Progress in Flight Physics **5** (2013) 545-556
DOI: 10.1051/eucass/201305545

MODELING INTERMEDIATE EXPERIMENTAL VEHICLE CONTROL THRUSTER PLUME – SURFACE INTERACTION

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The influence of the interaction between the thruster plume and the surface on aerodynamic characteristics of a model with a configuration similar to Intermediate eXperimental Vehicle (IXV) is assessed.

1 INTRODUCTION

During the initial part of the reentry, the IXV maneouverability is ensured by means of the Reaction Control System (RCS), which includes four thrusters located at the base of the vehicle. When the downward thruster(s) are fired, the plume is interacting with the free stream flow structure, which results in severe redistribution of flow properties in the vicnity of the base. Because of that, the aerodynamic characteristics of a space vehicle (especially, the pitching moment) are substantially changed. From the simulational aspect, the resulting problem simultaneously involves both rarefied and continuous packets of flows, which is a challenging problem for Direct Simulation Monte Carlo (DSMC) methods traditionally applied for early-stage reentry problems. In this paper, the influence of the thruster plume – surface interaction on aerodynamic characteristics of a model with a configuration similar to IXV is estimated.

2 FORMULATION OF THE PROBLEM AND INITIAL DATA

The draft of the IXV mission is envisioned as launching from Kourou (French Guiana) on a VEGA rocket to reach an orbit of about 180 × 300 km. The

VEGAs upper stage will trigger the reentry which formally begins around 120 km with 7700 m/s and $\sim$ 1.19 degree path angle. Landing is foreseen at the North European Aerospace Test Range at Kiruana (Sweden) after completing traveling a surface distance of 7500 km [1].

The motion of bodies at altitudes of the order of 100 km occurs in the transitional regime of the rarefied gas flow. The most suitable tool for studying such flows is the DSMC method [2]. The DSMC method simulates a gas flow by a set of particles, which move like gas molecules. The simulation is divided into two independent stages:

(1) transfer of all particles to a prescribed time step; and

(2) collision of particles with each other.

A grid is generated in the computational domain, and only those particles that are located in the same cell can collide with each other. The same cells are used to collect the statistical information subsequently used to extract flow macroparameters: the density, the temperature, etc.

The present study was performed with a SMILE software system [3].

For correct operation of the DSMC method, the cell size should be commensurable with the mean free path of molecules, and the particle should cover a distance smaller than or equal to the mean free path during one time step. It is desirable to have more than five particles in a cell. Intermediate experimental vehicle is equipped with a thruster with the nominal thrust of 380 N and with an exhaust velocity of 2500 m/s. The mean free path (and, correspondingly, the cell size) in the core of the plume of this thruster is approximately 4 μm. As the IXV length is about 4.4 m, the resources necessary to perform computations even on a nonuniform grid include several tens of million of cells, approximately one billion of particles, and several million of time steps. Obviously, such simulations are extremely expensive, and it is rather difficult to perform multiparameter computations.

The main goal of the study performed is to estimate the effect of the thruster plume – incoming flow interaction on aerodynamic characteristics of the IXV at various altitudes and whether this effect has to be taken into account. Therefore, the study was performed in a model formulation. The IXV geometric shape was modeled by a wedge (Fig. 1) of length 4.4 m and half-width 1.2 m, which was mounted at the angle of attack 30°. Owing to the use of flat surfaces, the side influence of the plume is estimated more clearly. The nozzle exit is located at the distance of 0.05 m in the plane of the windward surface of the wedge (working surface). The mean velocity vector of the plume is normal to the working surface; it is indicated in Fig. 1 by the large arrow. The figure also shows two planes of symmetry: the horizontal plane of symmetry cutting off the upper part of the flow and the vertical plane of symmetry passing through the center of the

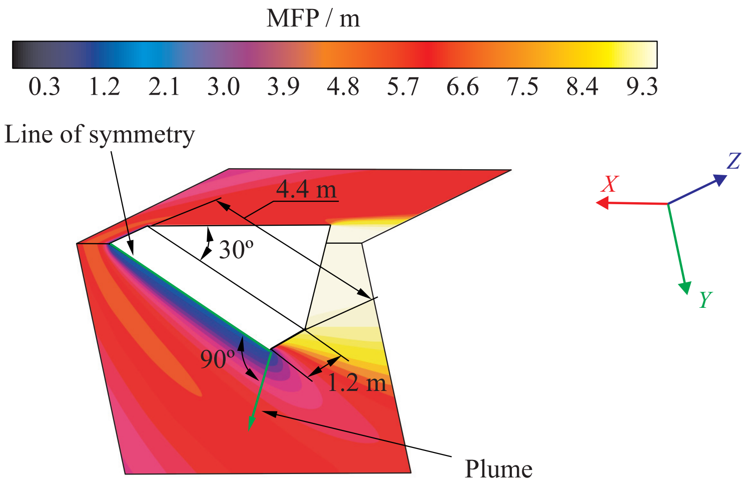


Figure 1 Geometric model, plume vector, and mean free path (MFP) of molecules; $H = 100$ km.

