Development of Gas Dynamic Probe for High Total Temperature Measurement in High Speed Flow

Tahzeeb Hassan Danish¹, Yash Mistry², Sathiyamoorthy K¹, Srinivas J¹ and Pratheesh Kumar P¹

¹Propulsion Division, NWTC, CSIR-National Aerospace Laboratories, Bangalore, Karnataka, India
²Graduate, IIAEM, Jain University, Bangalore, Karnataka, India

thdanish@nal.res.in

Abstract. Total temperature measurement in high speed and high temperature exhaust of air breathing engines like scramjet, ramjet and turbojets with afterburner is a challenging problem. The temperature of such hot gases is approximately 2000-2200 K. Conventional technique of temperature measurement by thermocouple suffers oxidation, doesn’t withstand aerodynamic load, and lacks robustness. Unconventional technique like optical method is expensive. These limitations have withheld the temperature measurement in high speed high temperature exhaust streams. Present work describes the design and development of a water cooled gas dynamic probe for total temperature measurement of high speed and high temperature gases. The probe consists of two choked nozzles in series. The hot flow is cooled after passing through the first nozzle, in a small settling chamber, using a heat exchanger. The flow from settling chamber is accelerated to Mach 1 in second nozzle. Using gas dynamic relations and measured parameters, the incoming flow total temperature is obtained. The probe has been calibrated for probe constant at total temperature range of 1200 to 1700 K at inlet Mach number 2. Probe constant varies proportional to the square of incoming flow total temperature. First restriction with C-D nozzle gave higher probe constant value than convergent nozzle.

1. Introduction

Supersonic Combustion Ramjet engines (Scramjets) are the futuristic and most promising candidates in air breathing propulsion systems. Scramjets are similar to ramjets in operation but the combustion takes place at supersonic speeds. A scramjet vehicle operates efficiently at Mach number above 5. The operation of Scramjet engine is predominately based on the production and utilization of thermal energy due to combustion. Precise and reliable instruments for stagnation temperature and pressure measurements in the most hostile sections of the scramjet combustor are needed to improve engine designs, for the active control of the engine and for engine health monitoring. The enormous rise in temperature and high velocity at the exit of the scramjet combustor makes the temperature measurement very challenging task. Thermometry is fundamental to the control and monitoring of this process and hence the correct operation of engine. A rise in temperature often results in malfunctioning of equipment. Accurate and robust temperature measurement and control are therefore critical for maintaining and optimizing engine performance. Lack of information about the scramjet combustor exit temperatures affects the accuracy of predictions of engine performance, efficiency, component life and the development and maintenance costs.
Different types of instruments and sensors are used for temperature measurements in scramjets. These include thermocouples, infrared thermometry, and coherent anti-stroke Raman scattering and Acoustic techniques. Nevertheless, the low cost, and simplicity of thermocouples make them the most widely used sensors. A thermocouple sensor measures the temperature of the thermocouple junction itself, which of course is not what we usually want to know. Rather, we wish to determine the temperature of the body in which the thermocouple is embedded. In addition to that, their accuracy is affected by radiation and conduction errors. At high temperature radiation error increases enormously. For accurate measurement bead of thermocouple should be as small as possible. If a sheathed thermocouple is used then metal protective sheath around the thermocouple should be also thin. Thermocouples are thus fragile and unsuitable for extreme environments at high temperature and supersonic speeds [1]. Infrared thermometry has high initial cost and accuracy is affected by surface emissivity, reflections, fluorescence, absorption and scattering of signal. Other techniques like Coherent Anti-Stroke-Raman Scattering and Acoustic techniques are very costly and complex in operation [2].

It is thus clear that a new technique is required to measure high temperature at supersonic speed. Development of a gas dynamic probe to measure temperature in such high speed environment is discussed in this paper.

2. Experience to Date

Perry L. Blackshear Jr. [3] developed a pneumatic probe which consisted of two sonic-flow type orifices in series. Comparison with iron-constantan thermocouple over a progressive variation of temperature from 400K to 650K gave excellent agreement. In comparison with Sodium D-Line method within the range of 1800K to 2222K it indicated a difference in temperature of less than 2% at equilibrium conditions and 6% at non-equilibrium conditions.

Marvin D. Scadron [4] constructed a pneumatic probe based on continuity of mass flow through a subsonic orifice plate and sonic converging-diverging nozzle separated by a cooling chamber. Comparison was made with a rake of radiation shielded thermocouples at maximum temperature of 1100K and indicated Mach number up to 0.8. Maximum error in measurement was observed to be 1.5%.

C. Dewey Havill & L. Stewart Rolls [5] developed a temperature-measuring system using two sonic-flow orifices in series to measure the exhaust gas temperature of an afterburning jet engine. Comparison was made with shielded chromel – alumel thermocouple and measurement of exhaust temperatures of 1700 K was obtained during afterburner operation in flight.

