Experimental and Numerical Research of the Influence of Thrust Vector Control on the Missile Aerodynamics by Cold and Hot Jet Simulations

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The flow field phenomena that occur as a result of thrust vector control (TVC) system activity on a missile with lateral jets are very complex and influence all other components of the missile. Influence is more significant when TVC is generating commands, when jets are asymmetrically directed. The main goal of these study was to determine the influence of of the hot rocket motor's combustion products on the basis of the CFD model proven with the cold-jet simulation. Based on obtained experimental aerodynamic coefficients for the cold-jet simulatiom the preliminary aerodynamic CFD model was designed. Three-dimensional Reynolds averaged Navier–Stokes numerical aerodynamic and hot-jet simulations were carried out to predict the aerodynamic loads of the missile based on the finite volume method. The study resulted in the definition of a methodology for the investigation of the jet reaction effects in a wind tunnel. A method for determining of the TVC system interference on the aerodynamic characteristics, as a basic prerequisite for structural, stability and performance analysis, was proposed. Mutual verification and validation process was carried out through experiment and proper application of the commercial CFD software code for calculation aerodynamic effects of the hot gaseos lateral jets on the performance of a guided missile.
Experimental and computational results of the pitching moment coefficients are presented and agreed well with.

Keywords: *wind tunnel, experimental aerodynamics, missile model, TVC, jet tab, hot-gas jet, cold-air jet, lateral jets, CFD.*

1. INTRODUCTION

Aerodynamic control, using canard or fin surfaces has several limitations, in response time due to the delay between the steering command and the effective manoeuvre, but also in manoeuvrability when the dynamic pressure is low, i.e. at low velocity or high altitude [1],[2]. To ensure the required missile performance, modern air defence interceptors use lateral thrusters, especially at difficult targets or unusual conditions of use, even if this type of control leads to complex aerodynamic interactions, which are not easily foreseeable [3],[4]. In the case of a subsonic missile, when the jet thruster is switched on, the hot gases blow out of the thruster and cause an interference with the cross-flow around the missile. The resulting jet plume is deflected and acts as a massive obstacle located on the surface of the missile producing a complex flow developed by the interaction of the laterally blowing gas jet with the subsonic cross-flow, Figure 1., [5].

The effects of TVC on the aerodynamics of a missile model were investigated experimentally in a wind tunnel and numerically by using commercial Computational Fluid Dynamics (CFD) software. Research and characterization of the flow field was experimentally performed in tests of a guided missile model in a subsonic wind tunnel.

Figure 1. Missile with thrust vector control by tabs

The objectives of the study were to fully analyze the effects of cold jet TVC system on the basis of the results of wind tunnel tests and CFD simulations, to complement the knowledge base about the influence of the supersonic lateral jet and subsonic crossflow, and to define the most appropriate similarity parameters for subsequent simulation of hot combustion products [5]. Wind tunnel testing with cold jets sustainer simulation was performed for the determination of aerodynamics characteristics. Also it was used for verification of the CFD model. Finally, with proven CFD model the influence of the hot rocket motor's combustion product lateral jets was determined.

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As the results of the experiment, the jet normal force amplification factor K_N and the interaction moment center XC_{Pi} are reported and their definitions are given.

2. TEST FACILITY

The T-35 subsonic wind tunnel of Military Technical Institute, Belgrade (VTI), Figure 2. is a continuous flow, closed/circuit facility powered by 7.2 MW AC motor driving (Figure 3.) a 23 variable pitch blade fan (Figure 4.) which has a test section 4.4 x 3.2 m and is capable of operation at a Mach number range of $0.1<M<0.5$ at atmospheric pressure [6],[7].

Figure 2. The T-35 wind-tunnel CAD/CAM model

The test section has octagonal cross-section which cross-section area is 11.93 m^2. The length of the test section is 5.5 m. At the maximum operation condition the tunnel is capable of obtaining a unit Reynolds number 12 millions/m [8].

Figure 3. The T-35 wind-tunnel power

Figure 4. The T-35 wind-tunnel fan

The wind tunnel T-35 is operational since 1964 and upgraded 1989. It is a closed circuit, pressurized, continuous wind tunnel Cross-section shape is variable due to section position: The octagonal (exiting part of the collector, test section, small diffuser and 'half' of downstream corners); The elliptical (exiting part of large diffuser, upstream corners and entry part of the collector); and The circular (exiting part of downstream corners, entering part of large diffuser that caries propeller). The length of the tunnel circuit is 72m and width is 30.6m (viewing from top). The test section is closed and it is placed in the laboratory building.Wind tunnel construction is made of metal. Test section and downstream corners are moveable.

3. WIND TUNNEL MODEL

The test object was an actual missile modified for use as a wind tunnel model, Figure 5. and 6. Simulation of the missile engine was performed with a high-pressure cold-air pneumatic installation, Figure 7.[8].

