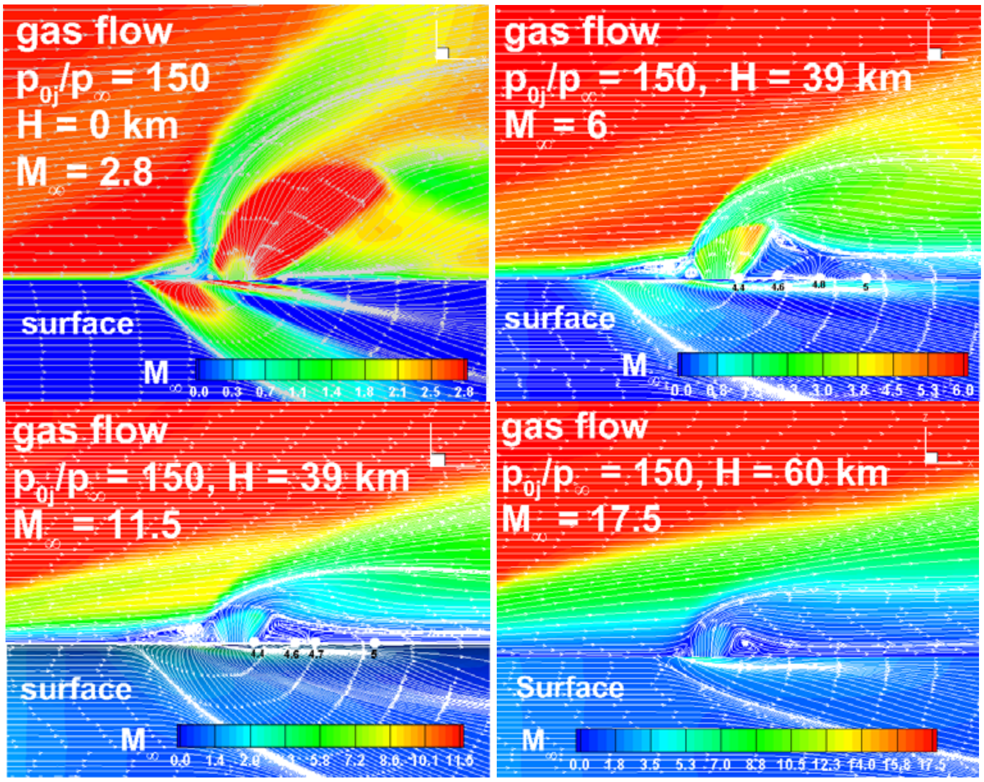

Fig. 8 Visualization of the aerodynamic interaction of a lateral jet with a supersonic cross flow

The numerical visualizations in Fig. 8 are calculated for Mach numbers 2.8 / 6 / 11.5 and 17.5. Real gas effects were taken into account for Mach numbers 11.5 and 17.5. The jet ratio is for the four cases: p_{0j}/p_∞ = 150. Rising Mach number means that the missile flies more and more at higher altitudes at lessening atmospheric pressure. The observation of the pictures in Fig. 8 shall lead to the conclusion that at low Mach number the jet extends a considerable distance into the outer flow with a steep bow shock in front. This extension decreases rapidly with increasing Mach number and the bow shock becomes more and more inclined towards the missile body.

In Figs. 9 and 10 the force amplification factor K is depicted versus the flight Mach number M and flight altitude H. It is obviously shown that with increasing Mach number at high altitudes the factor K rise powerful and the side jet steering technology becomes essential in this flight domain where rudders and flaps lose more and more their effectiveness.

