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An approach of drag force decrease for combined cylinder AD bodies under the action of microwave and laser energy deposition

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ABSTRACT

The effect of microwave and laser "heat spots" on a supersonic flow past a hemisphere-cylinder and a hemisphere-cone-cylinder at Mach 2.1 to 3.45 is studied. Drag forces are evaluated for the known experimental data on stagnation pressure dynamics. The energy deposition by laser and microwave discharges in the oncoming flow is approximated by heated rarefied layer/layers ("filaments"). Approaches for decreasing the frontal drag force for the considered microwave and laser experiments are suggested. Complex conservative difference schemes are used in the simulations.

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1. Introduction

An idea of flow control with the use of spatially distributed energy sources located in an oncoming supersonic flow was suggested in the last decades of the previous century and now the effect of an energy source on the flow past an aerodynamic (AD) body is a wide research area of aerospace engineering (see survey in [1]). Details of unsteady interaction of a space distributed energy source with a supersonic shock layer produced by a sphere were examined in [2,3]. Drag reduction on the surface of a sphere was shown to be connected with a rarefaction wave reflection. In [4] laser energy impact on supersonic flow for the purpose of flow control was suggested. Effects of a local heating on wave drag reduction are investigated in [5–7]. In [8] a potential of simulations using the Euler equations for obtaining the evolution of localized energy deposition zones during an interaction with a shock wave in air is demonstrated via the comparison with the available experimental data for an optical discharge.

In [9,10] the interaction of a microwave (MW) discharge with AD bodies "hemisphere-cylinder" and "hemisphere-cone-cylinder" is examined experimentally and simulated numerically using the Euler equations added by a consideration of a large number of chemical reactions. In [11] the laser action on the flow past a hemisphere-cylinder is examined experimentally for three values of the impulse energy. A longitudinal heated channel (layer) as a model of energy deposition was suggested in [12]. Vortex mechanism of drag force reduction under the action of MW filament (modeled as a heated channel) on a supersonic shock layer was established in calculations in [13]. It was shown that in the result of the interaction of a MW filament with a shock layer produced by a blunt cylinder a vortex is generated which affects the body surface and is responsible for drag reduction together with stagnation pressure decrease. In [14] a combined filament consisting of two heated layers was considered for modeling a spatially inhomogeneous energy source. A double-vortex mechanism which enforced the drag force reduction was observed in this case. These vortices were shown to be generated as the result of the Richtmyer–Meshkov instability [15].

The effect of the heated gas areas ("heat spots") action on supersonic flow due to MW and laser discharges was considered in [16]. The parameters of these "heat spots" were found at the conditions of the experiments from [9–11] assuming their shapes to be heated rarefied layer/layers ("filament" or "combined filament").

This paper is a continuation of [16]. We analyze the resultant drag forces here. Details of the flows past a hemisphere-cylinder and a hemisphere-cone-cylinder and mechanisms of the drag forces decrease are evaluated. Analysis of the drag force dynamics together with the stagnation pressure dynamics for dif-

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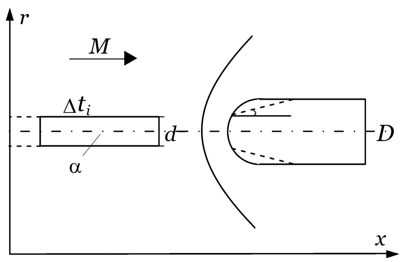

Fig. 1. Flow past consider AD bodies containing the MW filament.

ferent values of gas rarefaction degree, radius and length of the filaments for two considered simple AD shapes is presented.[1]

2. Methodology and example of scheme validation

Numerical simulations are based on the Euler equations for an ideal gas with the ratio of specific heats $\gamma = 1.4$:

$$\frac{\partial \mathbf{U}r}{\partial t} + \frac{\partial \mathbf{F}r}{\partial x} + \frac{\partial \mathbf{G}r}{\partial r} = \mathbf{H}, \tag{1}$$

$\mathbf{U} = (\rho, \rho u, \rho v, E)^T$, $\mathbf{F} = (\rho u, p + \rho u^2, \rho uv, u(E + p))^T$, $\mathbf{G} = (\rho v, \rho uv, p + \rho v^2, v(E + p))^T$, $\mathbf{H} = (0, 0, p, 0)^T$, $E = p/(\gamma - 1) + 0.5\rho(u^2 + v^2)$.

Here ρ, p – density and pressure of the gas, u and v are x- and r-components of the gas velocity, $\varepsilon = p/\rho(\gamma - 1)$, $E = \rho(\varepsilon + 0.5(u^2 + v^2))$. The energy deposition is assumed to have the shape of a heated rarefied layer (filament) with the density $\rho_i = \alpha\rho_\infty$ and other parameters equal to those of undisturbed flow (the index ∞ is referred to the freestream parameters). Here α is the parameter of gas rarefaction in the filament. The flow configuration and applied notations are presented in Fig. 1. The considered shapes of AD bodies are indicated.