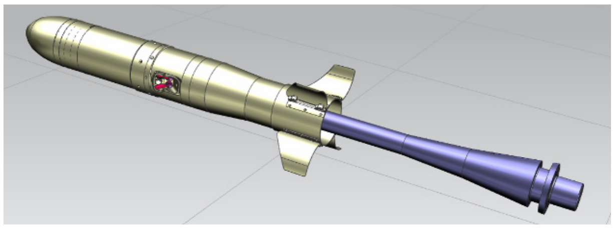


Figure 5. CAD/CAM missile model

The missile model was made in scale 1:1 from aluminium alloy and steel. Diameter of the model is 136 mm.

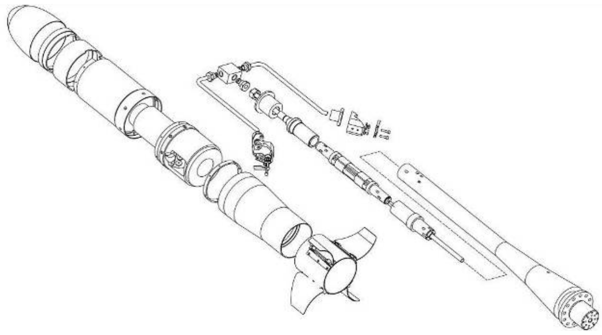


Figure 6. CAD/CAM model of the missile, assembling

The model was fixed to the mechanism for changing the angle of attack of the model through rear tail sting.

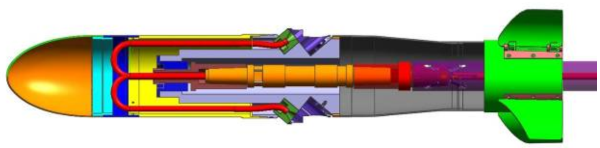


Figure 7. CAD/CAM model with jet simulation installation

The missile model has internal space of adequate size for setting up five-component wind tunnel balance *VTI385*, with diameter of 38mm and housing of the jet installation, Figure 8. [8].

Figure 8. Adaptor for the jet installation housing

4. EXPERIMENTAL SET-UP

4.1 The high pressure cold-air supply

Simulation of the cold-air jet was performed with the high pressure installation where the high pressurized air was used instead of the combustion products, Figure 9. [11].

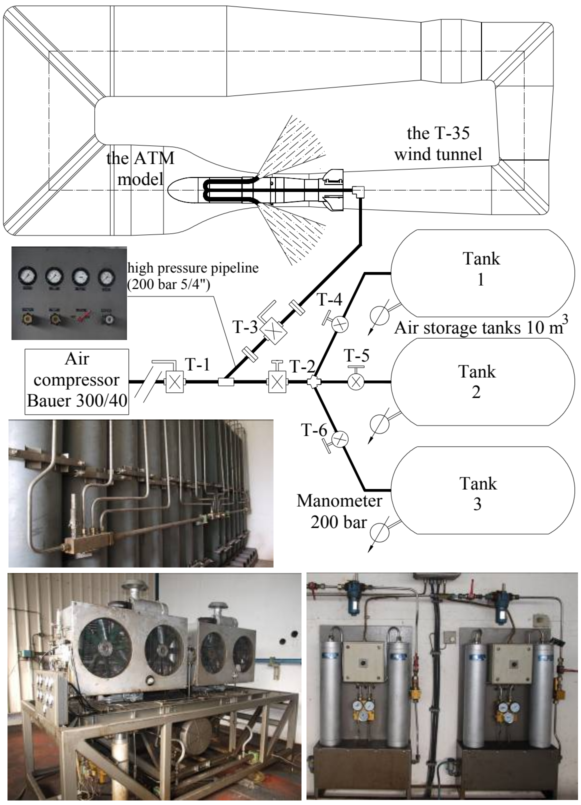


Figure 9. The high pressure cold-air instillation

Installation includes the following elements [12]:

- two stages pistons air compressor Bauer 300 bar, Figure 10,
- high pressure pipelines 200 bar,
- air storage tanks, total volume 10 m^3,
- Druck absolute transducer range 50 bar, which was used for static pressure measurement in the jets installation, accuracy 0.02% of the F.S,
- Druck absolute transducer range 100 bar, which was used for total pressure measurement in the jets installation, nonlinearity and hysteresis 0.02% of the F.S.,

Figure 10. Bauer compressor

- power supply Hottinger Baldwin, which supplies Druck transducers, digital data were received by NEFF data acquisition system and written on disc for further processing,
- two lateral nozzles,
- thermocouple copper-constantan probe with closed head 2 mm diameter, which was used for temperature measurement in the jets installation, accuracy of ±1K,
- four tabs (two upper and two lower) for exchange jets directions, Figure 11.

Figure 11. Deflector detail and tabs for jet direction change

4.2 Instrumentation and data acquisition

Data acquisition system is based on NEFF 600/620 system. The NEFF system series 600 data acquisition system is a high speed system designed for measuring and recording multi-point, low-level analog signals. The system has 64 analog channels and the possibility to expand to 2048 channels. This computer controlled system provides fully programmable differential input preamplifiers with post filtering for each analog input point. Input points are multiplexed to programmable gain and sample &hold amplifiers, which in turn provide inputs to an A/D converter. The digital data output provides a 16 bits word to a host computer.