wedge and the plume axis. With the use of the planes of symmetry, there can be needed half as many computational resources.

As the plume parameters are the governing parameters in the method used, three plumes with the density 10, 100, and 1000 times lower than the initial density were used in the study, while other parameters were not changed (Table 1).

Table 1 Plume parameters

Parameters	Plume 1	Plume 2	Plume 3
Nozzle exit radius, m		0.0441	
Temperature, K		371	
Velocity, m/s		2540	
Mach number		4.3	
Mass fraction of N_2		0.57	
Mass fraction of H_2		0.09	
Mass fraction of NH_3		0.34	
Density, kg/m^3	$9.7 \cdot 10^{-6}$	$9.72 \cdot 10^{-5}$	$9.72 \cdot 10^{-4}$
Number density, 1/m^3	$4.99 \cdot 10^{20}$	$4.99 \cdot 10^{21}$	$4.99 \cdot 10^{22}$
Pressure, Pa	2.55	25.5	255.
Mean free path, m	$4 \cdot 10^{-3}$	$4 \cdot 10^{-4}$	$4 \cdot 10^{-5}$
Nominal trust, N	0.381	3.81	38.1
Moment, N·m	1.676	16.76	167.6

Table 2 Atmosphere parameters

Altitude, km	Density, kg/m^3	Number density, 1/m^3	Temperature, K	Mean free path, m	Mole fraction of O_2	Mole fraction of N_2	Mole fraction of O
120	$2.2642 \cdot 10^{-8}$	$0.52128 \cdot 10^{18}$	368	3.10	0.084	0.733	0.183
110	$9.6068 \cdot 10^{-8}$	$2.12460 \cdot 10^{18}$	247	0.66	0.123	0.770	0.107
100	$55.8240 \cdot 10^{-8}$	$11.89800 \cdot 10^{18}$	194	0.12	0.177	0.784	0.039

It is easier to model the exhaustion of such plumes. A comparison of flow structures for different plumes allows estimating the influence of a plume density on the processes of its interaction with the incoming flow and extrapolating the conclusions to the real plume.

The study was performed for three altitudes (100, 110, and 120 km). The atmosphere parameters for these three altitudes were borrowed from [4] and are summarized in Table 2. In all cases, the incoming flow velocity was 7500 m/s, the surface temperature was 300 K, the diffuse law of the gas–surface interaction was accepted, the Variable Hard Sphere (VHS) model of molecular collisions was used, and the discrete model of the internal energy of molecules with the energy redistribution during the collision in accordance with the Larsen–Borgnakke model was applied. The moment reference point is located at leading edge of the wedge.

The study was performed in the following sequence:

1. The exhaustion of all plumes without the incoming flow (exhaustion into absolute vacuum) was simulated.

2. The flow around the wedge at different altitudes without a plume was simulated. The results of this stage were considered as a reference.

3. The flow around the wedge at different altitudes with different plumes was simulated. These computations were compared with the reference computations to estimate the effect of the thruster plume.

3 EXHAUSTION INTO VACUUM

The exhaustion into vacuum was modeled for each plume (without the external flow). As the plume velocity vector is normal to the surface, the molecules have to turn approximately by 180° to reach the surface. Obviously, only some of the molecules can turn to such an extent; therefore, the fluxes onto the surface are

