Flowfield Features on Hypersonic Flow over Rectangular Obstacles

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Abstract: The complex separated flows induced by shock wave/boundary layer interaction were studied at hypersonic speed of Mach number 5. The experimental results on hypersonic flow over a set of rectangular cylinders are presented in this paper. The rectangular cylinder mounted on a flat plate worked as a typical model to simulate the obstacle on the vehicle surface. The effects of flow interaction on the aerodynamic characteristics have to be predicted for various geometrical parameters. So the static pressure distributions on the model surface were measured, the complex shock wave system was shown by schlieren photos, and the separated flow patterns around the obstacle were visualized by oil flow technique. All of the results describe the interactive flowfield features including peak pressure levels and their locations as well as separated boundaries associated with influence regions.

Keywords: separated flow, shock wave/boundary layer interaction, flow visualization, hypersonic flow.

1. Introduction

During the last five decades, extensive works have been done on the separated flow induced by the shock wave/boundary layer interactions in transonic, supersonic and hypersonic flows. Many works for the two-dimensional flowfield have been obtained for both laminar and turbulent boundary layers. The more complicated three-dimensional flowfields resulting from separation forced by simple protuberances have been reported in some detailed studies and reviewed by Korkegi (1972), Holden (1972), Sedney (1973), Settles and Dolling (1986). The obstacles mounted on the vehicle surface are unavoidable. The induced three-dimensional separation phenomenon is of importance in determining not only the aerodynamic loads but also the aerodynamic heating in these interactive regions. Many different types of shock wave interactions have been observed for various different flow models postulated.

Some are dominated by inviscid effects, whereas viscosity is of prime importance in others. One type of models was chosen as a cylinder with different height scale mounted on the flat plate, such as the contributions by Miller (1966), Dolling and Bogdonoff (1981), Dolling and Smith (1989), Li, et al. (1995)(1996)(2000). In the present paper, a set of rectangular cylinders is used as the test model, which is mounted on a flat plate and the cylinder length scale can be changed from zero to definite height during one test run. The rectangular cylinder with an infinite leading edge radius would induce the largest influence range compared to the definite leading edge radius such as circular cylinder or others. The influence region forced by an infinite radius cylinder cannot be beyond that limit range at the same test conditions and height/width scales.

This experimental work was conducted in the hypersonic blowdown wind tunnel with Mach number 5.0 in Beijing Institute of Aerodynamics. The test results are presented in this paper, including measured pressure distributions on the model surface, schlieren photographs and the oil flow patterns to visualize the complex three-dimensional separation phenomena based on these measurements. The effects of parameter \( \frac{H}{D} \) (the ratio of height
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to width of cylinder) on the interactive flowfield are examined.

2. Experimental Program

2.1 Wind Tunnel and Test Conditions

The experiments were carried out in the hypersonic blowdown wind tunnel with test section of 17 cm x 17 cm. This facility can operate at a nominal freestream Mach number of 5 to 8. For this experiment the Mach number 5.0 and the Reynolds number per meter of $5.3 \times 10^7$ based on freestream flow conditions were chosen. The stagnation pressure of $3 \times 10^6$ N/m$^2$ and stagnation temperature of 400K were chosen to ensure the turbulent boundary layer of interest in the measurements. The schlieren photo system was used during the test processing.

The test section was covered by a big tank, and the test model was set up as Fig. 1. The axis OX is chosen as the center line of the flat plate in freestream flow direction and axis OZ is perpendicular to OX and along the leading edge of the cylinder.

The model geometry and coordinate system are shown in Fig. 1.

![Model set up and coordinate system.](image)

2.2 Model Geometry

The model consisted of a flat plate and a rectangular cylinder. The flat plate was set up parallel to the freestream direction, and it expanded from the nozzle exit bottom floor. The cylinder was mounted on the flat plate perpendicularly. The distance between the leading edge of the plate and the cylinder was 16.75 cm.

The rectangular cylinder was considered as a circular cylinder with an infinite leading edge radius and two sharp shoulders.

The geometrical characteristics of the model are as following:

- Area of the flat plate: $33 \times 24$ cm$^2$
- Length of the cylinder $H$: $0\text{ to } 5.5$ cm
- Width of the cylinder $D$: 2.5 cm

More than 200 holes were made on the flat plate and the cylinder for static pressure measurements. The length of cylinder can be changed from 0 to 5.5 cm during one test run.

2.3 Boundary Layer Characteristics

A fully developed turbulent boundary layer on the flat plate without cylinder was measured. At O point the boundary layer thickness was about 2.2 cm because the boundary layer was developed from channel and nozzle.

During test, the height $H$ of the cylinder was increased from $0$ to $5.5$ cm, and the shock wave around the leading edge of the cylinder and strong shock wave/turbulent boundary layer interactive phenomena were resulted. The separated flow around the cylinder in a limited region can be visualized by schlieren photos and oil flow patterns. Pressure distributions were measured by pressure transducers.