Important features of this system include: Programmable gain and filter frequency per channel; High resolution (16 bits), high accuracy A/D converter with 100kHz throughput rate; Programmable gain amplifier. Overall precision of data acquisition system NEFF 600/620 is about 0.1% FS. Data acquisition system is controlled by a VAX 8250 computer. The COMPAQ Alphaserver DS 20E with its numerous advantages is available for data reduction.

For the measurements of the aerodynamic loads a five-component VTI-designed monolithic strain gauge balance with flow-through air duct was used, Figure 12. The test included the determination of model aerodynamic coefficients.

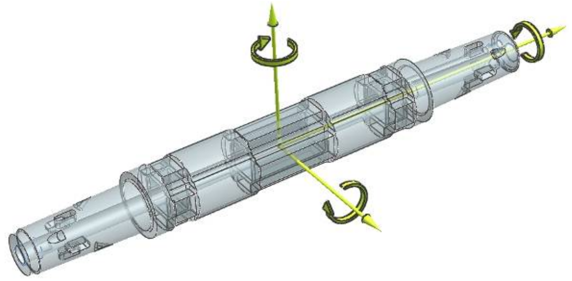


Figure 12. CAD/CAM model of the five-component monoblock wind tunnel balance

The range of balance is 2200N for the normal force, 2200N for the side force, 220 Nm for the pitching moment and yawing moment and 120 Nm for the rolling moment. The accuracy of the balance is approximately 0.3% FS. Balance was calibrated before the measuring. It was set on the 50 mm diameter sting.

4.3 Mass flow determination

Mass flow stays constant for a given ratio of pressures in the tank and in the exit of the nozzle. Mass flow is analyzed based on pressure ratio.

Equation of mass flow:

$$\dot{m} = \sqrt{\frac{2\cdot\kappa\cdot p_0\cdot\rho_0}{(\kappa-1)}\cdot\left[\left(\frac{p_{st}}{p_0}\right)^{\frac{2}{\kappa}}-\left(\frac{p_{st}}{p_0}\right)^{\frac{\kappa+1}{\kappa}}\right]} \tag{1}$$

If density is computed based on the relation of the ideal gas and isentropic state as:

$$\rho_0 = \frac{p_0}{R\cdot T_0}, \tag{2}$$

mass flow can be defined based on measured parameters in the installation, p_0 – stagnation pressure, p_{st} – static pressure and T_0 – stagnation temperature.

Cross-section area on the measurement location of the high-pressure 10mm tube is 7.85×10-5 m^2, ratio of specific heats k = 1.4 and gas constant R = 287 Nm/kgK.

5. RESULTS AND VALIDATION

5.1 Experimental results

Experiments were carried out in the T-35 wind tunnel at Mach number 0.1 to 0.3, Figure 13. Test results are given for model aerodynamic center, located at the distance of 483 mm upstream of the reference plane. Model reference length for Reynolds number calculation is diameter of the model.

The origin of the wind axes system was in the model reference point. Figure 14. shows the relative positions of these axes systems.

Figure 13. The missile model on the support mechanism in the T-35 wind tunnel

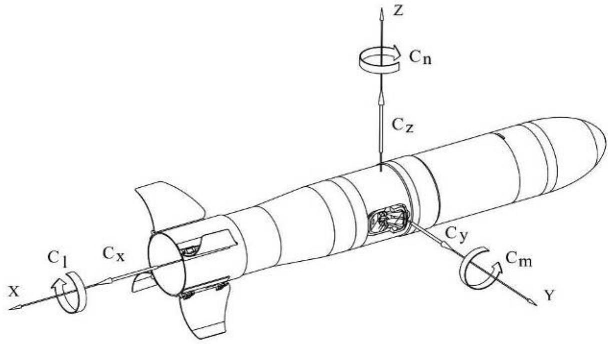


Figure 14. The non-rotated body axes system

Results were obtained by testing at M=0.1, 0.2 and 0.3 in the T-35 wind tunnel, at the model rolling angle ϕ = 0˚. Results are presented by pitching moment coefficients C_m, Figure 15.

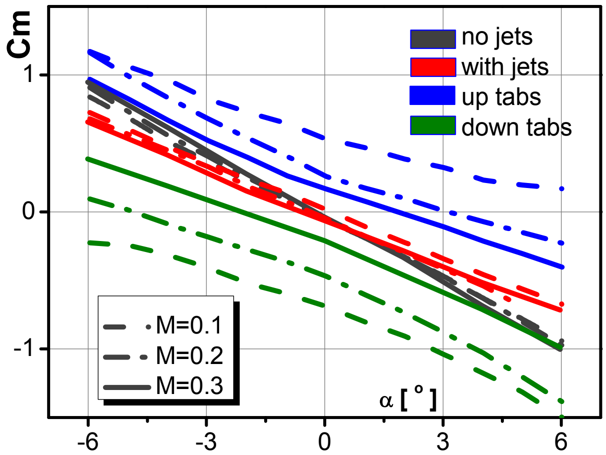


Figure 15. Pitching moment coefficient

5.2 Jets interaction factors determination

Mathematical formulas for definition of the normal force amplification factor and the interaction moment centre XC_{Pi} are given on equations (3) and (4), respectively [13].