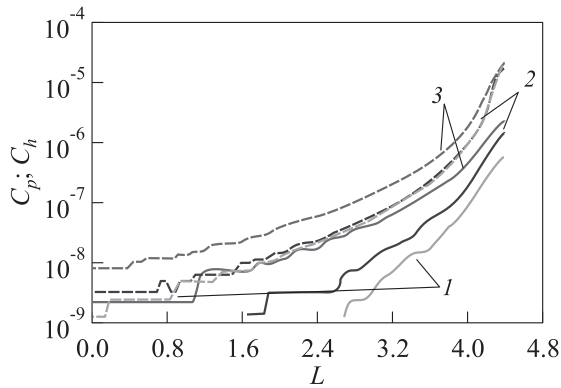


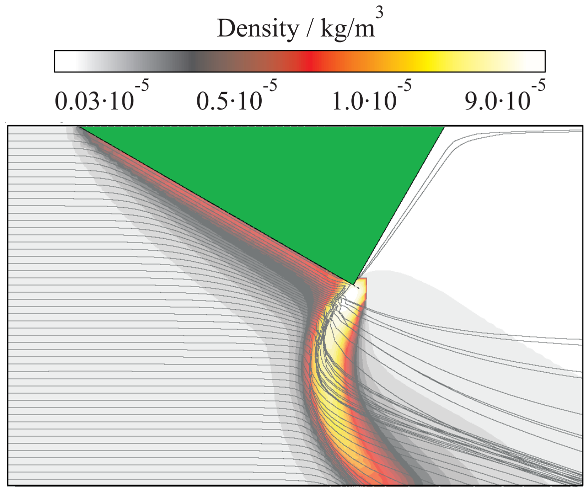
Figure 2 Distribution of the pressure, C_p (dashed curves), and heat-flux, C_h (solid curves), coefficients along the line of symmetry (exhaustion into vacuum): *1* — jet 1; *2* — jet 2; and *3* — jet 3

extremely small. As a result, the influence of the plume on the surface is also small. This is clearly seen in Fig. 2, which shows the distributions of pressure (C_p) and heat-flux (C_h) coefficients along the line of symmetry. The values are given in a logarithmic scale and do not exceed 10^{-4}. In the dimensional form, the increment of the pitching moment due to the gas flow onto the surface is approximately 0.01% of the moment generated by the engine. Therefore, the plume–surface interaction in the absolute vacuum can be neglected.

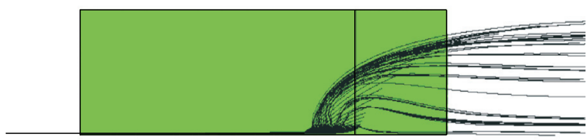
4 PLUME INTERACTION WITH THE INCOMING FLOW

The flow pattern becomes substantially different in the presence of the incoming flow. The flow molecules collide with the plume molecules, lose their velocity, and become scattered in space ahead of the plume. As a result, the pressure ahead of the plume increases. Similar changes in the flow would occur if there were a solid wall instead of the plume. Figure 3 shows the density field and the streamlines for the configuration with the plume 3 at the altitude of 100 km. It is seen that the streamlines spread on the plume contour as if it were a solid body.

The increase in the pressure ahead of the plume alters the pressure on the working surface of the wedge. Figure 4 shows the superimposed isolines of the coefficients C_h (Fig. 4*a*) and C_p (Fig. 4*b*) for the flows without a plume and with the plume 2 for the altitude of 110 km. Only the right half of the working surface of the wedge is shown (the plane of symmetry is on the left edge of each figure).



(*a*)



(*b*)

Figure 3 Streamlines and density field (H = 100 km, plume 3): (*a*) side view; and (*b*) bottom view.

Figure 4*b* also shows the scale of distances from the leading edge (in meters). The isolines almost coincide approximately within 2 m from the leading edge, while the influence of the plume further downstream is appreciable.

The distance of the plume influence is determined by the distance that can be traveled by molecules flying away from the interaction zone before they collide with incoming flow molecules. Obviously, this distance depends on the mean free path of molecules in the incoming flow and increases with altitude. This is clearly seen in Fig. 5, which shows the distributions of the coefficients C_p and C_h along the line of symmetry of the working surface of the wedge for different altitudes for the flow with and without a plume. At the altitude of 120 km, the plume influence zone extends up to the leading edge of the wedge. At 100 km, the plume influence zone does not exceed 1.5 for the plume with the greatest density. It is also seen that an increase in the plume density increases the number of interacting molecules; therefore, the action on the working surface of the wedge is enhanced. When the density in the plume becomes commensurable