Frederick S. Simmons & George E. Glawe [6] developed a pneumatic temperature probe. Temperatures between 880 K and 2200 K were measured with an experimental probe in hydrocarbon combustion exhaust gases and the results compared were in good agreement with thermocouple pyrometers and line-reversal pyrometer.

Yang, X.L, Miller, and Hodson, H.P [2] measured the temperature using the choked nozzle in the hot flow and the orifice as the second restriction. They calibrated the probe in the range of 300 K to 900 K. They obtained the accuracy of 1% at 2000 K.

Michela Massini, Robert J. Miller & Howard P. Hodson [7] developed a probe which consisted of a choked nozzle located in the flow and a downstream system including a cooler, flow-meter and a valve. The probe prototype was tested up to 900K and showed an accuracy of ±6K.

K. Sathiyamoorthy [8] developed a low cost, simple in construction gas dynamic probe for total temperature measurement of hot gases. Experiments were conducted by varying \( P_{01} \) from 4 to 6 bar, \( T_{01} \) from 300 K to 900 K and Mach number from 0.4 to 1.8. It was observed that the variation in probe constant C with Mach number and total pressure \( P_{01} \) for a particular total temperature \( T_{01} \) was less than 1%.

3. Gas Dynamic Probe
This section describes the aero-thermodynamic design of gas dynamic probe for total temperature measurement of high temperature ($T_{\infty}$) flow at Mach 2. The gas dynamic probe measures the total temperature indirectly using gas dynamic relations. Schematic diagram of gas dynamic probe is depicted in figure 1. It consists of two choked nozzles in series. Since the incoming flow is supersonic at Mach 2, a bow shock is formed at upstream of the probe and makes the incoming flow to the probe subsonic. It is accelerated by the first nozzle so that the flow gets choked at its throat. Since the flow gets choked at throat of first nozzle, the flow rate is a function of total temperature, total pressure and specific heat ratio and gas constant. The hot flow is cooled after passing through the first nozzle, in a small settling chamber, using water based heat exchanger. The flow temperature is reduced to 380-430 K in the settling chamber. The flow from settling chamber is then accelerated to Mach 1 in second nozzle, to choke at its exit. Second nozzle is a convergent nozzle type with throat diameter 2.1 mm. Total temperature is measured in the settling chamber using a K-type thermocouple. Also a static pressure tapping is made in the settling chamber. When the shut-off valve (SOV) is open it gives static pressure ($P_2$) value of the flow in the settling chamber. But when SOV closes the flow it reads total pressure ($P_{o1}$) in the settling chamber is obtained. Two configurations of gas dynamic probe have been designed. Configuration-1 has a convergent-nozzle as the first nozzle followed by the settling chamber, while the configuration-2 has a convergent-divergent nozzle as the first nozzle followed by the settling chamber. Throat diameters of first nozzles in both the configuration is same and equals to 2 mm. In both the configurations second nozzle is convergent type having same dimensions (having throat diameter of 2.1 mm). The miniature settling chamber has diameter of 4 mm. The first nozzle for both the configurations is shown in figure 2. The total pressure loss due to formation of shock at the exit of the first nozzle of second configuration will be lesser than that in configuration-1. This is because of sudden increase in area at nozzle exit in configuration-1. Whereas, in configuration-2 there is gradual increase in area after throat to settling chamber. Nozzles are made of SS304 material using electric discharge machining. Figure 3 shows the fabricated gas dynamic probe (configuration-2) along with its major components, cooling water path and settling chamber measurements. Figure 4 shows the flow path of gas and cooling water. Blue and red arrows depict the cooling water and gas flow paths respectively. The cooling water first goes to the first nozzle followed by the settling chamber. The heat exchanger is a combination of parallel and counter flow types. The cooling water flows opposite to the gas flow to reach first nozzle. After that it turns and goes to settling chamber, parallel to the gas flow as shown in figure 4.
Under steady state condition and from the continuity equation, it can be stated that the mass flow rate through the first nozzle should be equal to the mass flow rate through the second nozzle. Suffixes \( \infty \), 1 and 2 correspond to aero-thermodynamic and geometrical properties of free-stream incoming air, first nozzle (before settling chamber) and second nozzle (after settling chamber) respectively. Mass flow rate through the first nozzle can be calculated using choking mass flow parameter equation as below:

\[
\dot{m}_1 = A_1^* P_{o\infty} \sqrt{\frac{Y_1}{R_{o\infty}}} \left(\frac{Y_1+1}{2}\right)^{\frac{Y_1+1}{2(Y_1-1)}}
\]

(1)

