34. GLOBAL THERMAL-BARO-DIFFUSION EFFECT IN WEAKLY IONIZED NONEQUILIBRIUM SHOCK LAYER

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Abstract. A numerical study of the weakly ionized shock layer structure is carried out through a stagnation line flow analysis with an accurate treatment of ambipolar diffusion phenomena in two-temperature argon plasma. Computations have been performed for free stream conditions related to a ballistic range test. It is shown that baro-diffusion and thermal diffusion caused by the separation of the electron temperature and gas temperature in the bow shock affect the entire shock layer structure and provide the "anomaly" diffusion of the charged particles. The ratio of the electron partial pressure and gas pressure in the free stream is found as a factor of the bow shock standoff and weakening. The two-peak structure of the ambipolar thermal-baro-diffusion-induced electric field inside the bow shock is discovered.

Nomenclature

- $c_i$: mass fraction of ions
- $D_{IA}^{(1)}$: binary ion-atom diffusion coefficient in first approximation
- $D_{Iamb}^{(1)}$: ion ambipolar diffusion coefficient in a three-species mixture in first approximation
- $e$: electron charge
- $E_{A26}$: ambipolar electric field
- $I_{J}^{m}$: ion mass diffusion flux
- $k$: Boltzmann constant
- $k_{PI}$: ion ambipolar baro-diffusion factor
- $k_{TI}$: ion ambipolar thermal diffusion factor
- $MM$: Mach number
- $p_e$: electron partial pressure
- $p$: pressure of the mixture
- $Re$: Reynolds number
- $R_w$: nose radius
- $T_h$: gas temperature
- $T_e$: electron temperature
- $V$: flow velocity
- $y$: dimensionless distance from the body

Greek symbols

- $\rho$: mass density

Sub- and superscripts

- $e$: electrons
- $h$: heavy particles
- $w$: wall
- $\propto$: free stream

Introduction

Since prior Russian data [1-3] indicating the bow shock weakening in the weakly ionized supersonic flow, many researches have focused attention on this phenomena and on the accompanying ill-understood effects such as an increase in shock standoff distance. The questions associated with nonuniform heating, molecular relaxation processes and proper plasma physics have been discussed, novel ballistic range plasma experiments in air and argon have been conducted and new measurement techniques have been developed [4,5]. But so far we lack on the supersonic plasma remains an open issue. An adequate fluid dynamic model with the key thermodynamic and plasmadynamic features should be developed in order to explain the data and to predict aerodynamic drag reduction. We believe that such a model must include an accurate mathematical theory of transport processes in plasmas [6]. In Refs. 7 and 8 a rigorous formalism of the ambipolar diffusion in multi-component two-temperature plasmas was developed and an application of the Stefan-Maxwell relation for ions in the three-species plasma was given through CFD analysis of the supersonic weakly ionized argon plasma flow along the stagnation line. It was indicated that thermal diffusion caused by the separation of the electron and heavy particle temperatures and coupled baro-diffusion effect provided the global effect on the ions in entire shock layer.
model of the weakly ionized frozen three-species two-temperature supersonic plasma flow along the stagnation line is applied to study the weakly ionized shock structure for conditions related to a ballistic range test in argon. Some results of CFD analysis of the shock layer structure and details of the ion diffusion inside the bow shock and boundary layer are presented. The special attention has been paid to the ambipolar electric field switching due to tendency of charge separation within the bow shock structure and boundary layer as well.

1-D Fluid Dynamic Model

The supersonic flow of an argon flow past a blunt body is supposed to be weakly ionized in the free stream with different gas and electron temperatures and the shock layer is considered as a frozen one. The governing equations for the 3-species two-temperature plasma in the case of ambipolar diffusion include the simplified 1-D Navier-Stokes equations, the electron energy equation, the heavy particles energy equation, and the ion diffusion equation. According to Ref. 8, the expression for the diffusion flux of ions was used in the "field-free" form and it included contributions due to the concentration diffusion, the baro-diffusion effect, and a novel thermal diffusion term linked to the gradient of the ratio of the electron and heavy particle temperatures:

\[ \frac{\partial c_I}{\partial t} = D_{lamb}(t) \left( \nabla c_I + k_{pl} \nabla \ln p + k_{TI} \nabla \theta \right) \]

\[ D_{lamb}(t) = (t+0)^\frac{1+c_I}{1+c_I} D_A(t) \]

\[ k_{pl} = 0 \frac{1+c_I}{1+c_I} \left( \frac{c_I}{c_I+1} \right)^2 \]

\[ k_{TI} = \frac{1}{1+c_I} \left( \frac{c_I}{c_I+1} \right)^2 \]

\[ \theta = T_e - T_h \]

The ambipolar electric field can be expressed as:

\[ \frac{\partial E_A}{\partial t} = -k_{Te} \frac{c_I}{e} \left( \frac{1}{1+c_I} \nabla \ln c_I + \nabla \ln p + \nabla \ln \theta \right) \]

Results and Discussion

Computations were carried out at \( M = 3, Re = 2.33 \times 10^4 \), \( p = 3.25 \times 10^3 \) N/m\(^2\), \( T_{in} = 600 \) K, \( T_{out} = 200 \) K, \( c_p = 0.75 \) and \( T_{wall} = 20, 100 \) and 200. Some of these parameters were close (more or less) to conditions of the ballistic range tests in weakly ionized argon reported in Ref. 5.

