

## A PROBE FOR THE MEASUREMENT OF HIGH-TEMPERATURE GASES

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### ABSTRACT

The objective of this paper is to describe the development and testing of a technique for the measurement of temperature in hot gasses. Two limitations of the existing temperature measurement techniques are their lack of robustness and their inaccuracy when used in practical environments. These limitations have led to modern aeroengines having limited temperature measurement instrumentation.

The technique works by switching the flow on and off through a choked nozzle located in the hot flow. The mass flow rate through the choked nozzle is a function of total pressure and total temperature. When the flow is switched on, the mass flow through the choked nozzle is measured using a downstream orifice plate. When the flow is switched off, the total pressure is measured downstream of the inlet nozzle. These two measurements allow the total temperature of the gas to be determined. Between the choked nozzle and the downstream measurements the flow is cooled to ambient environments so that accurate measurements can be made.

The probe was calibrated over a temperature range of 300K to 900K and a thorough error analysis undertaken. Three factors that affect the accuracy of the probe have been investigated: Inlet Mach number and flow angle; Variation of inlet nozzle throat area due to thermal expansion and Variation of gas properties with temperature and gas composition.

The paper shows that the probe can be designed to avoid the effects of first factor and that the probe can be calibrated to remove the effects of the second factor. The effects of third factor are shown to be split into two parts. The first part is caused by the variation of the gas specific heats ratio  $\gamma$  and specific heat capacity at constant pressure  $C_p$  with temperature, the effects of which can be removed by calibration. The second part is caused by the variation of gas composition that occurs in real engine environments, the effects of which cannot be calibrated for. The paper shows

that the resulting accuracy of the technique at 2000K is  $\pm 6K$ .

### INTRODUCTION

The operation of a gas turbine engine is a process based predominately on the production and utilization of combustion thermal energy. Thermometry is fundamental to the control and monitoring of this process and thus the correct operation of the engine. A rise in temperature often indicates an equipment malfunction. Accurate and robust temperature measurement and control is therefore critical for maintaining and optimizing engine performance.

Intensive work has been carried out to develop methods of measuring gas turbine temperature in the last few decades. Current techniques for measuring gas temperatures and their suitability for use in aeroengines are listed below.

#### **Thermocouples, [1] [2].**

Relative fragility due to the thin walls required for bead to obtain gas temperature; accuracy affected by the method of cold junction compensation and accuracy affected by both radiation and wire conduction.

#### **Infrared Thermometry, [3] [2].**

High cost; relative fragility; are subject to a number of error sources; characterization of the radiation process, surface emissivity, reflections, fluorescence; transmission path error due to absorption and scattering and signal processing error.

#### **Coherent Anti-Stroke-Raman Scattering, [2] [4].**

High cost and complex and requires specialist skills to set up.

#### **Acoustic Technique, [1].**

Appropriate sound source required; transducers and receivers required; accuracy and resolution of temperature profile dependent upon the number of transducer and receiver and their distribution.

In gas turbines the temperature is usually measured using thermocouples. At the combustor exit / turbine inlet the temperatures exceed those at which thermocouples can be accurately and

robustly used. In practice rakes of thermocouples are usually placed at the inlet to the second or third turbine stage. The turbine inlet temperature is then inferred using these and other measurements.

Thermocouples suffer from measurement errors caused both by both conduction and radiation. For a bare wire thermocouple, it is common for an error of 60K to occur at 1300K. With special care, and the use of radiation shielding, this error can be reduced to 5K at 1300K. For accurate measurements to be made using a thermocouple the design of probes has to be such that the bead attains the temperature of the surrounding gas. If a sheathed thermocouple is used then the metal protective sheath around the thermocouple must be thin if an accurate measurement is to be made. Thermocouples are thus often fragile and unsuitable for use in extreme environments. This lack of robustness and measurement inaccuracy means that thermocouples are not ideal for use in engine monitoring systems.

In addition to monitoring global engine performance, improved temperature measurements are also required if the operation of individual components is to be monitored. At present, thermocouples are not suitable for making point measurements at combustor exit. A small fault in a particular combustor therefore goes undiagnosed until either, it is spotted as part of a routine maintenance check, or it develops to the point where a major deterioration in engine performance is noticed.