$$K_N = \frac{C_{N_{jets}on} - C_{N_{jets}off}}{C_{N_{jets}on}} \tag{3}$$

$$X_{C_{Pi}} = \frac{C_{m_{jets}on} - C_{m_{jets}off}}{C_{N_{jets}on} - C_{N_{jets}off}} \tag{4}$$

The first equation is a measure of how the interaction forces affect the normal force. If K_N is greater than unity, the total added normal force to the missile by the jet is greater than the jet alone normal force; thus the jet force is amplified. If it is less than unity, the jet force is de-amplified. X_{CPi} is the measure of the distance where the combination of the interaction and the jet forces act with respect to the moment reference centre.

The values of the aerodynamic coefficients were determinates in three tests, first run when jets and wind tunnel working simultaneously (Figure 16-1), second, when working wind tunnel (Figure 16-2), and third when working only jets system (Figure 16-3).

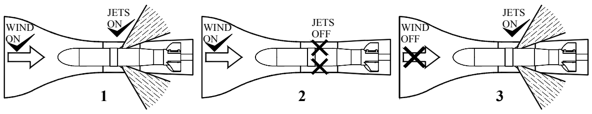


Figure 16. Aerodynamic coefficients determination.

The normal force coefficients with and without jets are given on equations below.

$$C_{N_{jets\,on}} = C_{N_1} \quad (3)$$

$$C_{N_{jets\,off}} = C_{N_2} + C_{N_3} \quad (4)$$

In the Figures 17. and 18. the diagrams of the normal force amplification factor and the interaction moment centre are shown.

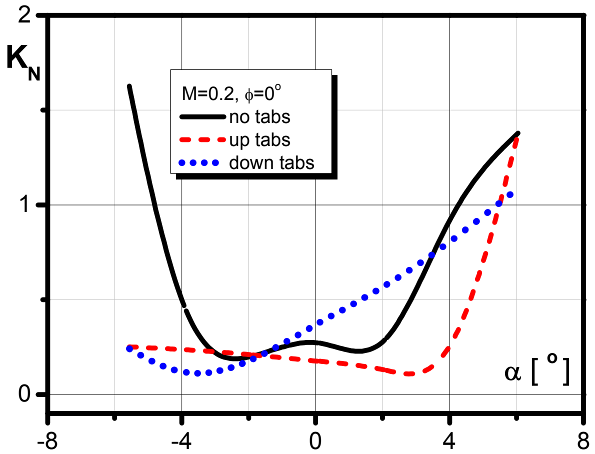


Figure 17. Normal force amplification factor

The most significant effect of the lateral jets and TVC on the pitching moment coefficient C_m. The greatest influence of the jets was observed in the initial phase of the missile's flight when jets significantly modified the low Mach number airflow field.

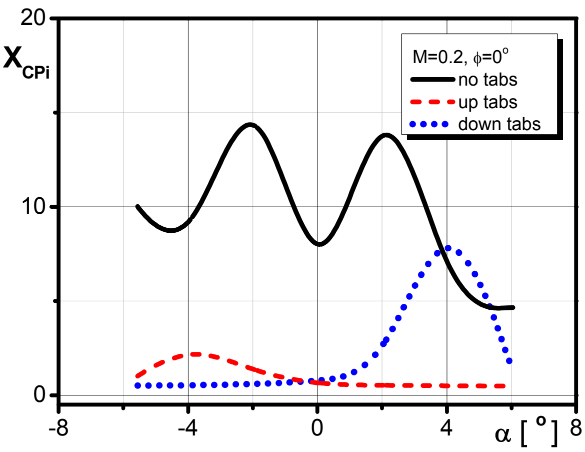


Figure 18. Interaction moment centre factor

Smaller velocity also meant less missile stability, so after-lunch phase is the most sensitive part of flight, and must be properly investigated.

5.3 Numerical simulation

The solid model of the missile is done in Invertor by software. Control volume in shape of an ellipsoid with major axis three times greater than the length of the missile and minor axis sixteen times greater than the missile diameter was done by software Gambit [14]. Due to very complex geometry of the model unstructured meshes were used. Mesh consists of about 2 million cells, and only the computer resources dictate this number. Unstructured mesh composed of tetrahedral elements is generated in the control volume.

Fluent package was used to calculate the aerodynamic characteristic of the model, flow-field and missile model behavior with cold-air simulation using the aerodynamic database which was developed by wind tunnel tests. The code used in this study employs a cell-centered finite volume method based on the linear reconstruction–evolution method of Anderson-Tomas-Van Leer [15]. Diffusion terms are discretized by central differences. The discretized algebraic equations are solved using point-wise Gauss-Seidel iterative algorithm.