Complex conservative difference schemes are used in the numerical simulations [17]. Fig. 2 displays an example of the scheme validation. Simulations on two different numerical grids are compared at one instant of time for supersonic flow past a blunt cylinder interacting with a filament of infinite length at Mach 1.89. Here the grid 1 has 400 points per D (Fig. 2a) and the grid 2 has 200 points per D (Fig. 2b). The related drag forces dynamics have been considered (Fig. 2c). The curves practically coincide with each other (for convenience the body face was moved in the case of grid 2). Other examples of the schemes validation and comparison of numerical and experimental data are presented in [16,18].

3. Vortex and double-vortex mechanisms of front drag force reduction

Comparison of one-layered and two-layered energy sources action on supersonic flow past a hemisphere-cylinder is displayed in Fig. 3 (here the enlarged parts of the calculation domain are presented). One can see the vortices resulting from energy release – shock layer interaction. In [14] the increasing drag force reduction from 23% to 36% was obtained via the introduction of an internal more heated part into the filament. Indeed, the model of two-layered combined filaments gives a possibility of modeling inhomogeneous heated gas areas changing the frontal drag force. In [16] the one-layered model was shown to be adequate for MW impact on supersonic flow simulation, and two-layered model was shown to be adequate for laser impulse impact. Vortex and double-vortex mechanisms are acting there, accordingly.

[1] The results were presented at European Drag Reduction and Flow Control Meeting, March 2015, Cambridge, UK and 6th European Conference for Aeronautics and Space Sciences June–July 2015, Krakow, Poland.

Table 1
Filament parameters.

Definition	Dimensional parameter	Non-dimensional parameter	Normalizing parameter
d	4.5×10^{-3} m	0.09	5×10^{-2} m
Δt_i[a]	17 µs	0.095	178.6 µs
α		0.65	

[a] Time duration of the filament/bow shock wave interaction.

4. Interaction of MW and laser energy sources with supersonic cylinder bodies

4.1. Effect of MW discharge on the drag force on a hemisphere-cylinder

Supersonic flow past the hemisphere-cylinder under the conditions of the experiments from [9] is considered ($M = 2.1$). The heat area produced by MW discharge is supposed to have a shape of a heated rarefied filament and characterized by the parameters obtained in [16]. These are the parameters which give the best agreement with the experimental stagnation pressure *vs* time.

The flow configuration and applied notations are presented in Fig. 1. The defining filament parameters are presented in Table 1. Here we are interested in a length of the filament in time. Density and pressure fields are depicted in Fig. 4 at an instant after the filament has completely penetrated the blunt body shock. Generation of a vortex is seen as the result of the Richtmyer–Meshkov instability [15]. The dynamics of the front drag force on the hemisphere and the stagnation pressure are presented in Fig. 5 (here p_0 is the pressure at the stagnation point for the steady flow without energy release). It is evident that under the conditions of the experiments [9] the maximum decrease in the stagnation pressure is about 20% but the corresponding maximum decrease in the front drag force is only about 3%.

Let us consider the details of an infinite filament/cylinder shock layer interaction [16] for the answer to a question: how it is possible to increase the front drag force reduction guided by the observed characteristics of the heated area? The dynamics of the related front drag forces on the hemisphere for different values of the rarefaction degree α in the case of the infinite filament are presented in Fig. 6. Here F_0 is the value of front drag force on the hemisphere for the steady flow without energy release.

In [16] two mechanisms of front drag force reduction have been demonstrated connected with rarefaction wave reflection (established in [2]) and the vortex action [13]. One can see the action of both mechanisms in Fig. 6 for different α, e.g. for $\alpha = 0.65$ at the first stage, for $0.77 < t < 0.81$ the drag reduction is caused by the rarefaction wave reflection and for $0.89 < t < 1.26$ it is connected with the vortex action. It is seen that the vortex causes larger drag reduction which is greater for smaller α. For $\alpha = 0.65$ it achieves 8%. Thus for increasing the drag force reduction it is necessary to lengthen the filament in order for a stage of the vortex action to be included.

Fig. 7 shows the dynamics of the front drag force on the hemisphere for the bounded filament under the conditions of the experiments from [9] and for the infinite one with the same characteristics. One can see that the drag force reduction can be increased up to 8.2% and in the steady state – up to 7.2% (see Table 2, here F_{st} is the steady value of the front drag force). It is easily shown that for this increased reduction the duration of the MW filament action on the hemisphere surface has to be increased approximately 90 µs. Thus, the length of the MW energy produced “heat spot” in the freestream flow has to be approximately equal to the diameter of the cylinder.

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