It is thus clear that a new technique, which can accurately and directly measure gas turbine inlet temperature is required.

## NOMENCLATURE

- $a$  Speed of sound
- $A_1$  Cross section area of inlet nozzle throat
- $A_2$  Cross section area of orifice plate
- $C$  Probe coefficient
- $C_D$  Discharge coefficient of orifice plate
- $C_p$  Specific heat at constant pressure
- $C_v$  Specific heat at constant volume
- $d$  Diameter of central hole in orifice
- $D$  Diameter of downstream tube
- $\dot{m}$  Mass flow rate
- $M$  Mach number
- $P_0$  Probe inlet total pressure
- $P_1$  Choked nozzle static pressure
- $P_2$  Static pressure upstream orifice plate
- $\Delta P$  Pressure difference across orifice plate
- $R$  Gas constant
- $Re$  Reynolds number
- $T_0$  Probe inlet total temperature
- $T_2$  Temperature upstream of orifice plate
- $V$  Velocity

## Greek symbols

- $\beta$  Ratio of  $d/D$
- $\gamma$  Gas specific heats ratio
- $\rho$  Density
- $\nu$  Kinetic viscosity

## Subscripts

- 0 Stagnation parameter

## THEORETICAL ASPECTS

A schematic diagram of the probe is shown in Figure 1. The probe operates by periodically opening and closing the exit valve (4). When the exit valve is open, flow passes through the upstream nozzle (1), the cooler (2) and the downstream mass flow measurement system (3), before exiting through the valve (4). The total to static pressure ratio across the probe is maintained at a value high enough to ensure that the inlet nozzle remains choked. When the exit valve is shut the flow in the probe stagnates and the pressure becomes the same at locations 1, 2 and 3.

The mass flow rate through the upstream nozzle is given by

$$\dot{m} = \frac{\gamma}{\sqrt{\gamma-1}} M \left( 1 + \frac{\gamma-1}{2} M^2 \right)^{-\frac{1}{2} \left( \frac{\gamma+1}{\gamma-1} \right)} \frac{A_1 P_0}{\sqrt{c_p T_0}}$$

where  $P_0$  is the total pressure and  $T_0$  is the total temperature. The total temperature of the gas at the throat of the upstream nozzle can thus be determined if the mass flow rate of the gas and the total pressure in the upstream nozzle are known.

In the particular experiments reported here, The mass flow through the probe is measured using an orifice plate (Figure 1, location 3) located downstream of the choked nozzle.

$$\dot{m} = A_2 C_D \left( \frac{2 \Delta P \rho}{(1 - \beta^4)} \right)^{\frac{1}{2}}$$

Between the upstream nozzle and the orifice plate the gas passes through a cooler which allows the gas temperature to be reduced to ambient conditions. This allows the mass flow rate to be accurately determined. The mass flow through the

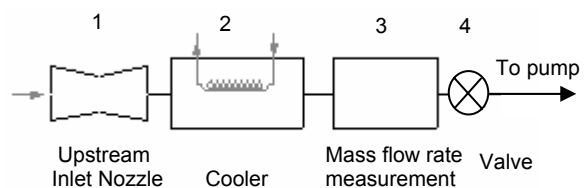


Figure 1 Schematic of probe

probe can then be determined by measuring the pressure difference across the orifice plate and its inlet temperature and pressure.

The total pressure at the throat of the upstream nozzle is measured when the exit valve of the probe is closed. This causes the flow to stagnate throughout the probe and allows the pressure to be measured at a location where the temperature is low enough to make accurate measurements. The location that was chosen for the pressure measurement was between the cooler and the orifice plate. In practice the pressure can be measured using the same instrumentation that is used to determine the mass flow through the orifice plate.

