Aerospace Science and Technology 43 (2015) 343–349

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Interaction of microwave and laser discharge resulting “heat spots” with supersonic combined cylinder bodies

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ARTICLE INFO

Article history:
Received 19 December 2014
Received in revised form 19 March 2015
Accepted 20 March 2015
Available online 26 March 2015

Keywords:
Flow control
Supersonic flow
Microwave discharge
Laser discharge
Richtmyer–Meshkov instability
Vortex structure

ABSTRACT

The models of energy deposition in an oncoming flow via heated rarefied channel/channels (“filaments”) are used for consideration of the effect of microwave and laser discharge energy deposition on supersonic flows past combined cylinder bodies. Flow details accompanying streamlining bodies “hemisphere–cylinder” and “hemisphere–cone–cylinder” are simulated numerically for an inviscid perfect gas at Mach 2.1 and 3.45. Unsteady vortex structures caused by the Richtmyer–Meshkov instability together with a rarefaction wave reflection are shown to be the reasons for the reduction in stagnation pressure. Optimization of the shape and parameters of “heat spot” areas resulting from MW and laser energy deposition have been realized on the basis of flow analysis and comparison with experimental data. Estimations of the value of energy needed for generating the heated gas area with the obtained parameters are provided.

1. Introduction

Experimental and numerical investigations of an energy deposition impact on supersonic flow have been conducted by many researchers since the final decades of the last century (see the survey [1]). Details of the unsteady streamlining of a sphere in a supersonic flow containing an energy source were obtained in [2]. The initial decrease in the stagnation pressure was shown to be connected with the reflection of the rarefaction wave. Laser energy deposition in supersonic flow for the purposes of flow/flight control was suggested in [3]. In [4] experimental data are presented for the interaction of laser discharge plasma with a supersonic body “hemisphere–cylinder”. In [5] the effect of microwave (MW) plasmoid was established to be effective in reducing the stagnation pressure (together with the drag force) for flows past a cylinder and a plane body. This effect was shown to be caused by another mechanism of drag force reduction, namely, the vortex action. The vorticity production was generated by the Richtmyer–Meshkov instability [6,7].

In [8,9] the interaction of an MW discharge with a hemisphere–cylinder and a hemisphere–cone–cylinder is examined numerically using the Euler equations coupled with an extended thermochemistry model and the experimental results on the stagnation pressure dynamics are presented. These experimental data were studied for the evaluation of the shape and parameters of the heat areas produced by the MW discharge in [10]. Details of similar flows corresponding to laser experiments are obtained in [11]. Flow structure rearrangement under the action of heated rarefied channel/channels (heat layers) originating in the oncoming flow was considered in [12,13]. Evaluation of discharge efficiency and the energy needed for the heated area production are presented in [14]. In [15] the effect of the energy source having a shape of an instantaneous explosion of the spherical gas volume is researched for the conditions of the experiments [4]. The results showed that the perfect gas Euler simulations with these initial conditions were incapable of accurately predicting the experimental stagnation pressure dynamics. In [16] the longitudinal energy source with the temperature profile is modeled for the evaluation of the laser discharge influence on the flow past a blunt cylinder at $M = 3$. In [17] the model of the heated channel/channels is used to study of the longitudinal heat area effect onto a flow past a hemisphere–cylinder under the conditions of the experiments [4].

The present paper generalizes the results of [10,17]. The attempts are made to clarify the understanding about the shape and characteristics of the heated gas areas (“heat spots”) resulting from the MW or laser discharge in the oncoming flow, and the interaction of the “heat spot” with a simple aerodynamic shape. The energy deposition is modeled as a heated rarefied channel(s) (“filament” or “combined filament”). Numerical simulations using the Euler equations for an ideal gas were performed. Aerodynamic

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http://dx.doi.org/10.1016/j.ast.2015.03.018
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Nomenclature

Variables

p_t	unsteady stagnation pressure
p_b	pressure on the surface of a hemisphere
β	angle of a point on the surface of a hemisphere
D, D_1	diameters of aerodynamic bodies
d, d_{ext}, d_{int}	diameters of energy sources
$\alpha, \alpha_{ext}, \alpha_{int}$	values of the degree of gas rarefaction inside energy sources
L	length of an energy source
t_i	time moment of energy source arising in the steady flow

Constants

M	Mach number of oncoming flow
γ	ratio of specific heats, $\gamma = 1.4$
R	ideal gas constant

Indices

∞	freestream parameters
0	parameters at the stagnation point for the steady flow without energy release

bodies "hemisphere–cylinder" and "hemisphere–cone–cylinder" are examined. Details of the flows and mechanisms of stagnation pressure decrease are evaluated. Parameters of the MW filaments which provide the stagnation pressure dynamics close to the experimental data from [8,9] are established. For the laser impulses with energies of 13 mJ, 127 mJ and 258 mJ the characteristics of the combined filaments providing the stagnation pressure dynamics approximating the experimental data from [4] have been found. Estimations for the values of energy necessary for the creations of the filaments with the obtained parameters are presented.