Mass flow rate through the second nozzle is similarly given as below:

\[
\dot{m}_2 = A_2^* P_{o\infty} \sqrt{\frac{Y_2}{R_{o\infty}}} \left(\frac{Y_2+1}{2}\right)^{\frac{Y_2+1}{2(Y_2-1)}}
\]

(2)

Probe constant is defined as the ratio of mass flow rate through second nozzle and mass flow rate through the first nozzle. Ideally the value of probe constant should be unity.

\[
C = \frac{\dot{m}_2}{\dot{m}_1}
\]

(3)

Equations 1, 2 and 3 can be re-written to find the inlet total temperature \( T_{o1} \), as below:

\[
T_{o1} = T_{o\infty} \left[ C \frac{A_1^* P_{o\infty}}{A_2^* P_{o\infty}} \right]^{\frac{Y_1+1}{2(Y_1-1)}} \left(\frac{Y_1+1}{2(Y_1-1)}\right)^{\frac{Y_2+1}{2(Y_2-1)}}
\]

(4)

Since the flow across a shock wave is isenthalpic, total temperature across the shock wave may be assumed constant. Hence measure of \( T_{o1} \) gives incoming flow total temperature \( T_{o\infty} \).

### 4. Experimental Setup

Experiments have been conducted at High Speed Combustor test Facility (HSCTF), Propulsion Division, CSIR-National Aerospace Laboratories, Bangalore. Figure 5 and 6 show the test rig schematic and test rig respectively. The clean and pressurized air is supplied by a centralized air storage facility. A gate valve and an Electro-pneumatic control valve are used to get the air at required mass flow rate and pressure. Pressures are measured at required points in the air supply system and mass flow rate is measured using orifice meters. The pre-heaters are kerosene based and result in vitiated type air heating. The air is heated in two stages in pre-heaters. The pre-heater-1 is a can combustor which uses kerosene as fuel to increase the temperature from 300K to 1000K. Pre-heater-2 is afterburner based which increases the temperature from 1000K to required value. The settling chamber after the pre heaters is made out of carbon steel and the walls are insulated with ceramic layers to absorb the thermal loads to protect the ducts from deterioration. Flow is accelerated to Mach 2.0 using C-D uniform flow nozzle at the exit of the settling chamber. The nozzle is 2-dimensional. Total pressure of the hot air (\( P_{o\infty} \)) and total temperature (\( T_{o\infty} \)) are measured in the settling chamber. Static pressure is measured at the nozzle exit. Using this static pressure and settling chamber total pressure, facility nozzle exit Mach number is obtained.

![Figure 5. Test Rig Schematic](image)

![Figure 6. Test Rig](image)
The probe is fixed at the exit of the facility of the test rig such that the upstream nozzle of the probe is inserted directly in the hot exhaust stream (shown in figure 7). The sequence of the experiment is as follows. The air is allowed through the test rig using gate valve and control valve at desired pressure and mass flow rate. Then pre-determined value of kerosene is injected in the pre heater to achieve the required temperature. Once the simulation parameters are achieved, the output of the sensors is recorded through the data acquisition system for the open and closed condition of the shut off valve in the gas dynamic probe. Data is recorded after reaching steady state. The pressure is measured using PCB make pressure transmitters and temperature is measured using R-type thermocouple. The pressure and temperature data is collected and stored by Data Acquisition System (DAS).

The total pressure (P_{o1}) of the flow approaching the first nozzle is measured by closing the shut off valve in the probe. Whereas the total temperature (T_{o1}) is taken equal to incoming flow temperature (T_{∞}). Using these total temperature and total pressure, mass flow rate through the first nozzle is calculated. Under the open condition of the probe shut off valve, the pressure measured is equal to static pressure (P_2) in the settling chamber. The total temperature obtained (T_{o2}) is around 380-430 K due to cooling by water. Using area ratio relationship and known temperature, Mach number at the settling chamber is calculated. Using this Mach number and static pressure (P_2), the total pressure of flow (P_{o2}) of second nozzle is obtained. Hence, using T_{o2} and P_{o2}, mass flow rate through second nozzle is obtained.

![Figure 7. Gas Dynamic probe assembled to the Facility Nozzle](image)

**5. Results and Discussions**

Mass flow rates through first nozzle and second nozzle are calculated using Eq. 1 and Eq.2 respectively. Specific heat ratios in both cases are calculated based on temperature at that condition using NASA SP-273 program. Probe constant is the ratio of mass flow rate through first nozzle and mass flow rate through second nozzle (Eq.3). The experimentally obtained values of probe constant for both the configurations are plotted below with respect to incoming flow total temperature (T_{∞}) and total pressure (P_{∞}).

