An Experimental Study on Transverse Hydrogen Gas Injection into Mach 1.8 Airflow Channel—The 1st report:
Single Circular Injector

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Experimental results from a series of injection tests of pressurized H₂, N₂ gases into Mach 1.8 airflows between parallel channel walls through a flush-mounted circular sonic opening have been presented. Schlieren pictures revealed complex interaction flow features including the occurrence of bow/separation shock waves due to the injection as well as the barrel shock/Mach disc structure inside the injected gas stream. The injectant penetration measured by the Mach disc height against the injection pressure showed a good agreement with the correlation curve based upon the “effective back pressure” concept. The reversed flow region beneath the separation shock wave, the injectant wake and its associated flow entrainment were also visualized by the oil paint method. Wall static pressure distributions around the injector were measured in detail, which corresponded very well to the above results of flow visualization. Gas samplings were also undertaken by using the pressure taps to confirm the presence of H₂ gas in the separation region ahead of the injector. Traversing of total pressure and H₂ gas concentration at the exit of the test channel showed monotonous increase of the loss while its profile was kept very similar with the injection pressure. The area indicating the loss and the presence of H₂ gas almost coincided with each other, which remained to be small to indicate very slow gas mixing/diffusion with the main air flow. With the increase of airflow total temperature to 1200 K, a bulk flame was first observed at the exit section. Further increase up to 1460 K observed an ignition flame at the injector. However, the reflection of the bow shock wave was found to be a more likely trigger of the bulk flame ignition within the test section.

Keywords: SCRamjet, supersonic, combustion, hydrogen, transverse injection.

INTRODUCTION

Research on SCRamjet, which was carried out extensively in US in the past at the late sixties and seventies, has been updated to raise new interest amongst several countries in the world because of the conceptual development of a frame integrated propulsion system for the next generation trans-atmosphere flight vehicle. However, full comprehension of the basic thermo-gasdynamic structure within the combustor is yet to be efforted from scientific and engineering point of views, which plays a key role in developing the firm technology of supersonic combustion. Fuel gas injection in SCRamjet combustor may be classified into two principle types, viz. either parallel or transverse to the main airstream. The former yields a shear layer with static pressure balance, thus avoiding the occurrence of strong shock waves, which leads to less total pressure loss. A demerit is that it needs a longer distance for the injectant mixing. The objective of the present study is rather on good penetration at a shorter mixing distance, so that the transverse injection will be treated. Since the latter accompanies a series of shock
waves including a strong bow shock wave, care must be always taken to find means to negotiate better mixing with less total pressure loss.

In case of transverse fuel gas injection from a wall into a supersonic airstream, the injectant is bent over to the main flow direction accompanying a wave system of barrel shock waves and Mach disc. Experimental observations\cite{3-9} reveal a complex flow structure with shock waves, i.e. separation shock wave, bow shock wave and expansion waves near the injector, as well as reattached shock wave in the wake region.

In order to achieve firm ignition and flame holding, the conditions of high temperature, low velocity and appropriate fuel concentration should be satisfied. The corresponding flow regions like the injectant interface with air behind the bow shock wave or the near wall boundary layer beneath the separation shock wave need to be identified for their spatial extent.

The injectant is required to complete the combustion efficiently with stable flame, this necessitates the investigation of the injectant mixing with the supersonic airflow, from the injector position to downstream, along the shear layer development.

The following are the results from a series of experiments, in which a parametric study has been performed to investigate the effect of injection pressure upon aerodynamic performance and combustion by using a single injector of circular opening at the sonic operation. A particular feature of the present experiments is that the main airflow temperature has been raised up to the maximum 1460 K. Due to the extremely high temperature condition which resulted in obscuring the observation windows of silica glass, a great difficulty was experienced, it made quantitative measurements impossible. The present results concerning the flame structure are thus tending to be more of qualitative nature. Nevertheless a change of flame profiles due to the injection pressure and the ignition phenomena near the injector have been successfully visualized. Up to now in Japan\cite{10-11}, there have not been many experimental reports on successful self-ignition of hydrogen gas in supersonic airstream.

**EXPERIMENTS**

The wind tunnel and measurement system in the present study are schematically shown in Fig.1. The main air is provided from a reservoir with pressure control, which passes through a pebble heater into a ceramic duct with 2D nozzle to establish Mach 1.77 hot airstream at the test section. The heater can raise the air temperature up to the maximum 1700 K with the flow rate 1 kg/s. The test section is 200 mm in length and shaped rectangular of width 45 mm by height 36 mm, with uncooled stainless top and bottom walls and silica glass side walls for optical observation. At the bottom wall, which is the injection plate, two circular openings of 1.5 mm diameter are installed at a separation distance 6 mm to operate as sonic nozzles. There are 48 static pressure taps of 0.8 mm diameter around the injectors, the detail of which is shown in Fig.2. The injectant from a regulated pressure bottle passes through a tube coiled around the heated duct to help increasing the injection temperature. Measurements have been carried out for schlieren and oil paint visualization and detailed static pressure distributions around the injector. Gas samplings have also been made by using those static pressure taps. At the exit cross section, Pitot pressure measurements and gas samplings were also carried out, whence the total pressure has been obtained by applying the normal shock wave relationships with the wall static pressure as the reference. The light source for schlieren observation is a mercury lamp, and the images are taken through a CCD camera to VTR with some graphic treatments. The tracer for oil paint consists of a mixture with titanium dioxide, oleic acid and soluted paraffin. The sampled gas is analyzed by gas chromatography method with argon gas as the carrier.

The main airstream conditions are that the total pressure $P_{to}$ is fixed to 0.4 MPa, the total temperature is ranged from the reference 300 K up to the maximum 1460 K. The injection pressure $P_{ti}$ is the principle parameter to be changed in the experiments. The injectant is hydrogen, but nitrogen was also employed in some cases under the unheated air condition. The main flow $Re$ number becomes $5 \times 10^6/m$, $(8 \times 10^6/m$ for heated air flow), so that the boundary layer thickness at the injector position is estimated to be 2 to 3 mm.

![Fig.1 Schematic diagram of wind tunnel and measurement system](image-url)