The total temperature at the throat of the upstream nozzle is then given by

$$T_0 = C \frac{A_1^2}{2A_2^2} \frac{P_0^2}{\Delta P P_2} \left\{ \frac{\gamma}{\sqrt{\gamma-1}} \left( \frac{\gamma+1}{2} \right)^{\frac{1}{2} \frac{\gamma+1}{\gamma-1}} \right\}^2 \frac{R}{C_p} T_2$$

The two unknowns that remain in this equation are the gas properties  $\gamma$  and  $C_p$  at the choked nozzle. The values of the gas properties vary, both with the composition and the temperature of the gas. This effect will be discussed later in the paper.

It should be noted that the technique presented in this paper assumes that the flow conditions in which measurements are made do not vary over the operating period of the probe. The length of this time period is determined by the time taken for the flow to reach steady state once the exit valve has been first opened then closed. This time is determined both by the area of the upstream nozzle and the length of the probe. The probe described in this paper can be accurately operating at frequencies in excess of 1Hz. This frequency response was considered suitable for probes used in engine rig tests and engine monitoring systems.

## PROBE DESIGN

Two designs of probe are considered here. The first is a relatively large scale test probe, the results of which are presented in this paper. This probe was tested up to temperatures of 900K. The second design is the final probe and is for use in real engine environments (engine monitoring and performance testing) and thus must be suitable for temperatures of up to 2000K.

The test probe was split into four parts, the upstream nozzle, the cooler, the downstream mass flow rate measurement system and an exit valve. The first three parts of the test probe are shown in Figure 2. The upstream nozzle converges to a throat diameter of 1.5mm then has a step increase in area (Figure 11a). The final design of the probe could vary from a MEMs type device with a throat

diameter of microns and a high frequency response, to a large very robust probe for use in very high temperature gases. Due to the upper temperature limit of 900K used in the testing presented in this paper the upstream nozzle was manufactured from stainless steel.

The cooler used in the test probe consisted of a gas-water counter-flow heat exchanger.

The mass flow measurement in the test probe was made using an orifice plate (Figure 2c). Two pressure tapings were located either side of the orifice. One, one orifice diameter upstream of the orifice plate and one, half an orifice diameter downstream [5]. A number of orifice diameters were tested and an orifice plate of 2.6mm was found to give the lowest measurement error (ie highest  $\Delta P$  across the orifice) while not choking the flow. It should be noted that if the orifice plate becomes choked the mass flow in the probe will be limited and the upstream throat may not choke. The temperature upstream of the nozzle was measured using a K-type thermocouple.

The final probe is required to work in the high temperature environments found both in high pressure turbines and at the exit of combustors. One of the limiting factors when designing thermocouples for use in high temperature flows is that the sheathing material must be thin so that the bead of the thermocouple attains the gas temperature. Because the operation of the new probe does not require heat-transfer through a protective sheath the wall thickness of the probe can be selected to ensure its survival at high temperatures.

The material chosen for the manufacture of the upstream nozzle must withstand temperatures of 2000K. The basic requirements for the chosen material are: Strength at high-temperatures; Resistance to thermal fatigue; Resistance to oxidation and corrosion; Low coefficient of thermal expansion; Low cost; Easy to fabricate. A final choice of materials for the upstream nozzle has yet to be made, however one possible choice is Platinum-Rhodium which can be used for long periods at temperatures over 2000K.

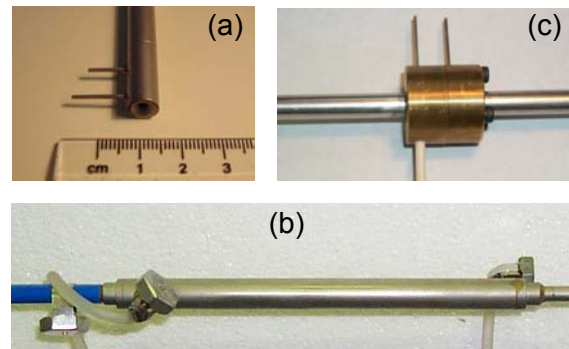


Figure 2 Upstream nozzle, cooler and orifice plate

## EXPERIMENTAL ASPECTS

The probe was tested in three different facilities. Each of the facilities allowed the gas temperature to be, varied but allowed a different aspect of the probes performance to be tested.

