Effect of Variation of Thermodynamic Property with Temperature on Modeling of Near-Surface Discharge

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I. Introduction

The electric discharge plasma as a flow control technique has been used for the enhancement of aerodynamic performance in the supersonic ducts and near surfaces,[1–3] such as drag reduction, separation control, manipulation of shock structures in inlet, and mixing enhancement in combustor. The main control mechanisms are distinguished as thermal and non-thermal. Magnetohydrodynamic (MHD) and electrohydrodynamic (EHD) are basically considered as a non-thermal method, and the thermal actuation due to Joule heating is assumed to be the primary influence of the notional electric discharge plasma employed in this paper.

The previous study[4] shows that the near-surface discharge has the ability to move the oblique shocks upstream in a Mach 2 inlet. However with increase of the discharge input energy, the temperature in the vicinity of the discharges is increased well above the range where the assumption of constant specific heat is valid, therefore the effect of the temperature on the thermodynamic properties should be taken into account.

The present study examines the effect of the near-surface discharges on the shock structures in a Mach 5 inlet comprised of two consecutive compression corners, and investigates the effect of the thermodynamic property on the modeling of the discharges. Four formulas of c_p (the specific heat at constant volume) are employed and the one for the perfect gas is used first. The other three will be presented in the full paper. Two discharges with 2kw per discharge are placed upstream of the first compression corner.

II. Flow Configuration

According to the flight corridor, an air-breathing vehicle can fly at Mach number up to 5 at 15km. Therefore a Mach 5 mixed compression inlet is considered with the freestream condition at 15km, where the static temperature and pressure are 200 K and 1.2×10^4 Pa, respectively. Two oblique shocks are generated at two consecutive compression corners in the streamwise direction, and interact with each other at the cowl lip. The near-surface discharge is modeled as a steady cuboid heat source and incorporated into the energy equation. The cross section is 3×3 mm, and the length in the streamwise direction is 20 mm to emulate the effect of vibrational-translational (V-T) relaxation on gas heating.

On the lower wall of the inlet, two compression corners are 7° and 14° in sequence and the first expansion corner is placed at 60mm downstream of the first compression corner. The inflow is fixed at 80mm upstream of the first compression corner which is designated as $(x, y) = (0, 0)$, and the inlet height at the inflow is 60mm. The cowl lip is designed according to the inviscid shock theory.

Two discharges are 6mm apart in the spanwise direction starting at 3mm away from the spanwse edge on the lower wall. Their trailing edge is placed at 20mm upstream of the first compression corner.

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III. Numerical Model

The differential form of the Navier-Stokes equations is written as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0 \quad (1)$$

$$\frac{\partial \rho \vec{V}}{\partial t} + \nabla \cdot (\rho \vec{V}\vec{V} + pI - \tau) = 0 \quad (2)$$

$$\frac{\partial \rho e}{\partial t} + \nabla \cdot [(\rho e + p)\vec{V} - q - \vec{V} \cdot \tau] = S \quad (3)$$

and the equation of state

$$p = \rho R T \quad (4)$$

where S is the power of energy input per unit volume. The above equations are solved by numerical discretization of space (x, y, z) and time (t). The third-order accurate AUSM scheme[5] is adopted for convective flux terms and the second order implicit method is used for time integration. The gradient reconstruction is based on node Green-Gauss method. Equations are solved using incomplete lower upper factorization (ILU), in conjunction with algebraic multigrid method. The time step is fixed at 1.0×10^{-7} s. The SST turbulence model[6] is used for the viscous assumption.

The c_p formula for perfect gas is written as

$$c_p = a + bT + dT^2 + eT^3 + ft^4 \quad (5)$$

where a =1048.698, b =-0.383719, $d = 9.45378 \times 10^{-4}$, $e = -5.48457 \times 10^{-7}$ and $f = 7.96425 \times 10^{-11}$ for $100 < T < 1000$, and a =873.915, b=0.384006, $d = -1.40056 \times 10^{-4}$, $e = 2.45385 \times 10^{-8}$, and $f = -1.6359 \times 10^{-12}$ for $1000 < T < 5000$.

