COMMUNICATIONS IN COMPUTATIONAL PHYSICS
Vol. **4**, No. 4, pp. 838-859

Commun. Comput. Phys.
October 2008

Electrostatic-Aerodynamic Compression in Hypersonic Cylindrical Inlet

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Received 20 June 2007; Accepted (in revised version) 18 October 2007

Communicated by Jan S. Hesthaven

Available online 28 May 2008

Abstract. Hypersonic magneto-fluid-dynamic interaction has been successfully performed as a virtual leading-edge strake and a virtual cowl of a rectangular inlet. In a side-by-side experimental and computational study, the magnitude of the induced compression was found to depend on configuration and electrode placement. To better understand the interacting phenomenon the present investigation is focused on a direct current discharge at the leading edge of a cylindrical inlet for which validating experimental data is available. The present computational result is obtained by solving the magneto-fluid-dynamics equations at the low magnetic Reynolds number limit and using a nonequilibrium weakly ionized gas model based on the drift-diffusion theory. The numerical simulation provides a detailed description of the intriguing physics. After validation with experimental measurements, the computed results further quantify the effectiveness of a magneto-fluid-dynamic compression for a hypersonic cylindrical inlet. A minuscule power input to a direct current surface discharge of 8.14 watts per square centimeter of electrode area produces an additional compression of 6.7 percent for a constant cross-section cylindrical inlet.

AMS subject classifications: 65Z05, 76K05, 76W05

Key words: Magnetohydrodynamics, hypersonic flows.

1 Introduction

At present, the scramjet appears to be the most promising hypersonic propulsion system due to its simplicity in construction and relatively few components in comparison with other systems [1,2]. The propulsion requirement for high-speed flight varies greatly

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from take-off to cruising condition and cannot be efficiently supported by a fixed configuration inlet. To improve propulsive efficiency in an operation range, modification of the inlet may be the most cost effective. However once a variable configuration inlet is implemented by an array of compression ramps and boundary-layer control slots, a complicated mechanical flow control must be adopted that leads to a potentially avoidable weight penalty. Meanwhile when operating beyond the design condition, managing and eliminating parasitic effects increases the complicity of the propulsive system. For this reason an alternative, non-intrusive, rapid response, flow control mechanism, other than mechanical means, is very appealing.

Numerous ideas have been advocated for using electromagnetic force for high-speed flow control [3–14]. Some of the research efforts include an externally applied magnetic field in an attempt to accentuate the magneto-fluid-dynamic (MFD) interaction by invoking the Lorentz force in addition to Joule heating [3–9, 12, 13]. Surzhikov and Shang [14] have shown that the Hall current exerts significant influence to the plasma generation via the electron collision process. The Hall current can even suppress the MFD interaction when the value of the Hall parameter attains an exceedingly high value. However, in a relatively weak applied magnetic field, $B \leq 0.2$ Tesla, the interaction is enhanced by the presence of an externally applied magnetic field. In a numerical simulation around a cone in hypersonic flow, Borghi et al. [13] also found that the Hall current can significantly weaken the MFD interaction. All the aforementioned computing simulations are in a general agreement with experimental observations by Bityurin et al. [7] on the effect of Hall current in MFD interactions.

The inefficient plasma generation process has prevented the plasma actuator from becoming a cost effective device for flow control or aerodynamic performance enhancement [15–17]. Shang et al. [9,18,19] conducted a series of side-by-side computational and experimental investigations to show that a small electromagnetic perturbation near the hypersonic leading edge can be amplified by the viscous-inviscid interaction to become an effective flow control mechanism. They first demonstrated that the MFD interaction can perform as a virtual leading edge strake. Using a power supply of 50 Watts to the surface plasma discharge at Mach five, the MFD interaction induces a compression over an immobile surface that acts as though this control surface has executed a one-degree pitching movement [8, 9]. More than a five-degree equivalent pitching angle has been produced by using a total power supply of 350 Watts to the plasma actuator. The similar idea has also been applied successfully to a rectangular constant cross-section area inlet to perform as a virtual inlet cowl [18, 19].

The basic operating principle of the dielectric barrier discharge (DBD) high-speed flow control mechanism is a combination of a small electromagnetic perturbation and a subsequent amplification by the viscous-inviscid interaction. A simple direct current discharge (DCD) near the sharp leading edge of a configuration introduces three mechanisms for flow control; the volumetric Joule heating, convective electrode heating, and the electrostatic force. The dissipative Joule heating is the consequence of electric current movement in a partially ionized gas, the electric conductivity of this medium is typically