11. GAS DYNAMICS OF SUPERSONIC WAKE BEHIND A PLANAR ENERGY SOURCE

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Abstract. Gas dynamic structure and parameters of supersonic wake behind a planar energy source were investigated. The subcritical regimes of energy input (regimes of weak detonation or supersonic combustion) are considered. The planar and the axisymmetric flow of a monoatomic gas were analyzed. Two numerical approaches: the direct simulation Monte Carlo and the complete Navier-Stokes equations were used for the investigation. The investigation was carried out for the range of Mach number M=5-20 and Reynolds numbers Re=1-10^5 of undisturbed flow.

The peculiarity of this kind of supersonic flows is small velocity variation in the flowfield. For Re>Re_k (Re_k≈100 - for planar, Re_k≈10^4 - for axisymmetric flow) this fact leads to the formation of a very long high-temperature region with almost constant parameters near the axis behind the initial gas dynamic region. In this region density and dynamic pressure are significantly lower than in the undisturbed flow. This effect may be used for reduction of drag and thermal loadings of an object by energetic influence on supersonic flow in front of the object.

Introduction

The works [1-3] were focused on the investigations of supersonic flow behind a planar energy source, which constitutes the gas dynamic discontinuity with energy input. Supersonic wake behind such energy source represents the supersonic under-expanded jet in the supersonic concurrent flow. Under certain conditions in the paraxial zone of the wake the value of dynamical pressure can be considerably lower than in undisturbed flow. The object’s drag in this wake zone is lower than in undisturbed flow. The effect of the object drag (and heating load) decrease, naturally, depends on the wake gas dynamic structure and position of the object in the wake.

This work continues the investigations [1-3]. Here, the results of the numerical flow investigations in the wake behind a planar discontinuity with energy input, in the weak detonation regime (supersonic combustion) are discussed. The planar and axisymmetric monoatomic gas (argon) flow is considered. The investigation is carried out for the numbers M=5-20, characteristic Reynolds numbers Re=1-10^5 (from free-molecular to continual flow regimes) and different values of energy input.

1. Parameters of the energy source

Parameters behind a planar energy source are determined by the mass, energy and impulse conservation laws, amplified with the state equation

\[ ρ_i u_i \left( \frac{u_i^2}{2} + c_p T_i \right) = ρ_\infty M_\infty \left( \frac{u_\infty^2}{2} + c_p T_\infty \right) + \rho_\infty H_\infty q, \]  

\[ p = ρ \cdot R \cdot T. \]  

Here \( ρ \) - density, \( p \) - pressure, \( T \) - temperature, \( u \) - longitudinal velocity component, \( R \) - gas constant, \( c_p \) - specific heat capacity at constant pressure, \( q \) - energy input to the mass unit at time unit in the source, indexes \( \infty \) and \( i \) are related to the parameters on front of and behind the source accordingly.

Solution of the system of equations (1)-(4) for the weak detonation regime can be presented in the following way [1].

\[ T_i = \frac{1}{2(1+β)^{1/2}} \times \left[ \frac{1}{T_\infty} + \frac{1}{T_\infty} \left( \frac{λ_{\infty}}{λ_i} - \frac{λ_i - 4\cdotβ}{λ_{\infty}} \right)^{1/2} \right]. \]

\[ \frac{ρ_i}{ρ_\infty} = \frac{λ_{\infty} \cdot u_{\infty}}{λ_i \cdot u_i}, \]  

\[ \tau = \frac{T_i}{T_\infty} = \frac{1 - λ_{\infty}^2 / ε}{1 - λ_i^2 / ε} \cdot (1 + β), \]

\[ \frac{p_i}{p_\infty} = \frac{ρ_i \cdot T_i}{ρ_\infty \cdot T_\infty}. \]
Here, $\lambda = u/u_*$ - velocity coefficient, $u_*$ - critical velocity, $\beta = q/c_p T_\infty$ - heating parameter, $T_\infty$ - the stagnation temperature of the gas at the infinity, $\varepsilon = (\gamma+1)/(\gamma-1)$, $\gamma$ - ratio of heat specific capacities.

The important peculiarity of the gas flow through the gas-dynamic discontinuity with energy input is relatively small variation of $u$ and $p$ with considerable change of $T$ and $\rho$ [2]. For the monoatomic gas the change of $u$ at the discontinuity is in the limit $1 > u_i/u_\infty > \gamma/(\gamma+1)$. The limit value of energy input in the weak detonation regime for monoatomic gas corresponds to $\lambda_\infty = 1$, $M_\infty = 1$ and $\beta = 0.56$ [1].

2. Computation methods

For the simulation of the flow in the wake two methods are applied: direct Monte Carlo simulation method (DSMC) and numerical method of solving the complete system of Navier-Stokes equations (NSE). For DSMC the program of direct simulation, based on the Bird’s version [4], was used. The DSMC algorithm is described in [5]. In the terms of molecular gas dynamics the wake flow is determined completely by the set of the following basic parameters: $M$, $Re$, heating parameter $\beta$ and particles model [5]. The model of particles is the model which determines the section and mechanics of particles collisions. The collisions were supposed to be elastic. For the collision partners selection the NTC Bird’s scheme was used. The mechanics of intermolecular collisions corresponded to the VHS model [4]. The algorithm of data parallelization of DSMC for multiprocessor computers with shared memory [6] were used for computation.