The main goal of the numerical experiments was to assess the repeatability of the cold air wind tunnel tests. The viscous computational fluid dynamic simulations were used to calculate the flowfield around the projectile model in subsonic flows. The computations were performed for Mach number 0.2 at and the angle of attack from –6º to 6º. The density-based, explicit, compressible, unstructured-mesh solver was used. A modified form of the k- ε two-equation turbulence model (realizable k- ε) was used in this study. This turbulence model solves transport equations for the turbulence kinetic energy, k, and its dissipation rate, ε. Convergence was determined by tracking the change in the flow residuals and the aerodynamic coefficients during the solution. The solution was deemed converged when the flow residuals had reduced at least 2 orders of magnitude and the aerodynamic coefficients changed less than about 2% over the last 100 iterations.

5.4 CFD cold-air simulation

CFD modelling was conducted in three stages: high-pressure air flow with mass flow 0.24kg/s in installation for sustainer's cold simulation, Figure 19. up to Figure 21., aerodynamic simulations with and without jets and hot jets simulation at real mass flow 0.5kg/s [16][17].

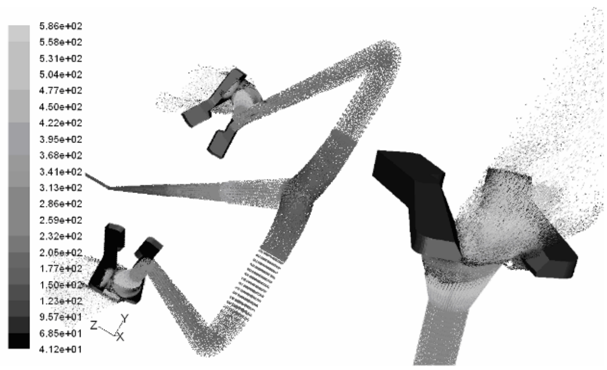


Figure 19. High-pressure air flow installation for sustainer's cold simulation

5.5 Validation

Validation and comparative review of the normal force aerodynamic coefficient (C_N) and the pitching moment coefficient (C_m) values are given for Mach number M=0.2 at roll angle ϕ=0°, mass flow into the jets installation 0.24kg/s [18],[19].

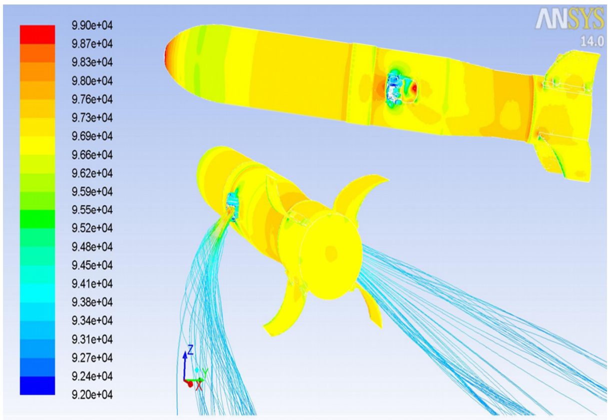


Figure 20. Pressure contours - cold jets, up tabs.

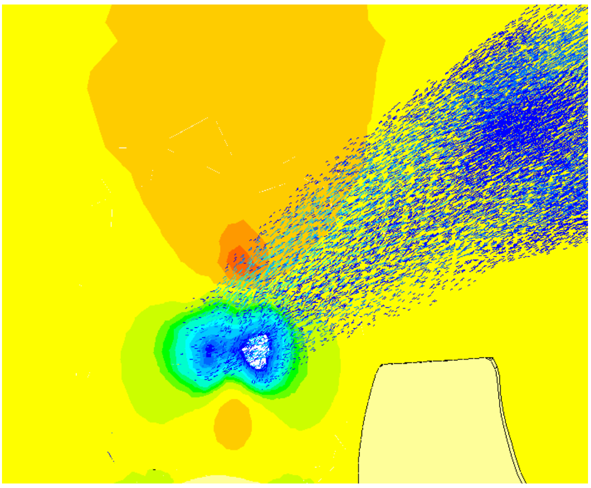


Figure 21. Velocity vector - cold jets simulation

Comparative reviews are shown in Figures 22. to 25.