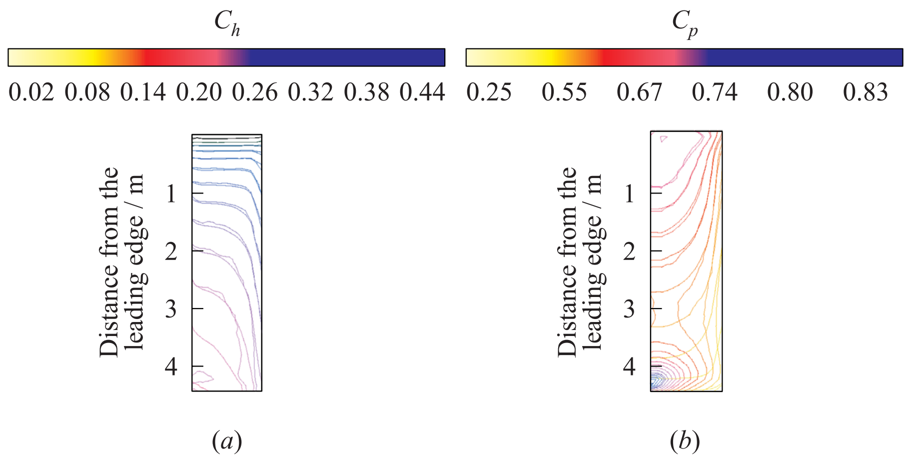


Figure 4 Effect of the plume on the wedge surface ($H = 110$ km, plume 2): (a) C_h; and (b) C_p.

with the incoming flow density (plume 1 for the altitude of 100 km), the plume is actually entrained downstream by the flow and exerts a minor effect on the working surface.

Table 3 shows the variations (in percent) of the coefficients of the drag force (ΔC_A), the lift force (ΔC_N), heat fluxes (ΔC_H), and the pitching moment (ΔC_m) with respect to the values of these coefficients in the flow without a plume. The changes in these coefficients increase with the altitude in proportion to the change in the zone of the plume influence on the surface.

It should be taken into account that the flow density considerably decreases with the altitude, and the dimensional values of the forces and moments are rather low. Therefore, Table 3 also shows the dimensional value of the moment M, the difference between the moment and its value in the flow without the plume ΔM, and the ratio $\Delta M/M_{\text{jet}}$ (the moment generated by the plume M_{jet} is given in Table 1). It is seen that the increment of the dimensional moment is rather small at altitudes above 120 km and decreases with increasing plume density.

Extrapolating the results obtained to the thruster with the thrust of about 400 N, one can say that the plume interaction with the incoming flow should be taken into account at altitudes below 120 km for better IXV control. The effect of this interaction can increase the forces and moments by 10% and more.