**1) Precision high-temperature oven.** The oven, a Lenton WHT6/120, allowed the temperature to be accurately varied between 300K and 900K. The working section of the oven is 0.6m<sup>3</sup> and has a temperature stability of ±0.1K. The temperature at the inlet of the probe was measured locally using a K-type thermocouple.

**2) Electrically heated jet.** The hot jet allowed the probe to be calibrated in a low Mach number flow up to temperatures of 900K. The hot jet exhausted into the atmosphere. The temperature of the jet was held constant with an accuracy of ±3K at 900K.

**3) Aerodynamic calibration facility.** The facility, shown in Figure 6, is a closed circuit wind tunnel that allows the Mach number and Reynolds number of the flow to be independently varied. The facility also allows the angle of the probe to be systematically altered during testing. The facility was used to test the angle and Mach number sensitivity of the probe.

## HIGH TEMPERATURE CALIBRATION

The high temperature calibration of the probe was performed both in the high temperature oven and the hot jet. The probe inlet temperature and pressure were measured local to the head of the probe. In the initial calibration tests the temperature measured by the probe was determined using the theoretical equation given below.

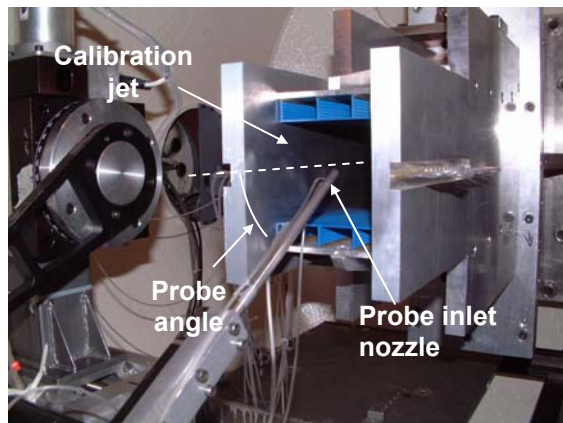


Figure3 Aerodynamic calibration facility

$$T_0 = C \frac{A_1^2}{2A_2^2} \frac{P_0^2}{\Delta P P_2} \left\{ \frac{\gamma}{\sqrt{\gamma-1}} \left( \frac{\gamma+1}{2} \right)^{-\frac{1}{2} \left( \frac{\gamma+1}{\gamma-1} \right)} \right\}^2 R C_p T_2$$

The gas properties,  $\gamma$  and  $C_p$ , were assumed to be equal to their values at 300K. The probe coefficient  $C$  was determined experimentally determined at 300K. Measurements from six subsequent probe calibrations are shown in Figure 4. The data is plotted as true gas temperature against measured temperature. It should be noted that during the testing the temperature measured by the probe rose above 900K while the true gas temperature remained below 900K. This is due both to the variation in the gas properties and inlet nozzle area with temperature. These two effects will be discussed in more detail later in the section.

To determine the random measurement error incurred by the probe the average probe calibration curve was subtracted from each of the raw probe calibrations (Figure 5). The measurement error in the hot jet experiments was found to be ±3.66K (95%) and in the high temperature oven experiment ±2.89K (95%). The probe's total measurement error is composed of errors in all the pressure and temperature measurements that comprise the calibration. The random measurement error from each of the pressure and temperature measurements was individually determined and a Taylor series expansion of the probe calibration equation was used to determine the total theoretical probe measurement error was ±2.46K (95%). This is in good agreement with the error measured in the high temperature oven tests. The larger error measured in the hot jet tests is the result of temperature fluctuations in the jet over the probe measurement period. This was caused by the pressures being