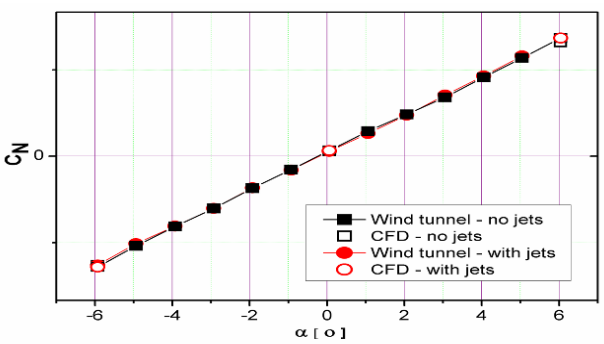


Figure 22. Normal force coefficient, without command

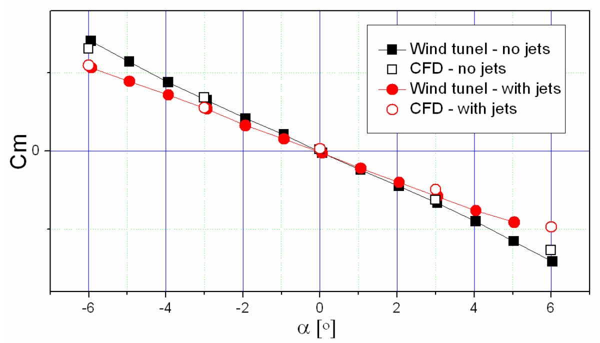


Figure 23. Pitching moment coefficients, without command

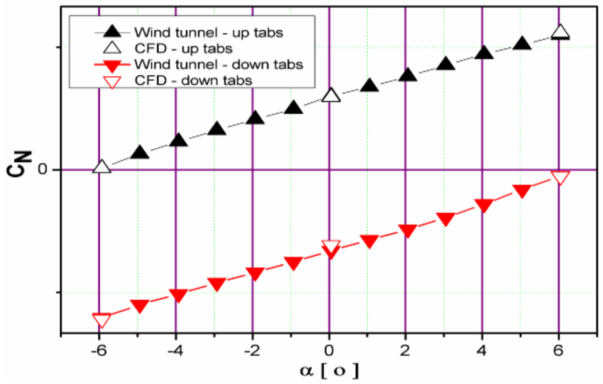


Figure 24. Normal force coefficient, with command

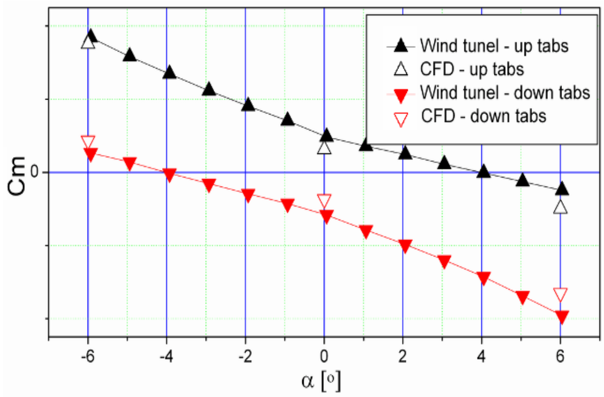


Figure 25. Pitching moment coefficients, with command

The jet stands in the horizontal position such that when it is active up tabs, it creates positive normal force.

The experimental data and the CFD results are in good agreement with each other for all model configurations.

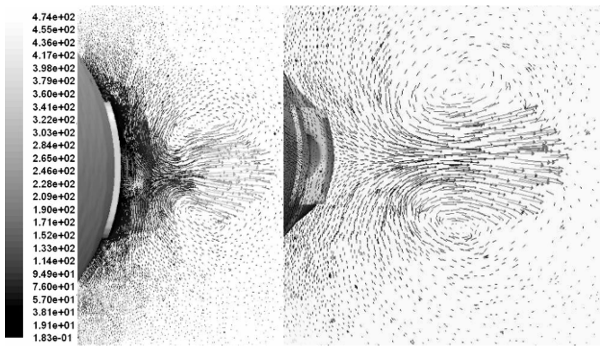
5.6 CFD hot-gases simulation

In Figure 26. the velocity vector for the hot jets simulations, no tabs configuration at mass flow 0.5kg/s is shown.

In Figures 27. and 28. the velocity vector for the hot jets simulations, up tabs configuration at mass flow 0.5kg/s are shown.

As a result, a numerical methodology for solving lateral-jet controlled subsonic missile problems has been developed. This methodology can be used as a part of the lateral-jet controlled missile design.

In Figure 29. the static pressure distribution on the surface of the model, hot jets simulations, upper tabs configuration at mass flow 0.5kg/s are shown.



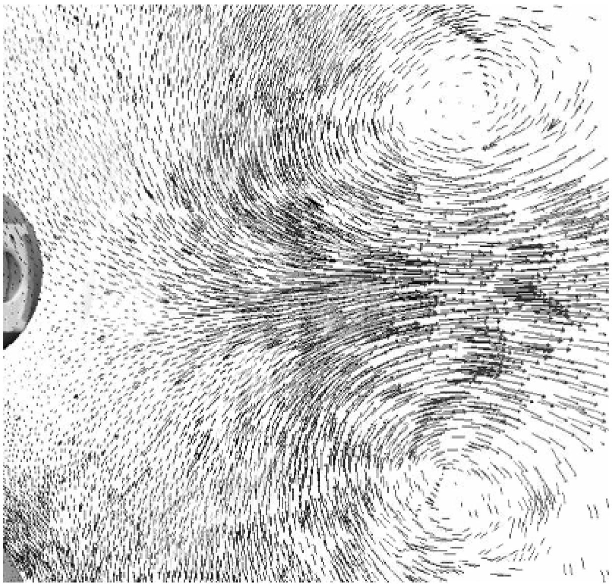


Figure 26. CFD simulation with hot jets, no command; velocity vector.