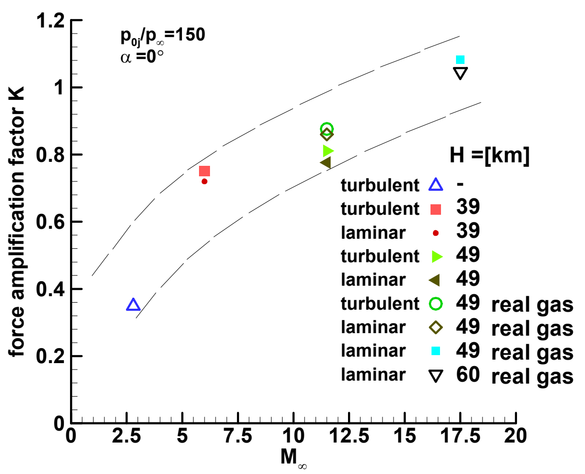

Fig. 9 Force amplification factor K vs. Mach number

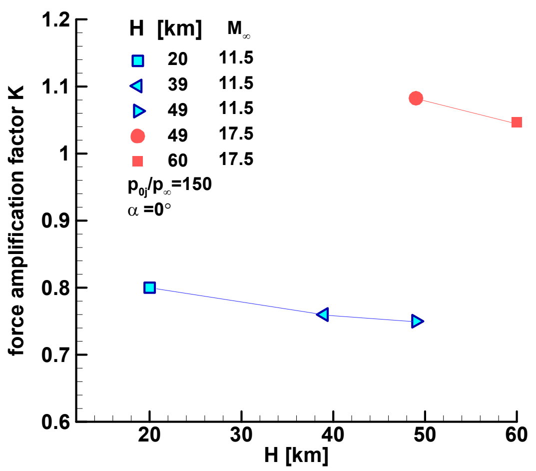

Fig. 10 Force amplification factor K vs. altitude

The vortex separation in the jet's wake is seen in Fig. 11 at four cross sections downstream for p_{0j}/p_∞ = 50. It is apparent that two big counter rotating vortices are formed. They become visible as horseshoe vortices which laterally grow during their downstream motion. The vortices wrap around the body and make the jet's influenced region very extended.

Besides the big wake vortices shown in Fig. 11 a second separation is formed in the wake of the jet nearby the missile surface. The marker D in Fig. 7 denotes that zone directly on the surface where a backflow prevails. Downstream in the region where the separated gases lie on again a weak horseshoe vortex street is formed underneath the wake vortices as obviously shown in Fig. 11. These weak vortices having only marginal strength are also seen in Fig. 11 near the missile surface. With increasing x/D these vortices broaden by side and finally vanish downstream. In Fig. 12 the vortex formation is shown at two pressure ratios p_{0j}/p_∞ = 50 and 100. The wake vortices as well as the vortices near the surface are able to be seen. The higher pressure ratio makes the wake vortices begin more downstream and they have laterally a larger extend.

4 Conclusion

This work analyzes the interaction between a lateral jet and a supersonic as well as a hypersonic inflow using the TAU-code of DLR in Germany. The TAU-solution was adapted by mesh refinement and turbulence modelling. Parameters of the aerodynamic interference study are: cross flow Mach number M = 2.8 / 6 / 11.5 / 17.5, atmospheric altitude H = 0 / 39 / 49 / 60 km and jet pressure ratio p_{0j}/p_∞ = 50 / 100 / 150. The numerical results give an increase in basic knowledge about the plume-inflow interactions focused on future requirements by qualitative visual information on the flow field formation and quantitative information on the force amplification factor K. Important numerical outcomes are:

- the lateral extend of the jet influenced zone depends strongly on the flow Mach number M,
- increasing Mach numbers diminish the lateral extension, see Fig. 8 and streamline visualizations in Fig. 13,

- a big horseshoe vortex street is induced by the jet obstacle moving downstream,
- a rising Mach number induces the force amplification factor K to rise as well,
- the jet pressure ratio plays a minor role with respect to K,
- the angle of attack also plays an important role influencing K, but is not discussed herein, details Adeli [10].