IV. Numerical Results

The discussion is organized as follows. First, the inviscid basic state with no discharges is established to verify the theoretically designed cowl lip. The turbulence model is then added to account for the viscous effect. Last, the effect of the temperature is discussed.

The steady state without discharges is obtained first. Figs. 1 and 2 show the pressure and Mach number contours on the central plane for the inviscid state, respectively. Two oblique shocks originated from the compression corner is clearly observed to interact at the cowl lip. The expansion fans formed downstream propagates out of the computational domain and no visible reflection on the domain of interest is observed.

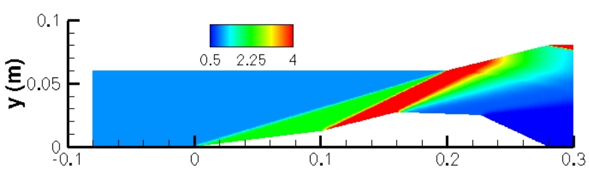

Figure 1. Pressure contours (inviscid)

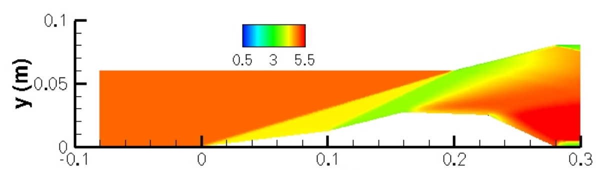

Figure 2. Mach number contours (inviscid)

The viscous effect is considered by SST model. The pressure and Mach number contours are shown in Figs. **??** and **??**, respectively. The oblique shocks interact with the boundary layer growing on both lower and upper walls, resulting in a small deviation of the shock interaction point from the designed cowl lip.

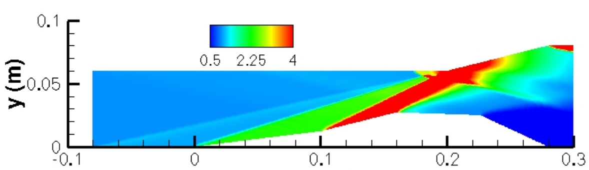

Figure 3. Pressure contours (SST)

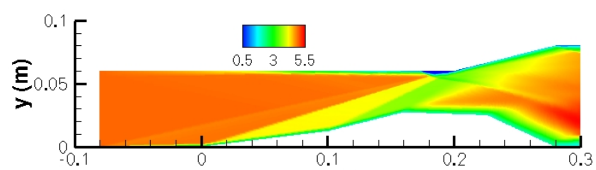

Figure 4. Mach number contours (SST)

Two discharges are integrated into the Navier-Stokes equations as a steady heat source, and the energy input is 2kw per discharge. Figs. 5 and 6 show the pressure and Mach number contours on the center plane, respectively. The first oblique shock formed at the first compression corner is moved upstream by the discharges while the second one is hardly moved since it is located far away from the first one and the effect of the discharges is small.

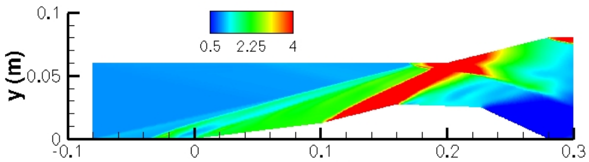

Figure 5. Pressure contours at 2kw

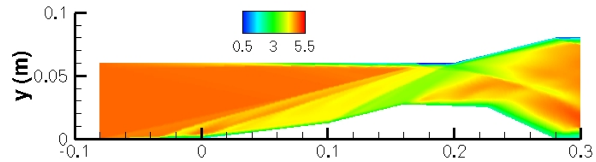

Figure 6. Mach number contours at 2kw

V. Acknowledgments

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