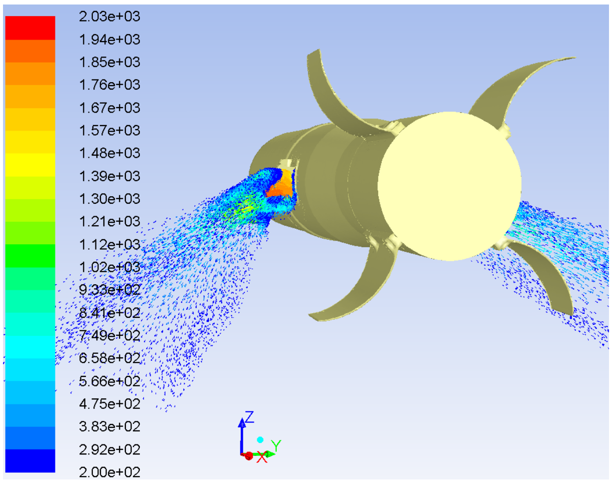


Figure 27. CFD simulation with hot jets, up tabs; velocity vector.

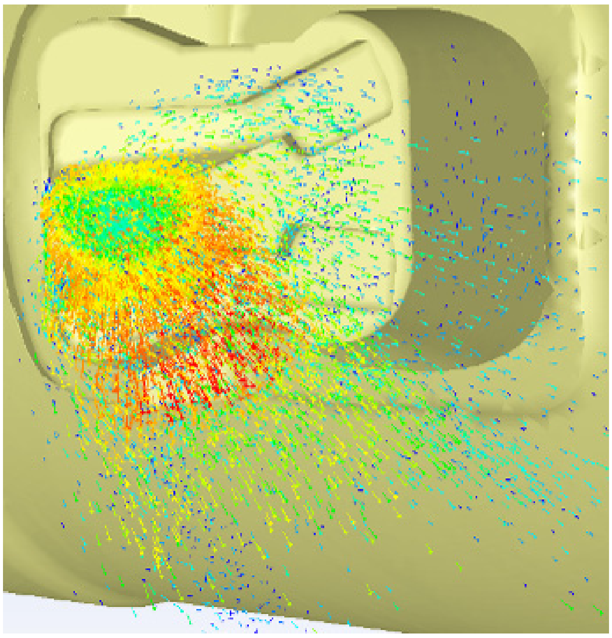


Figure 28. CFD simulation with hot jets, up tabs; velocity vector; up tabs, nozzle detail.

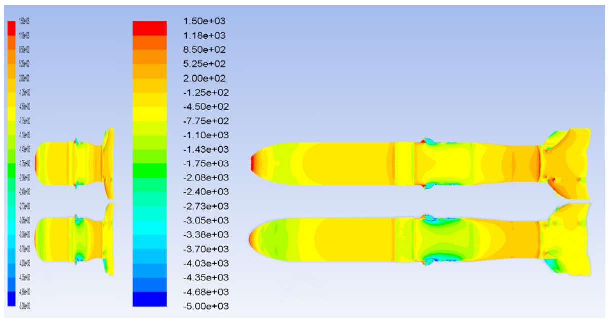


Figure 29. Static pressure distribution at M=0.2 and α=-6°, upper surface; downer surface of the missile model.

6. DISCUSSION

The study resulted in the definition of a methodology for the investigation of the jet reaction effects in a wind tunnel. A method for determining of the TVC system interference on the aerodynamic characteristics, as a basic prerequisite for structural, stability and performance analysis, was proposed. Mutual verification and validation process was carried out through experiment and proper application of the commercial CFD software code for calculation aerodynamic effects of the lateral jets on the performance of a guided missile [20].

Figures 30 and 31 show the comparison between experimental and CFD results for a model with and without cold lateral jets (mass flow 0.24kg/s) and hot-gases.

