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HYDRO-GAS-DYNAMIC IN TECHNOLOGICAL PROCESSES

EFFECT OF A SUPERSONIC COUNTERFLOW JET ON BLUNT BODY HEAT TRANSFER RATES FOR ONCOMING HIGH ENTHALPY FLOW

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Heat transfer reduction studies, in the presence of a supersonic counterflow jet from the stagnation point of a 60-deg apex angle blunt cone, are conducted in a free piston driven hypersonic shock tunnel, HST3, to verify the effectiveness of this technique for high enthalpy flows. For flow of Mach number 8 with stagnation enthalpy of 5 MJ/kg, it has been observed that the heat transfer rate at some location decreases initially with increase in the injection pressure ratio until the critical injection pressure ratio is reached. A forty-five percent reduction in heat transfer rate near the stagnation point has been measured for the critical injection pressure ratio, equal to 14.91. A further increase in the injection pressure ratio reduces the overall percentage heat transfer reduction. The dependence of fluidic spike length on percentage heat transfer reduction has been confirmed.

Keywords: *Hypersonic flow, drag reduction, free piston shock tunnel.*

Introduction. A highly blunted nose cone configuration is an essential feature of hypersonic flight due to the associated aerodynamic heating phenomenon. The maximum temperature that a space vehicle experiences in hypersonic flight is far above the maximum sustainable temperature of any material. Forward facing supersonic jet, as one of the techniques to alleviate this oncoming heat load, has been studied in various aspects by various researchers. In an earlier investigation, McMahon [1] studied different ways of ejecting a cool gas from the nose of a blunt body and concluded that 'straight out' ejection in the direction opposite to the main air stream is the most prominent way for effective heat transfer reduction. Warren [2] carried out experimental investigation of swirl and straight injections of various coolants from the nose of a bluff body. During these investigations in a hypersonic wind tunnel, straight-out injection of helium was observed as the most efficient technique for reduction of heat transfer. Niranjan Shaoo et al. [3] studied the effect of supersonic jet opposing the oncoming hypersonic flow on the surface heat transfer rates during explorations in a conventional shock tunnel. These low enthalpy hypersonic flow investigations have proved the usefulness of this technique for reduction of the heat transfer rate; therefore, current investigations are carried out to verify the usefulness of this technique for high enthalpy flows. In this view, experiments are conducted in the newly established free piston driven shock tunnel at free stream Mach number of 8.0 and stagnation enthalpy of 5 MJ/kg using a 60-deg apex angle blunt cone model with provision at the stagnation point for gas injection. A solenoid-based injector is developed and used for injection of a supersonic jet. The details of the experimental results along with the test facility and test model are given below.

Experimental Facility. The experimental results reported here are obtained in the newly established free piston driven shock tunnel, HST3. The HST3 tunnel, which is shown schematically in Fig. 1, is of moderate size with a piston weight of 20 kg. The tunnel consists of a 10 m long, 165 mm internal diameter compression tube; 4.4 m long, 39 mm diameter shock tube; a convergent-divergent Mach number 8 conical nozzle, and 2 m long, 1 m diameter size test section cum dump tank. The piston is driven by nitrogen gas in 1 m long, 500 mm diameter reservoir. The compression tube is provided with sensors at four locations to measure the acceleration and speed of the piston during the