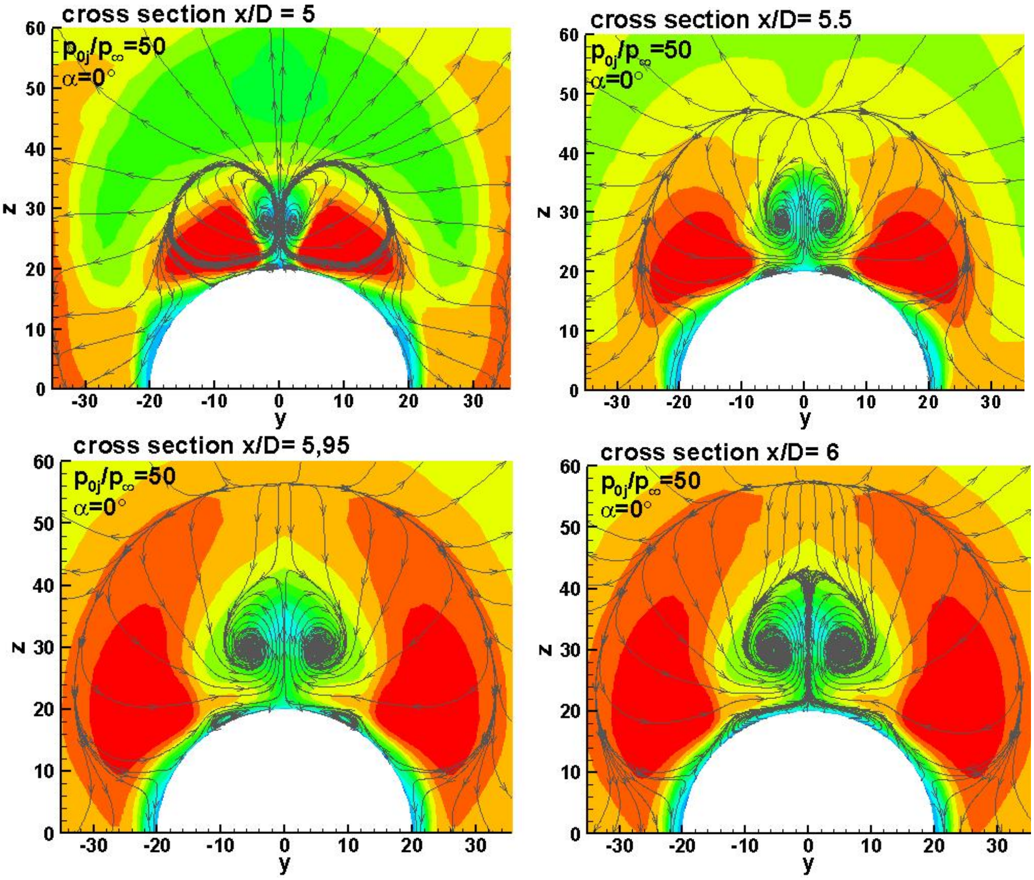

Fig. 11 Wake vortices

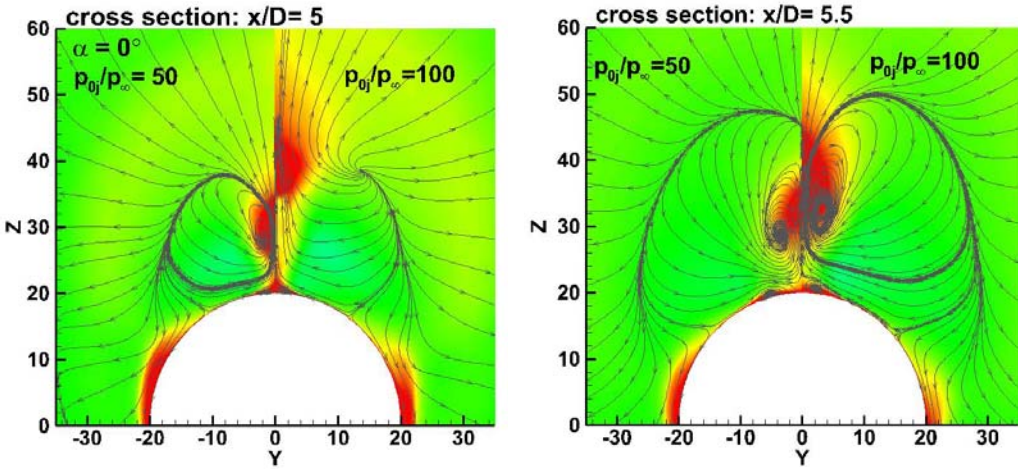

Fig. 12 Wake vortices for two jet pressure ratios p_{0j}/p_∞

Finally streamlines imagine visibly in Fig. 13 the flow motion around the generic missile applied at flight Mach numbers 2.8 and 17.5. Obviously at the low Mach number the jet obstacle is wider extended into the cross flow as compared to the higher Mach number: This outcome can also be observed on the Mach numbers distributions presented in Fig. 8.

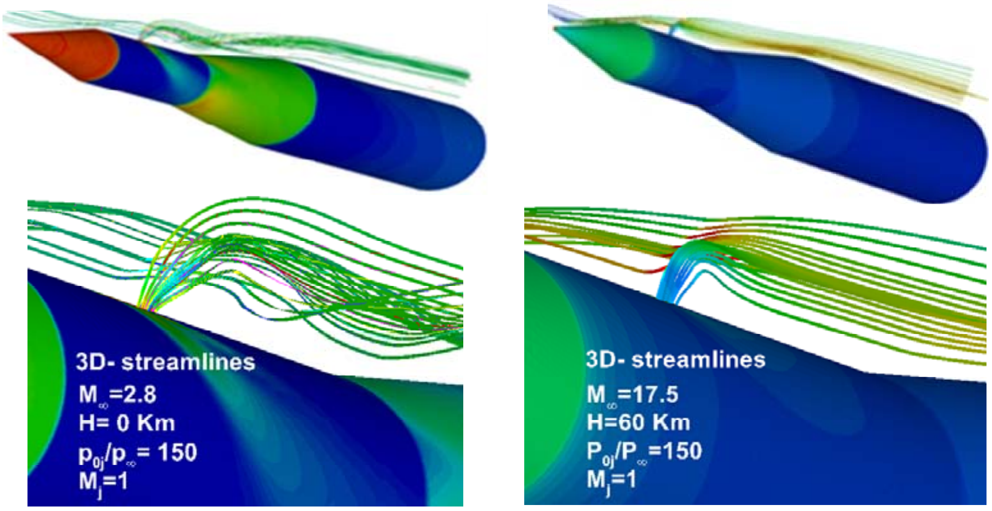

Fig. 13 Streamline side jet visualizations: left M = 2.8, right M = 17.5

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