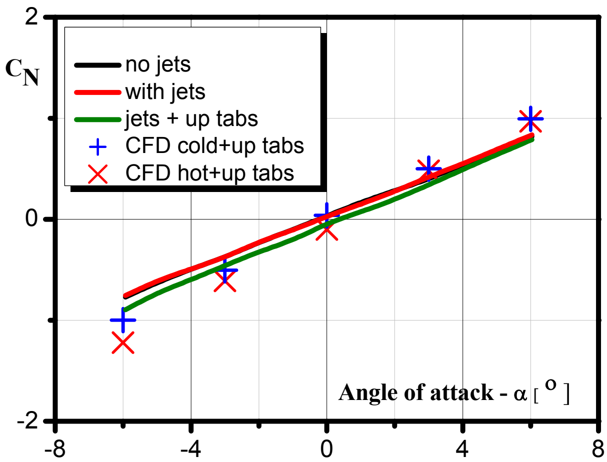


Figure 30. Cold-air and hot jets comparison, - C_N

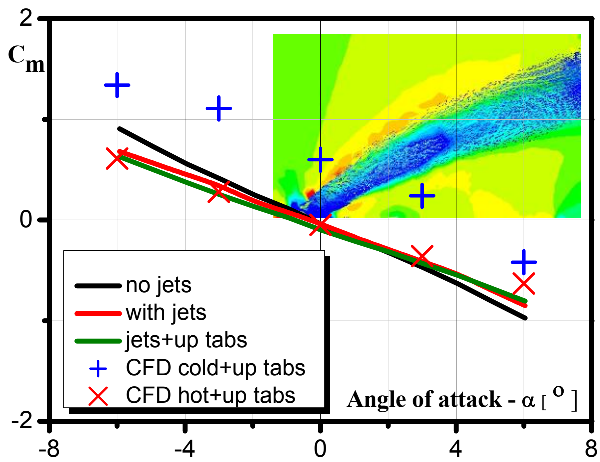


Figure 31. Cold-air and hot jets comparison, - C_m

The hot rocket motor's combustion products was determined on the basis of the CFD model proven with the cold-jet simulation the influence but with the real mass flow of the product 0.5kg/s.

7. CONCLUSION

The use of cold air for the simulation of jet exhaust has the primary advantage of relative simplicity in set-up and operation. Cold-air is particularly appealing when the simulation of jet temperature is considered of little importance. Since high pressure air supplies are most commonly available, the use of cold air has found wide application for jet studies.

For missile with lateral jet control, the flowfield is very complex because of the interaction. Moment and pressure at nozzle exit are the main factors that influence the lateral force [21].

In this study cold air and hot gas jet will give nearly the same results.

The objectives of the present study are to deeply analyze the effects of the cold-air jet by the use of wind tunnel testing and CFD simulations. Finally, the main goal is to define the most appropriate similarity parameters for CFD simulations using hot gases. Experiments from the T-35 subsonic wind tunnel of VTI on missile model are used to achieve numerical simulations of the interaction between a lateral jet and a subsonic cross flow around the missile. These experiments are using either a cold-air jet wind tunnel tests data for the validation of the numerical simulation, on an ideal gas.

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NOMENCLATURE

C_N	normal force coefficient
Cm	pitching moment coefficient
M	Mach number
K_N	normal force amplification factor
X_{CPi}	interaction moment centre
$\dot{m}$	mass flow in the jet installation
k	ratio of specific heats, k = 1.4
R	gas constant, R = 287 Nm/kgK
p_{st}	static pressure-jet installation
p_0	stagnation pressure-jet installation
T_0	stagnation temperature-jet installation
$C_{N_{jets}^{on}}$	normal force coefficient with jets
$C_{N_{jets}^{off}}$	normal force coefficient without jets
$C_{m_{jets}^{on}}$	pitching moment coefficient with jets
$C_{m_{jets}^{off}}$	pitching moment coefficient without jets

Greek symbols

α	angle of attack
β	sideslip angle
ϕ	rolling angle
ρ_0	density of the air-jet installation

ABBREVATIONS

VTI	Military Technical Institute
TVC	Trust Vector Control
CAD	Computer Aided Design
CFD	Computer Fluid Dynamics
RANS	Reynolds Average Navier-Stokes
$T-35$	Large subsonic wind tunnel of VTI
$VTI385$	Wind tunnel balance produced by VTI
FS	Full Scale
NEFF	Data acquisition system serial 600/620

ЕКСПЕРИМЕНТАЛНО И НУМЕРИЧКО ИСТРАЖИВАЊЕ УТИЦАЈА РАДА СИСТЕМА УПРАВЉАЊА ВЕКТОРОМ ПОТИСКА НА АЕРОДИНАМИЧКЕ КАРАКТЕРИСТИКЕ РАКЕТА СИМУЛАЦИЈОМ ХЛАДНИМ И ТОПЛИМ МЛАЗОМ

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Струјни феномени који се јављају као последица дејства рада система УВП веома су сложени, а ефекти дејства евидентни су на свим компонетама ракете. Циљеви ове студије су да се у потпуности анализирају ефекти дејства хладног реактивног млаза система УВП на основу резултата из аеротунелских тестова и CFD симулације и да се дефинишу најадекватније параметри сличности, које би произвели топли продукти сагоревања. Нумеричка аеродинамичка анализа и симулација топлих продуката сагоревања спроведена је решавањем 3D Reynolds Averaged Navier–Stokes једначина на основу методе коначних запремина.
У студији је дефинисана методологија истраживања ефеката реактивног млаза у аеротунелима и предложен је начин одређивања интерференције рада система за управљање вектором потиска на аеродинамичке карактеристике вођених ракета, као једног од основних предуслова за структурну, анализу стабилности и анализу перформанси. Узајамна верификација и валидација процеса извршена је кроз експеримент и одговарајућу примену комерцијалног нумеричког софтверског кода за прорачун аеродинамичких ефеката млаза на перформансе вођене ракете. Приказани су експериментални резултати коефицијента момента пропињања, као и резултати добијени CFD анализом и добијено је веома добро слагање.