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Investigation of the double ramp in hypersonic flow using luminescent measurement systems

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ABSTRACT

Compression ramp flows in supersonic and hypersonic environments present unique flow patterns for shock wave-boundary layer interaction studies. They also represent the generic geometry of two-dimensional inlets and deflected control surfaces for re-entry vehicles. Therefore, a detailed knowledge of the flow behaviour created by such geometries is critical for optimum design. The flow is made more complicated due to the presence of separation regions and streamwise Görtler vortices. The objective of the current research is to study the behaviour and characteristics of the flow over the double ramp model placed in hypersonic flow at freestream Mach number of 5. Three different incidence angles of 0°, −2°, and −4° are studied using colour Schlieren and luminescent paints consisting of anodized aluminium pressure-sensitive paint (AA-PSP) and the temperature-sensitive paint (TSP) technique. The colour Schlieren provides description of the external flow while the global surface pressure and temperature distribution is obtained through the AA-PSP and TSP methods. The TSP technique also proves that it is very effective in identifying the location and properties of the Görtler vortices; revealing the effect of incidence on the magnitude and pattern of Görtler vortices formed.

1. Introduction

Supersonic and hypersonic flows over compression ramps present a unique opportunity to study: shock waves, shock–shock interactions, boundary layer instabilities, shock–boundary layer interaction, flow separation and reattachment, and streamwise vortices [1,2]. The compression ramp also represents a generic geometry such as a deflected control surface or even a two dimensional hypersonic intake, making the study of such complicated flows crucial for hypersonic vehicle design [3,4]. In most research work, the flow pattern is visualised by optical techniques such as Schlieren or shadowgraph. The quantitative data relies on the discreet pressure tap and thermosensors. These conventional experimental techniques have their intrinsic drawbacks which makes it difficult to distinguish complicated flow phenomenon.

In recent years surface non-intrusive temperature measurement techniques such as infrared (IR) thermography [5–7], thermographic phosphors [8,9], liquid crystals [10,11], and luminescent temperature sensitive paints (TSP) [12], have been developed and applied. IR thermography, although successfully used in the supersonic/hypersonic wind tunnel testing, requires the expensive IR camera along with special Germanium or Zinc selenide windows. Additionally, the measurement or estimation of surface emissivity and transmittance of the windows and air require exact knowledge. Liquid crystals on the other hand have a narrow measurement range. Temperature sensitive paints and thermographic phosphors both operate using a similar principle based on a photochemical mechanism. Thermographic phosphors usually work at higher temperatures whereas TSP has a range of −196 to 200 °C [13].

Visualisation of roughness induced vortices using a ruthenium based TSP was conducted by Matsumura et al. [14] in a Mach 4 Ludwieg tube. Due to the high spatial resolution and sensitivity of TSP, weak induced streamwise vortices were detected on an axisymmetric scramjet inlet model. Ishiguro et al. [15] studied the compression corner flow at Mach 10 using TSP. Görtler vortices which appear as striation like structures were observed on the rear of the reattachment line off the heat flux images. These vortices alter the heat transfer coefficient distribution on the wall and under certain conditions cause boundary layer transition [16–18], making the measurement of the heat transfer coefficient a critical parameter.

Pressure sensors are the common pressure measurement equipment in the wind tunnel testing. Depending on the size of the model, multiple pressure tappings and transducers might be necessary, leading to large amounts of tubing and wiring. Thus the process is time/space consuming and expensive. Tappings must also be limited in number, so the shape of the model and therefore the local pressure distribution is not altered.

The pressure sensitive paint (PSP) method, which is also a luminescent measurement technique, provides a global non-intrusive map of the model surface pressure [13]. Taghavi et al. [19,20] used

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PSP to obtain pressure data for a multi-jet supersonic ejector. The PSP method was able to successfully capture key flow features such as bubbles of separated flow and the shock cells. Huang et al. [21] applied PSP on a micro scale to study micro shock structures. Compared to ordinary PSP, the anodized aluminium pressure sensitive paint (AA-PSP) is believed to have a faster response characteristic and high pressure sensitivity [22]. This is owed to the porous aluminium structure of the model surface obtained through electrochemical processes.

The current study investigates the flow properties over a double ramp model using luminescent coatings in a hypersonic flow of $M = 5$. Different incidence angles of 0°, −2°, and −4° are examined. Schlieren visualisation is employed to visualise the external flow pattern. Anodized aluminium pressure sensitive paint and the temperature sensitive paint techniques are utilised to analyse the pressure distribution and heat transfer rate on the double ramp surface.