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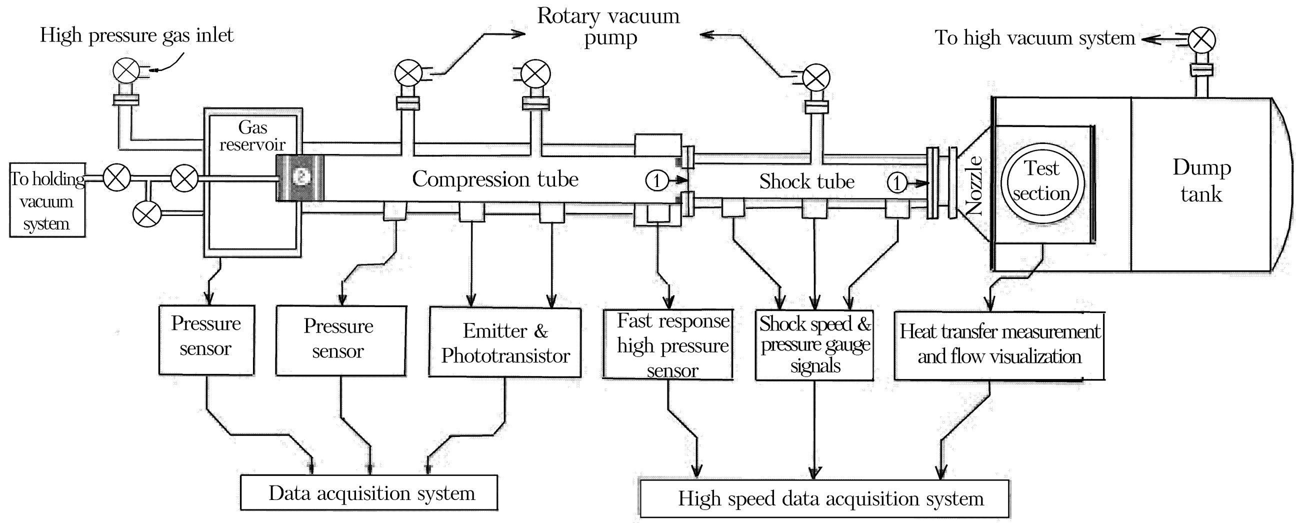


Fig. 1. Schematic diagram of the free piston driven hypersonic shock tunnel HST3 with pressure sensors mounted along the tube surface.

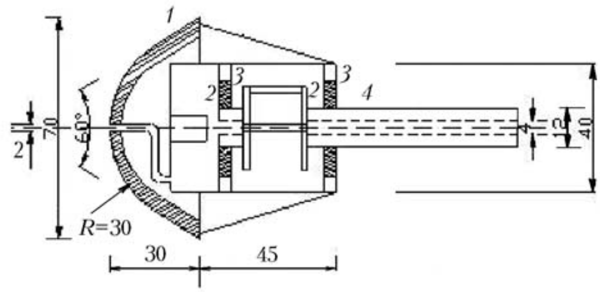
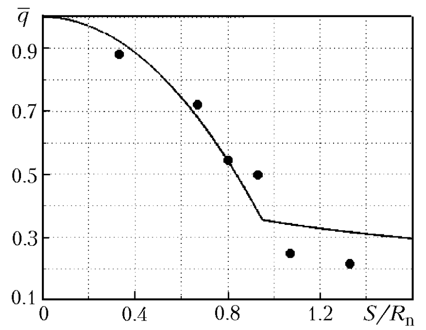


Fig. 2. Schematic diagram of the 60-deg apex angle blunt cone fitted with an accelerometer-based balance system and pipeline for injecting a supersonic jet from the stagnation point: 1) thermal sensors; 2) rubber bush; 3) stainless steel ring; 4) central sting. All dimensions are in mm.

run. A pressure transducer is mounted at the end of the compression tube to monitor the compression tube pressure. The shock tube has two pressure sensors mounted at a known distance apart towards the end to monitor the shock speed and one pressure transducer at the end of the tube to measure the stagnation pressure at the entrance of the nozzle. The tunnel has been calibrated for stagnation enthalpy of about 5 MJ/kg. The flow quality and uniformity inside the test section is checked using the Pitot rake on a traverse mechanism. The performance of the tunnel is estimated using different numerical codes based on the measured Pitot signals and typical tunnel operating parameters. The free stream conditions of the tunnel are the following: static pressure 0.284 kPa, static temperature 316 K, Mach number ~8, and stagnation enthalpy ~5 MJ/kg. In the present set of experiments for the calibrated free stream conditions, 60-deg apex angle blunt cone with 70 mm base diameter and bluntness ratio (defined by the ratio of nose diameter to base diameter) of 0.857, as shown in Fig. 2, is used. Platinum thin film sensors painted on a Macor substrate are used for heat transfer measurement with and without injection of supersonic jet from stagnation point. A solenoid-based injection system is developed for injection of supersonic jet from the 2 mm orifice provided at the stagnation point of blunt cone model.