2. Methodology

Numerical simulations of the interaction of an energy release with a supersonic shock layer are based on the Euler equations for an ideal gas for cylindrical flow symmetry:

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

$$\mathbf{U} = (\rho, \rho u, \rho v, E)^T, \qquad \mathbf{F} = \big(\rho u, p + \rho u^2, \rho u v, u(E+p)\big)^T,$$

$$\mathbf{G} = \big(\rho v, \rho u v, p + \rho v^2, v(E+p)\big)^T,$$

$$\mathbf{H} = (0, 0, p, 0)^T, \qquad E = p/(\gamma - 1) + 0.5\rho\big(u^2 + v^2\big). \tag{1}$$

Energy deposition is modeled via creation of a heated rarefied channel/channels [12] ("filament" or "combined filament"). The filament is modeled via the inflow boundary condition ($x = 0$) as a channel of low density. The static pressure and velocity of the gas in the channel are equal to those of the undisturbed flow. The filament is supposed to arise instantly in the steady flow in front of the bow shock wave at the time moment t_i. The parameters at the stagnation point differ from the theoretical ones by 1–2% at this moment.

The numerical code is based on the complex conservative difference schemes [18]. The schemes use the differential consequences of (1) for achieving second order accuracy in space and in time and the expanded set of the divergent variables for enlarging a complex of the conservation properties. The body's boundaries are included into the calculation area without breaking the conservation laws within it. A staggered Cartesian difference grid is used.

In Fig. 1 the comparison of the calculation results with the results from [15] and the experimental ones from [4] is presented for the steady flow past a hemisphere–cylinder at Mach 3.45. It is seen that the computational results on a basis of the complex conservative difference schemes agree with the results from [15] and are close to the experimental data.

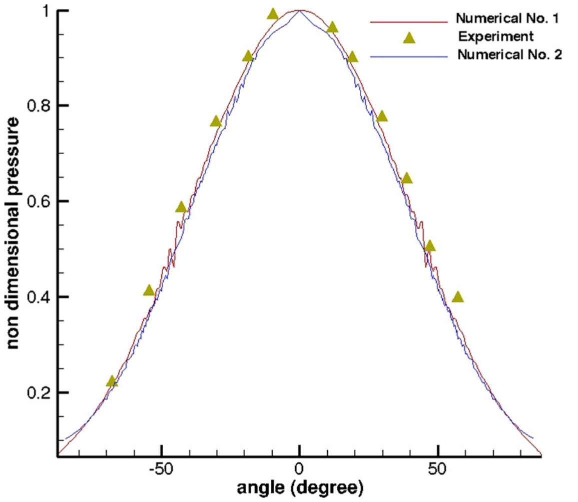

Fig. 1. Relative pressure values on the hemisphere at the steady state: Numerical No. 1 – calculation [15]; Numerical No. 2 – calculation based on the complex conservative scheme; Experiment – results from [4].

3. MW filament interaction with supersonic combined cylinder bodies

Supersonic flow past a cylinder body with the axis parallel to the oncoming flow is considered. Two shapes of the cylinder body are examined: hemisphere–cylinder and hemisphere–cone–cylinder. The filament of diameter d is modeled as a channel of low density ρ_i where $\rho_i = \alpha\rho_\infty$ for $0 \le r \le 0.5d$ (the calculation area is bounded by the axis of symmetry). Schematic sketches and applied notations for the two considered body shapes are presented in Figs. 2, 3. The computational grid used equal spatial steps $h_x = h_r$, with 400 nodes per body diameter D.

3.1. Interaction of MW filament with the supersonic body "hemisphere–cylinder"

Consider the flow past a hemisphere–cylinder as illustrated in Fig. 2. The governing flow parameters for the calculations are in accordance with the experiments in [8] (Table 1) Here the value of the Mach number is determined based on the experimental data from [8], and the normalizing parameter for time is $t_n = 178.6$ µs. In Fig. 4 density contours are presented for the interaction of the MW discharge heated area (modeled as a filament of bounded length) with the cylinder shock layer for $\alpha = 0.65$, $d/D = 0.2$ and $L/D = 0.4$. The values of the absolute non-dimensional time are indicated. The dynamics of the stagnation pressure normalized by 1.01325×10^5 Pa are presented in Fig. 5.