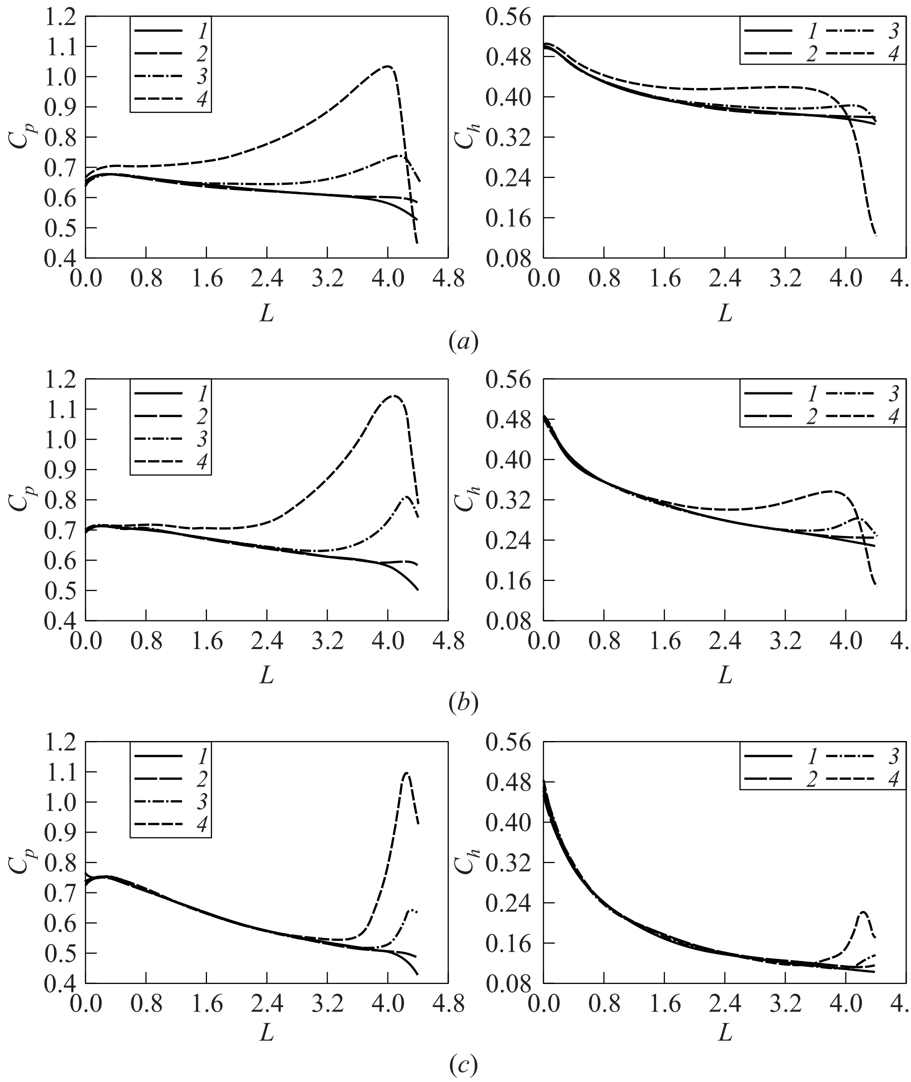


Figure 5 Pressure and heat-flux coefficients for different altitudes along line of symmetry: (*a*) $H = 120$ km; (*b*) 110; and (*c*) $H = 100$ km; *1* — flow; *2* — jet 1; *3* — jet 2; and *4* — jet 3

Table 3 Changes in aerodynamic characteristics due to plume – flow interaction

	ΔC_A, %	ΔC_N, %	ΔC_H, %	ΔC_m, %	M, N·m	ΔM, N·m	$\Delta M/M_{\text{plume}}$, %
Altitude 120 km							
No plume	0.0	0.0	0.0	0.0	4.58	0.00	—
Plume 1	0.3	2.1	0.4	1.3	4.64	0.06	3.6
Plume 2	1.6	18.2	2.7	9.9	5.03	0.45	2.7
Plume 3	6.0	74.8	9.7	35.4	6.20	1.62	1.0
Altitude 110 km							
No plume	0.0	0.0	0.0	0.0	19.80	0.00	—
Plume 1	0.2	0.7	0.0	1.1	20.01	0.21	12.5
Plume 2	1.3	8.6	1.8	7.2	21.22	1.42	8.5
Plume 3	7.5	44.1	11.2	35.1	26.74	6.94	4.1
Altitude 100 km							
No plume	0.0	0.0	0.0	0.0	101.2	0.00	—
Plume 1	1.1	0.9	2.3	0.2	101.4	0.20	11.9
Plume 2	3.0	0.9	2.6	2.0	103.2	2.00	11.9
Plume 3	5.3	8.3	6.1	12.1	113.4	12.20	7.3

5 TECHNOLOGY OF SIMULATING REAL PLUME – FLOW INTERACTION

As it was mentioned in Introduction, modeling a real plume for a 400-newton thruster is an extremely expensive task. At the same time, a multizone approach [5] was frequently used for plume flow simulations, in which the entire computational domain is divided into several nested zones. The smallest zone is constructed near the nozzle exit. The modeling results in the smallest zone are used as the starting (boundary) conditions for simulations in the next zone, etc. As the density in the expanding plume rapidly decreases, different parameters of the method (time step and cell size) are used in each zone. Such an approach allows consecutive investigations in the entire domain of interest, with the computational resources being maintained at an acceptable level.

This approach can be used in the problem considered. First, it is necessary to perform axisymmetric simulations of plume exhaustion from the thruster. From the results of these simulations, it is necessary to choose a boundary on which the mean free path of molecules is of the order of 10^{-3}–10^{-4} m (number density of the order of 10^{20}–10^{21} kg/m^3). This boundary can be used as the starting boundary in three-dimensional (3D) simulations. The axisymmetric computations are performed in a much smaller domain, which allows small computational cells and a small time step to be used. In 3D simulations, there are no regions with high densities. Therefore, it is possible to use large cells and a large time