Experimental Studies. The 60-deg apex angle blunt cone model is mounted at zero angle of incidence in the test section of HST3. Experiments without and with injection of a supersonic jet of different pressure ratios are conducted for the above-mentioned free stream conditions. Experiments without injection are carried out prior to the experiments with various injection pressure ratios. During the experiments with gas injection, the solenoid injector is



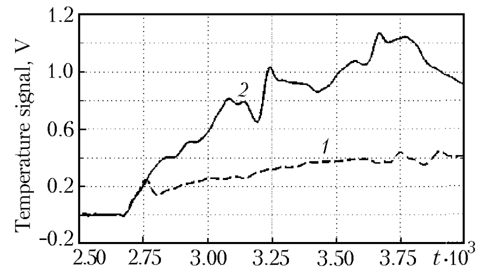
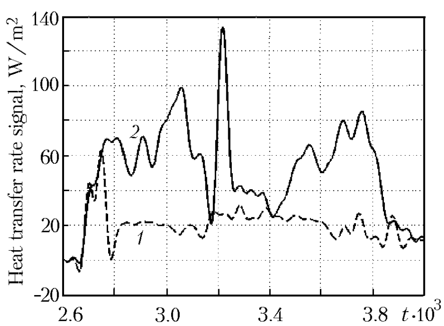


Fig. 3. Comparison of theoretical (curve) and experimental (dots) variation of the nondimensional heat transfer rate along the model surface.

Fig. 4. Comparison of a typical temperature signal with (1) and without (2) injection. t, sec.



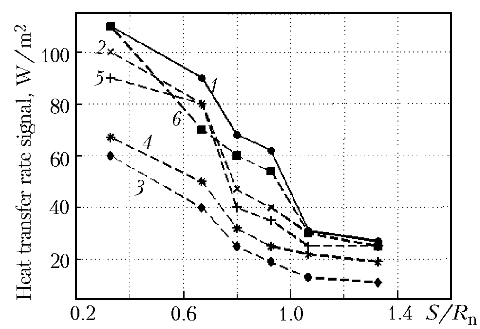


Fig. 5. Comparison of a typical heat transfer rate signal with (1) and without (2) injection. t, sec.

Fig. 6. Variation of the heat transfer rate along the model surface for different injection pressure ratios: 1) $P = 0$; 2) 7.45; 3) 14.91; 4) 22.36; 5) 29.82; 6) 37.27.

connected to the high pressure air cylinder equipped with a high pressure gas regulator to adjust and monitor the supply pressure of the gas to be injected. Synchronization of injection of the supersonic jet from the stagnation point with arrival of a high enthalpy flow in the test section has been achieved by electronic triggering of the injector using the signal output from the pressure sensor mounted at the end of the compression tube. The different injection pressure ratios P considered in the heat transfer measurement studies are equal to 7.45, 14.91, 22.36, 29.82, and 37.27.

Results and Discussion. The experimentally obtained temperature signal at a particular location is used to get the heat transfer rate signal at that location using backing material and sensor material properties and the methodology given by Cook and Felderman [4]. Due to the provision of orifice at the stagnation point for gas injection, the heat transfer rate at that location is not measured but is calculated using the expression given by Fay and Riddell [5]. The thus obtained stagnation point heat transfer rate is used to get the variation of the nondimensional heat transfer rate over the model surface in the absence of a supersonic jet. Comparison of theoretical [6] and experimental variation of the nondimensional surface heat transfer rate $\bar{q}$ in the absence of injection is shown in Fig. 3, where S is the distance along the model surface from the stagnation point and R_n is the nose radius.

