Simulation of multiple supersonic jets impinging with obstacle

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Abstract. In this paper the mathematical modeling of the interaction of a twin supersonic jet with a flat obstacle in Mars environment and Mach numbers at the nozzle exit 4.5 are considered. The effect of the distance between the nozzles on the shock-wave structure of the jets and their force on obstacle are investigated. The distance ranged from 0.1 to 4 nozzle exit diameters (L/D). It is found that the self-oscillating mode is observed only for the case L/D = 1.5, for the rest of the cases the stationary mode are implemented. With an increase in the distance between the nozzles, the maximum pressure on obstacle decreases from 33 kPa to 13 kPa. In the case when the plumes do not close L/D = 4, the force effect of the jets is 2.5 times less compared to L/D = 0.1.

1. Introduction

At present, the study of interaction of supersonic jets (M>3 at the nozzle exit) with obstacles for the tasks of launching and landing spacecraft is of practical interest. A number of experimental and theoretical works are devoted to the interaction of multiple and composite jets with obstacles [1-10]. In cases of gas outflow from a rocket multi-nozzle installation, supersonic jets form a multiple (composite) jet. As a result of a multiple plume flowing onto the surface, a complex flow is formed with a branched system of compression shocks containing local subsonic flows, contact discontinuities and flow sections with large gradients of gas parameters. Depending on the degree of pressure ratio, the distance from the nozzle exit to the surface shape and the angle of the surface, location of engines relative to each other, structure of their gas dynamic patterns are different. Plumes can close, affect each other, affecting the shape of each jet, the peripheral flow and the force influence on the streamlined surfaces.

The greatest influence on formation of structure of a composite jet is mainly due to the nozzles spacing, distance to obstacle, pressure ratio and Mach number on the nozzle exit. In experimental studies, the leakage of the jets (Mach number on the nozzle exit M<3) on flat (including inclined) obstacles under atmospheric conditions was studied. In theoretical studies, cycles of work have been carried out to simulate single and multiple (composite) turbulent jets, and their interaction with flat obstacles with varying various parameters.

Therefore, the aim of this work is mathematical modeling and parametric studies of the leakage of a twin supersonic jet onto a flat obstacle for M=4.5 at the nozzle exit under Mars conditions using the realized S.K. Godunov’s method in OpenFOAM.

2. Physical and mathematical model

The problem of supersonic gas flow from two nozzles and the leakage of twin jet onto flat obstacle is considered. In Figure 1 the schemes of interaction of a supersonic twin jet with a flat obstacle depending on the distance of the nozzles are shown.
3. Numerical results

The geometric characteristics of the nozzle were as follows: nozzle throat diameter \( D^* = 0.03613 \) m, nozzle diameter \( D = 0.19395 \) m, and the angle of the semi-solution of the nozzle is 10 degrees. For numerical calculations at the initial time unmoved environment was assumed. The ambient pressure was 650 Pa, and temperature was 250 K (Mars environment). The parameters at the nozzle inlet was: pressure \(- 0.28\) MPa, temperature \(- 1180\) K, adiabatic index \(- 1.33719\). The distance from nozzle exit to flat obstacle was \( H = 1 \) m. The distance \( L \) between the nozzles was varied in the following range \( L/D = 0.1 \div 4 \).

To illustrate the shock wave structure of supersonic twin jet, a density gradient is shown in Figure 3. The pressure distribution along the obstacle is shown in Figure 2. The pressure distribution along the section along the axis of the jets are shown. For \( L/D = 0.1 \) the general shock wave structure of two jets, interference waves arise and two pressure maxima from the resulting shock waves \( VT \) and the shock \( EE \) on the obstacle are realized. A similar shock wave system up to \( L/D = 1 \) are stored. An increase in the distance between the nozzles leads to a decrease in the maximum pressure on obstacle from 33 kPa \( (L/D = 0.1) \) to 19 kPa \( (L/D = 1) \) due to the restructuring of the system shock wave. After the jets open and there is a reverse gas flow in the opposite direction of the main gas stream. The backward supersonic gas flow reflected from the obstacle affects the shear layer of the jets up to \( L/D = 2 \). In this case, the pressure increases due to the interaction of peripheral flow. For \( L/D = 4 \), wall jets interact, they collide in the center, and some of the gas turn around downstream. In this case, two pressure peaks from each jet with a level of 13 kPa appear on the obstacle, which is 2.5 times less than \( L/D = 0.1 \). In all the cases considered, the flow was...
established and a stationary mode of interaction between the jets and the obstacle was observed, except for the $L/D=1.5$ variant, a self-oscillating regime was realized.

**Figure 2.** Density gradient of shock-wave structure for distances $L/D=0.1$, $L/D=0.5$, $L/D=1$, $L/D=4$.

**Figure 3.** Pressure distribution along the obstacle for distances $L/D=0.1$, $L/D=0.2$, $L/D=0.3$, $L/D=0.4$, $L/D=0.5$. 
4. Conclusion
The interaction of a composite jet with an obstacle under the conditions of Mars were simulated. The influence of the distance between the nozzles on the shock-wave structure of the gas flow and the force action of the plumes on the obstacle are investigated. The distance $L/D$ ranged from 0.1 to 4. It was found that with an increase in the distance between the nozzles, the maximum pressure on obstacle decreases from 33 kPa ($L/D=0.1$) to 19 kPa ($L/D=1$). In case when the jets do not close $L/D=4$ the force action of the jets is 2.5 times less compared to $L/D=0.1$. The self-oscillating regime was observed only for the case $L/D=1.5$, and for the remaining cases it was stationary.

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References
[1] Dyadkin A A, Sukhorukov V P, Trashkov G A, Volkov V F, Zapryagaev V I, Kiselev N P 2014 29th Congress of the International Council of the Aeronautical Sciences 0640 1–10
[2] Kudimov N F, Safronov A V and Tretyakova O N 2013 MAI 69 1–11
[3] Kudimov N F, Safronov A V and Tretyakova O N 2013 MAI 70 1–14
[4] Kudimov N F, Safronov A V and Tretyakova O N 2014 Applied problems of gas dynamics and heat transfer in power plants of rocket technology (Moscow: MAI) p168
[5] Degtyar V G, Merkulov E S, Hlibov V I and Safronov A V 2013 Cosmonautics and Rocket Engineering 70 (1) 37–45
[6] Mehta M, Sengupta A, Renno NO, Van Norman JW, Huseman PG, Gulick SD, Pokora M 2013 AIAA Journal 51(12) 2800–2818
[7] Mehta M, Renno NO, Cotel AJ, Grover III RM 2007 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit 1–11
[8] Plemmons DH, Mehta M, Clark BC, Kounaves SP, Peach Jr LL, Renno NO, Tamppari L, Young SMM 2008 Journal of Geophysical research 113 1–12
[9] Sengupta A, Kulleck J, Sell S, Norman JV, Mehta M, Pokora M 2008 IEEE/AIAA Aerospace Conference 1–10
[10] Glazunov A A, Kagenov A M, Kostyushin K V, Eremin I V, Kotonogov V A, Aligasanova K L 2019 Tomsk State University Journal of Mathematics and Mechanics 63 87–101