![Figure 8. Probe constant vs inlet total pressure temperature](image)

![Figure 9. (Probe constant)^0.5 vs inlet total temperature](image)
Configuration-1 has a convergent nozzle followed by settling chamber. Figure 8 shows the variation of probe constant against incoming flow total pressure for this configuration. It is observed that probe constant varies between 0.974 and 0.987. Figure 9 shows the variation square root of probe constant against total temperature of incoming hot flow for configuration-1. It is observed that square root of probe constant increases linearly with respect to total temperature of incoming flow. On observation of Eq.1, 2 and 3 it is evident that probe constant is proportional to first nozzle throat area. First nozzle sees high temperature gas, whereas the second nozzle gets incoming flow at relatively low temperature. As the diameter of throat of first nozzle increase linearly with temperature, hence its throat area increases proportional to the square of temperature, results in linear increase of probe constant.

Configuration-2 has convergent divergent nozzle followed by settling chamber. Figure 10 shows the variation of probe constant against incoming flow total pressure for this configuration. It is observed that probe constant varies between 0.991 and 0.996. Figure 11 shows the variation of square root of probe constant against total temperature of incoming hot flow for this configuration. It is evident that probe constant increases proportional to square of incoming total temperature.

Figure 12 and 13 show comparison between two configurations. Configuration-1 has a convergent nozzle followed by settling chamber. There is a sudden increase in area at the junction of convergent nozzle and settling chamber. Whereas configuration-2 has a convergent-divergent nozzle followed by settling chamber. Exit area of the nozzle is equal to the area of the settling chamber. Hence, there is smooth and gradual transition of flow. So the total pressure loss is higher in configuration 1 than configuration 2.
configuration 2. This is the reason for higher probe constant values for configuration -2 than that of configuration-1.

6. Conclusions
A water cooled gas dynamic probe was designed and calibrated for total temperature measurement of high speed (Mach 2) and high temperature gases using two choked nozzle as restrictions. Probe constant was experimentally obtained for two configurations of probe by varying incoming flow total temperature and total pressure. Probe constant approximately varies proportional to the square of incoming flow total temperature. First restriction with C-D nozzle gave higher probe constant value than convergent nozzle.

Acknowledgements
Authors wish to express their sincere thanks to the Director, CSIR-NAL Bangalore and Head, Propulsion for providing all the necessary support.

Nomenclature
\( \dot{m}_1 \) : Mass flow rate through first nozzle
\( \dot{m}_2 \) : Mass flow rate through second nozzle
\( A_1^t \) : Throat area of first nozzle
\( A_2^t \) : Throat area of second nozzle
\( P_{a1} \) : Total pressure at first nozzle (SOV closed)
\( P_{a2} \) : Total pressure at second nozzle (SOV open)
\( P_{a02} \) : Total pressure of incoming flow to the probe
\( T_{a1} \) : Total temperature at first nozzle (SOV closed)
\( T_{a2} \) : Total temperature at second nozzle (SOV open)
\( T_{a02} \) : Total temperature of incoming flow to the probe
\( \gamma_1 \) : Specific heat ratio at first nozzle
\( \gamma_2 \) : Specific heat ratio at second nozzle
\( C \) : Probe constant

References
[1] Manik and Brown, "Temperature: Its Measurement and Control in Science and Industry", American Institute of Physics, New York, 1992, p 1244-1249.
[2] X. L. Yang, R. J. Miller and H. P. Hodson, “A New Probe for the Measurement of High-Temperature Gases”, the 16th symposium on measuring techniques in transonic and supersonic flow in cascades and turbo machines, Cambrige U.K, 2002.
[3] Blackshear and Perry L, “Sonic flow orifice temperature probe for high gas temperature measurement,” NACA TN 2167, 1950.
[4] Scadron Marvin D, “Analysis of a Pneumatic Probe for Measuring Exhaust Gas temperature with some preliminary results”, NACA RM E52A11, 1952.
[5] Havill C, Dewey and Rolls L Stewart, “A sonic flow orifice probe for the in-flight measurement of temperature profiles of a jet engine exhaust with afterburning”, NACA TN 3714, 1956.
[6] Simmons, Frederick S and Gwale, “Theory and design of a pneumatic probe and experimental results obtained in a high temperature gas stream” NACA TN 3893, 1957.
[7] Michela Massini, Robert J. Miller, and Howard P. Hodson, “A New Intermittent Aspirated Probe for the Measurement of Stagnation Quantities in High Temperature Gases”, J. Turbomach Oct 2010 Volume133, Issue4, 041022(6pages).
[8] K. Sathiyamoorthy, et al., “Development of Gas Dynamic Probe for Total Temperature Measurement in gases”, ASET 2011- National Conference on “Emerging Trends in Propulsion Technology”.

7