Our computations have not indicated any influence of the on the aerodynamics at \( c_I < 10^{-4} \) as far as \( T_e/T_h < 10^2 \). A gasdynamic shock layer structure is found to be sensitive to the ionization at \( c_I = 10^{-4} \). Figure 1 shows some evidence of the shock standoff increasing at \( c_I = 10^{-4} \), if the electron temperature in free stream increases. The ratio of electron and gas partial pressures in free stream appears to be a factor of the bow shock standoff and wean, because electron temperature changes rather smoothly across the shock [10].

![Figure 1. Pressure distribution along stagnation line](image)

Figure 2 shows the distribution of the normalized ion mass fraction \( \frac{c_I}{c_I} \) along the stagnation line for the case \( c_I = 10^{-4} \). If the thermal-baro diffusion effects are not taken into account, the ion diffusion equation has an exact solution for a non-catalytic wall case as \( \frac{c_I}{c_I} = 1 \). Keeping this in mind, we see that the thermal and pressure gradients...
cause global changes of the ion distribution inside the boundary layer, shock layer and bow shock. The ions and electrons, reaching the bow shock, are braked by the strong gradients of the pressure and gas temperature. As a result of interference of the ion mass fraction, pressure and temperature gradients, the ion fraction reaches a local minimum just outside the gasdynamic shock and a local maximum inside the bow shock. At the present free stream conditions, the ion distribution looks even more complicated than observed in our prior computations [8], where a single maximum of the ion fraction was indicated. Inside the boundary layer, the ions are affected by the strong gas temperature gradient near the wall and are forced out in the direction of the ion fraction gradient. At the specified wall conditions, the strong "anomalous" ion fraction gradient near the non-catalytic wall compensates exactly the gas temperature gradient and the interference of these gradients leads to a second maximum of the ion fraction inside the shock layer. So, the entire shock layer structure is affected by the ambipolar baro-thermal diffusion.

Fig. 2. Ion mass fraction along stagnation line:

\[ \frac{C_{\text{ion}}}{T_{\text{ion}}} \propto \frac{T_{\text{ion}}}{T_{\text{e}}} \]

Figure 3 shows the distributions of the dimensionless ion diffusion flux along the stagnation line with the fine details concerning global ion diffusion. The ions accelerate just in front of the bow shock toward the body and brake inside the shock structure. The electron temperature in the free stream shifts the peaks of the ion diffusion flux upstream, though it does not affect much the peak magnitude. If, again, thermal-baro-diffusion of ions is neglected, the ion diffusion flux equals zero along the stagnation line in the non-catalytic wall case.

Fig. 3. Dimensionless ion mass diffusion flux along stagnation line:

\[ \frac{J_{\text{ion}}}{T_{\text{ion}}} \propto \frac{T_{\text{ion}}}{T_{\text{e}}} \]

Figure 4 indicates the switching of the ambipolar electric field inside the bow shock structure and inside the boundary layer as well. This electrostatic field prevents the charge separation due to diffusion of the electrons and ions. The distribution of the ambipolar electric field exactly follows the behavior of the ion diffusion flux: the directions, the peak positions, and locations of the points where both functions equal zero within shocks are the same. The analysis of the ambipolar electric field reveals two main findings: 1) The structure of the ambipolar electric field does not depend on the degree of ionization, and 2) The electric field amplitude reaches a level of \( \sim 2 \cdot 10^4 \) V/m. The presence of ion thermal diffusion in the non-catalytic wall case reveals some unusual trends. The ion diffusion flux equals zero along the stagnation line in the non-catalytic wall case.

In order to understand better how the electric field caused by charge separation can affect the shock structure, the parameter \( E_{\text{ion}}/p \), which characterizes the electric field, is shown in Fig. 5. The two-peak structure of this factor is discovered. The electron temperature in the free stream controls the location of the peaks. The increase of the electron temperature in the free stream causes both peaks to shift upstream. The amplitude of the outer peak is essentially higher than the amplitude of the inner one due to a pressure jump in the shock, while the electric field itself is higher at the inner layer.
Conclusions

The developed fluid dynamics model with an accurate treatment of ambipolar diffusion in two-temperature plasmas is found to be sufficient to explain some "anomalous" effects of the bow shock standoff decreasing and the shock weakening in the weakly ionized supersonic argon flow, though at the degree of ionization above $10^{-3}$.

The noticeable ambipolar thermal-baro-diffusion-induced electric field in shock structure is indicated. In order to enhance the sensitivity of our model to the lower ionization degree the effect of the charge separation-induced electric field should be implemented in the above fluid dynamic model.

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References