Temperature signals are obtained during the experiments with air injection for five different injection pressure ratios. A comparison of a typical temperature signal and the thus obtained heat transfer signal at the same location with and without injection for a typical injection pressure ratio is shown in Figs. 4 and 5, respectively (where t is the time). Reduction in the heat transfer rate is obvious from this comparison. The variation of the heat transfer rate on the model surface for different injection pressure ratios is shown in Fig. 6. The heat transfer rate near the stagnation point initially decreases with an increase in the injection pressure ratio. Maximum reduction in the heat transfer rate of 45% near the stagnation point has been observed for injection pressure ratio of 14.91. A further increase in the injection pressure ratio decreases the percentage reduction of the heat transfer rate near the stagnation region and overall

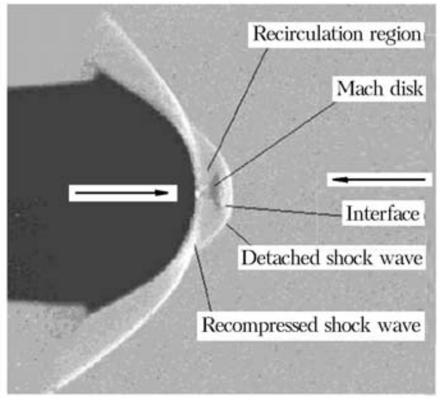


Fig . 7. Schlieren picture of flow features of hypersonic flow over the blunt cone with an opposing supersonic jet [7].

heat transfer rate over the model. This behavior of the heat transfer rate variation along the model surface with injection pressure ratio can be understood from the changes in the flow field which take place due to gas injection with different injection pressure ratio.

A typical flow field with a counterflow supersonic jet of particular pressure ratio given by Balla Venukumar et al. [7] is shown in Fig. 7. In the process of interaction with the oncoming hypersonic flow, the jet emanating from the blunt body forms a fluidic spike mounted at the stagnation point of the blunt cone model and pushes the bow shock wave away from the body. After this interaction, the fluid from the jet is deflected out and flows back till it reattaches to the blunt body, where it forms a buffer layer between the shocked high temperature flow and model surface. In this reversal flow path, the fluid from the jet forms a toroidal low pressure and low temperature recirculation region, the presence of which in the vicinity of the body reduces the surface heat flux. The length of the fluidic spike and the region of jet reattachment depend on the injection pressure ratio for the given free stream conditions. For an optimum fluidic spike length, the majority of the model surface gets covered by the recirculation region, and hence a further reduction in the overall heat transfer can be expected. From this understanding, the reason for the lower heat transfer reduction near the stagnation region at the lowest injection pressure ratio (7.45) is the smaller length of the fluidic spike which reattaches to the jet flow very close to the stagnation point. The reduction in heat transfer at further locations for the same injection pressure ratio is due to the presence of a buffer layer of the jet. For an injection pressure ratio of 14.91, a maximum reduction in the heat transfer rate has been observed for all locations. A similar trend in the surface heat transfer reduction has also been observed for an injection pressure ratio of 22.36. For these injection pressure ratios, the fluidic spike is expected to have an optimum length to delay the reattachment of the jet towards the edge of the model. However, a maximum reduction in the heat transfer near the stagnation region is measured as 45% for an injection pressure ratio of 14.91. Hence, this injection pressure ratio is called the critical injection pressure ratio, whereas the actual critical injection pressure ratio may be closer to these injection pressure ratios. With further increase in the injection pressure ratio, the length of the fluidic spike increases, which shifts the jet reattachment region towards the stagnation point. Hence, for higher injection pressure ratios, lesser reduction in the heat transfer rate is observed near the stagnation region.

Conclusions. Experiments for counterflow injection of a supersonic jet are conducted with a 60-deg apex angle blunt cone model integrated with platinum thin film sensors for heat transfer measurement with and without injection. Experiments with supersonic jet injection are carried out for five injection pressure ratios by varying the total pressure of the jet. A maximum reduction in heat transfer rate of 45% near the stagnation region is recorded for the critical injection pressure ratio of 14.91. The usefulness of this technique at higher enthalpy has been confirmed; however, the injection pressure ratio that defines the fluid spike length is found to be an important parameter in achieving higher percentage heat transfer reduction.

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