In NSE approximation the calculation algorithm is based on the method of physical factors splitting. In accordance with this method within one time iteration the whole problem is replaced with two more simple problems - inviscid gas flow problem and problem which incorporates viscous momentum transfer processes, energy dissipation and thermal conductivity. For numerical solution of non-viscous problem explicit ENO scheme of the second precision order was used [7], and for the solution of the viscous problem explicit scheme with the use of central differences was used [8]. The perfect gas flow was simulated. In the NSE approximation wake flow is completely determined by the values $M_\infty$, $Re_\infty$, $\beta$ and ratio of specific heat capacities $\gamma$ (here $\gamma = 1.67$).

Setting of $M_\infty$, $T_\infty$, and $\beta$ determines gas dynamics parameters of the gas behind energy source ($x=0$, $y\leq R$) uniquely. The rectangular simulation region was used. At the input ($x=0$, $y>R$) undisturbed flow parameters were settled. Transverse region size was selected rather big in order to exclude the impact of side bounds on the flow. In DSMC the “condensable” wall condition (particles that reached the exit bound, were excluded from consideration) at the exit boundary was used, in NSE approximation traditional “soft” conditions were used. The problem was solved by the time-asymptotic approach.

3. Computation results and analysis

The computations in the range of numbers $Re = \rho_\infty u_\infty R/\mu_\infty = 1 - 10^4$ were carried out by DSMC, in the range of numbers $Re_\infty = 10^3 - 10^5$ by NSE ($R$ - radius or half-width of energy source, $\mu_\infty$ - dynamical viscosity). In the range of numbers $Re_\infty = 10^3 - 10^4$ the results of the computation by both methods correlate with each other successfully. The main attention is paid to the jet flow gas dynamic structure specifications behind energy source. As it was already mentioned this flow is considered to be laminar under-expanded supersonic jet in the supersonic concurrent flow. The simulation region includes initial gas dynamical and transitional stream segments. For the initial segment the presence of shock-wave structure and strong pressure non-uniformity in longitude and transversal direction is typical. On transitional segment the viscosity impact gradually becomes determinative. Longitude and transversal pressure gradients decrease considerably. At the end of the transitional segment the isobar flow establishes.

In the Fig.1 (on the left) gas dynamic structure and parameters of the axisymmetric jet initial segment behind energy source (qualitative picture corresponding approximately to the ideal gas flow, i.e. $Re \to \infty$) are shown. The gas heating in energy source leads to increase of pressure and consequent gas expansion. In the wake behind the source there is a formation of the structure which incorporates several surfaces of strong discontinuity: head shock wave 1; tangential discontinuity 2, which divides cold and hot gases; hanging shock ACA etc. In the free ACA expansion region, which is limited by the hanging shock, gas expands intensively. This process is accompanied with decrease of $p$, $\rho$, $T$ and increase of $u$, $M$. Dynamical pressure $p_D = \rho u^2/2$ drops to the value that is considerably smaller than $p_D = \rho_\infty u_\infty^2/2$. Analogous gas dynamic structure and parameters of the planar flow behind energy source are shown in the Fig.1 (on the right).
Fig. 1. Gas dynamic structure of the initial segment (a, b) and axial profiles $p/p_\infty$ (c, d), M (e, f) and $p_D/p_{D\infty}$ (g, h) for axisymmetric (on the left) and planar (on the right) flow behind an energy source; $Ar, M_\infty=10, \tau=10, \beta=0.15, Re=6.5 \times 10^4$.

Fig. 2. Axial (a) and transversal profiles $p_D/p_{D\infty}$ for axisymmetric (b) and planar (c) flow behind energy source; $Ar, M_\infty=10, \tau=10, \beta=0.15, Re=6.5 \times 10^4$. 

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The planar flow structure differs from the axisymmetric flow structure significantly. The main difference consists in the absence of strong inner compression shocks in the heated gas planar flow. Gas dynamic structure of the inner segment determines the flow on the transitional jet segment. In the Fig.2 axial and transversal segments for the axisymmetric (b) and planar (c) flow behind energy source are shown. The simulation results demonstrate the effect of anomaly big long “range” - unusually long transitional segment with maintenance of paraxial zone with almost invariable parameters and transversal size. For the computation variant which is represented in the Fig.2, the transversal size of the axisymmetric zone is approximately $3R$, for the planar – $6R$. The stability of the parameters in paraxial zone is kept within the whole simulation region.

Regimes with large “range” realize in planar flow at $Re>10^4$ and axisymmetric flow at $Re>10^2$. At smaller numbers $Re$ there is no paraxial area with stable parameters on the transitional segment. In the Fig.3 axial and transversal profiles $p_D/p_{D\infty}$ for planar flow under $Re=0.65-6500$, obtained by DSMC, are shown.

As it is shown by the present investigations supersonic jet flows behind planar energy source form the separate class of jet flows with their special features. The presence of extended regions with decreased dynamical pressure in these gets can be used to obtain the drag decrease and object’s heat loading, placed in the wake behind energy sources of this type.

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References