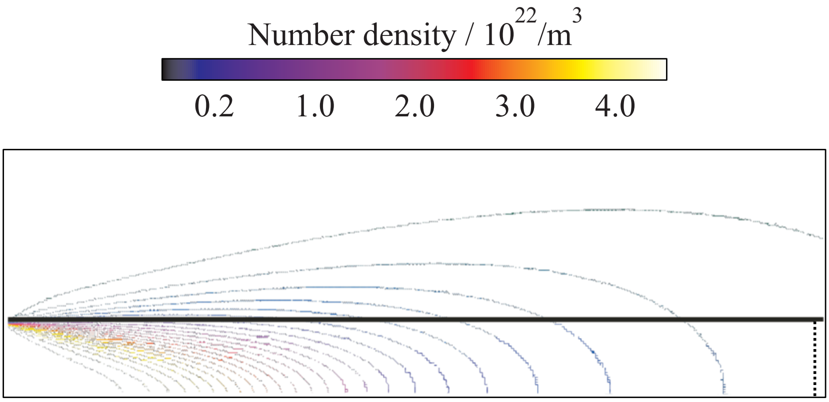


Figure 6 Axisymmetric modeling with plume 3 and starting boundary for 3D modeling.

step. As a result, the computational resources needed and the computational time are reduced.

It should be borne in mind, however, that it is only the initial flow that is generated on the starting surface. There should not be any particles in the domain bounded by the starting surface. If the boundary is too large, there is a probability that free-stream particles cross the starting surface without colliding with plume particles, and there are no partners for collisions inside the starting surface. Potentially, this process can distort the computation results. Therefore, the multizone approach was used in some of the above-described computations, and the results were compared.

Figure 6 shows the number density of axisymmetric simulations for plume 3 for the altitude of 100 km. The computational domain size was 0.5×0.15 m. The starting boundary for 3D simulations is indicated by the bold horizontal line emanating from the nozzle exit. In general case, it is necessary to generate particles emanating from the face indicated by the dotted line. These particles, however, interact with the incoming flow rather far from the body surface, and the influence of this interaction is negligible. Therefore, this surface was eliminated from 3D modeling; thus, the number of model particles was reduced. Though the starting surface is drawn from the nozzle exit, not far from the plume core, the density on the starting surface is lower by an order of magnitude or more.

Figure 7 shows the superimposed lines of the number density and the temperature obtained in 3D modeling with the plume 3 at the altitude of 100 km with the use of the single-zone and multizone approaches. The differences in the flow field are mainly observed downstream the plume. The isoline in the region of the working surface coincide. The difference in the distributions of the surface

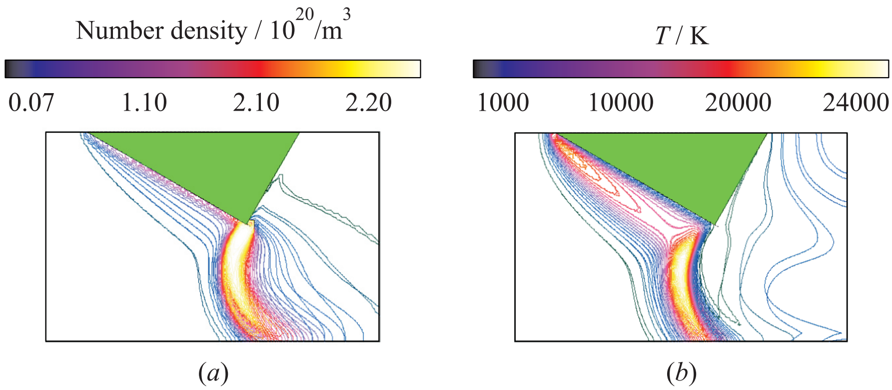


Figure 7 Comparison of single-zone and multizone simulations ($H = 100$ km, plume 3): (*a*) number density and (*b*) temperature.

(distributed) and integral characteristics is commensurable with the statistical error of the DSMC method.

In the example considered, the multizone approach allows 25% speedup of the computation process. The modeling time for a denser plume, however, can decrease severalfold. It should be borne in mind that the multizone approach in this problem formulation can lead to some distortions in studying the surface pressure distribution downstream the plume source. Nevertheless, this approach can be used for estimations.

6 CONCLUDING REMARKS AND FUTURE WORKS

The influence of the thruster plume – surface interaction on aerodynamic characteristics of a model with a configuration similar to IXV is estimated. Based on considered cases, the following conclusions can be done:

– it is important to take into account the interaction of the thruster plume with the incoming flow for altitudes below 120 km;

– changes in aerodynamic characteristics due to this interaction can reach 10% and more; and

– the multizone approach can be used to study this interaction.

Now that the technology and methodology is established, applying it on the actual configuration of the IXV is an ongoing work.

ACKNOWLEDGMENTS

The authors express their gratitude to the Information-Computational Center of the Novosibirsk State University for the possibility of using its computational cluster on which the major computations for the present study were performed.

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