2. Experimental setup

2.1. Hypersonic wind tunnel

The facility used in the present study is an intermediate blowdown type hypersonic wind tunnel, which uses dry air as the working fluid. The tunnel has a stable run time of 7.5 s. The entire system mainly contains a high pressure vessel, vacuum tank, electric heater, axisymmetric nozzle, working section and auxiliary system such as pumping, pressure supply and water cooling system. In the present research, a 152 mm diameter Mach 5 axisymmetric nozzle is employed. The gas temperature can be raised from 375 K to 700 K to avoid liquefaction in the test section. Meanwhile, the stagnation pressure is range from 6 to 8 bar. Unit Reynolds number of 4.5–15 $\times 10^6$ m^{-1} can be obtained from the aforementioned stagnation pressure and temperature setting.

The tunnel test section is a free-jet type with dimensions 325 × 325 × 900 mm (height × width × length) having two circular quartz windows of 195 mm diameter for optical access. The test section is equipped with a three component balance system which includes the measurement sting and supporting arc. The arc allows the angle of attack of the model to be varied in the range of −20° to 20° relative to the freestream direction. Fig. 1 shows the double ramp model installed inside the tunnel test section. The variation in flow Mach number and Reynolds number for different runs of the tunnel are ±0.4% and ±3.7–3.9%, respectively. More detailed description about the wind tunnel was reported by Ref. [23].

The dimensions of the aluminium double ramp model examined are shown in Fig. 2. The first ramp angle is 12° and second ramp of 22° relative to the axis. A 40 mm long flat shoulder follows the second ramp. The entire model is made of aluminium alloy 6061 chosen for its anodization capabilities. Experimental conditions of total pressure and temperature are monitored using the stagnation pitot and K-type thermocouple probe. The pitot probe is connected to a Kulite pressure transducer (XTE-190M, 0–100 psi) and data is acquired by National Instruments (NI) system and operated using Labview. Eight pressure taps are placed along the centreline of double ramp model and surface pressure is measured by Kulite transducers (XTE-190 M, 0–70 kPa). Specifications of the experimental conditions are shown in Table 1.

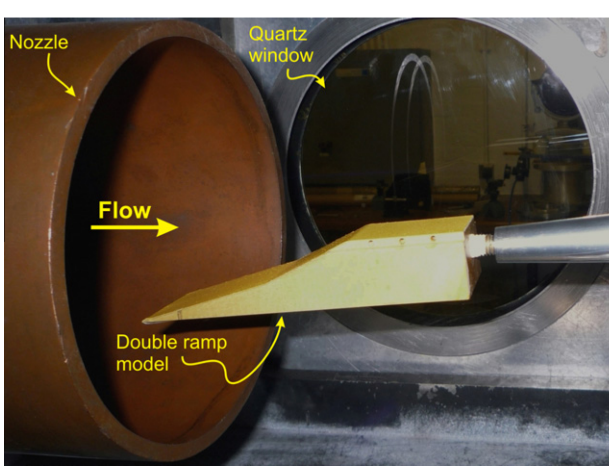

Fig. 1. Test section of the hypersonic wind tunnel with installed model.

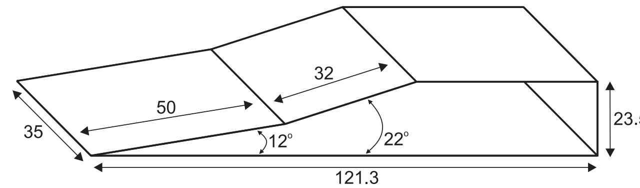

Fig. 2. Dimension of double ramp model.

Table 1
Experimental conditions.

Total pressure (kPa)	645.90
Total temperature (K)	372.3
Mach number	5.0
Freestream pressure (kPa)	1.22
Freestream temperature (K)	62.5
Unit Reynolds number (m^{-1})	13.5 $\times 10^6$
Incidence (deg)	0, −2 and −4

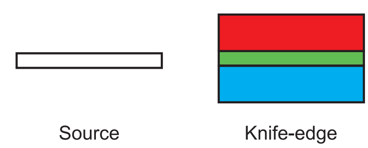

Fig. 3. Colour Schlieren light source slit and colour filter.

2.2. Colour Schlieren

Schlieren allows for the visualisation of invisible light refractions [24,25]. The benefit of colour Schlieren, used here, is that with the addition of colour it not only becomes easier to discern flow features but the intensity of the colour also gives an indication of the magnitude of the flow features.

A *z*-type Schlieren system similar to that of Erdem et al. [26] is employed to visualise the flow. The setup consists of a Palflash 501 continuous light source and two 8 in. diameter parabolic mirrors with a 6 ft focal length. Colour images are acquired by placing a horizontal slit at the source and a 3-colour (red, green, and blue) colour filter at the knife edge location, see Fig. 3. A digital Canon SLR camera, EOS-450D, with 12 MP resolution is used to capture the images. The camera is set to continuous shooting mode at 3.5 frames per second, while the shutter speed is set to the minimum value of 1/4000 s.

2.3. AA-PSP

The PSP technique has become an invaluable tool in aerodynamics, where the emitted intensity of the paint is related to surface pressure. Detailed descriptions of this technique are abundant in literature [27–29,13,30–32]. Anodized Aluminium Pressure