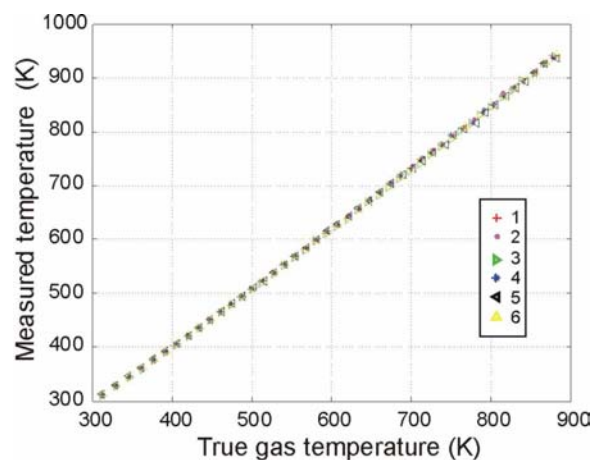


Figure 4 Six sets of probe calibration data  
– high-temperature oven

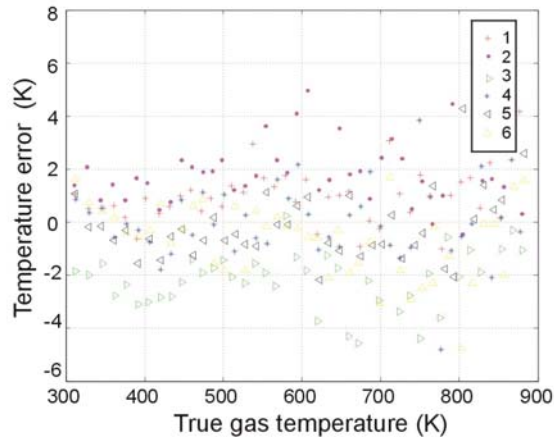


Figure 5 Random measurement error from six probe calibrations

measured sequentially rather than simultaneously. The sequential pressure measurement system (Scanivalve) was replaced by a simultaneous system (DSA 3017) and the testing repeated. The measurement error for the hot jet tests was found to drop to the same value as those measured in the high temperature oven.

The largest component of the random measurement error was found to be the accuracy in the measurement of the pressure difference across the orifice plate. This was limited by the bit resolution of the DSA 3017 ( $\pm 15\text{Pa}$ ). Future tests will include an improved resolution of this pressure measurement system. The theoretical analysis indicates that a final random error of the technique should be in the order of  $\pm 1\text{K}$  (95%).

In addition to random measurement error the calibrations, shown in Figure 4, exhibit a systemic error. This is caused both by a variation in the gas properties and inlet throat area with temperature. The two factors affected by temperature variation are shown below

$$T_0 = C \times \underbrace{\frac{A_1^2}{2A_2^2}}_1 \times \underbrace{\frac{P_0^2}{\Delta PP}}_{\Delta PP} \times \underbrace{\left\{ \frac{\gamma}{\sqrt{\gamma-1}} \left( \frac{\gamma+1}{2} \right)^{-\frac{1}{2} \left( \frac{\gamma+1}{\gamma-1} \right)} \right\}^2}_{C_p} \times R \times T_2$$

As the temperature is raised the stainless steel from which the nozzle is manufactured expands. This causes the nozzle area to change and alters the probe calibration. The variation of nozzle area with temperature was calculated and used to determine the effect of thermal expansion on the temperature measured by the probe. The effects of thermal expansion is shown Figure 6. As the temperature of air is raised the values of its gas properties change. The value of  $c_p$  rises as the

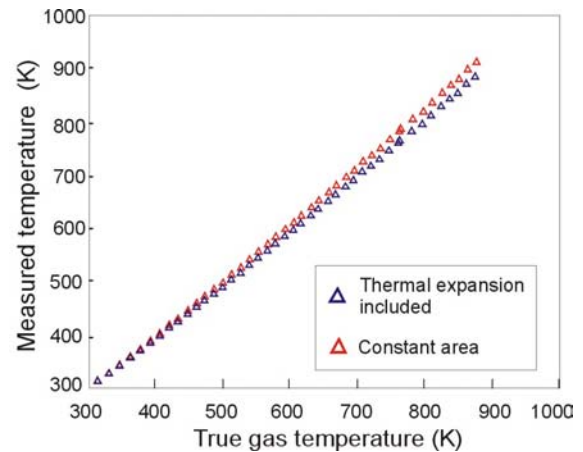


Figure 6 Effect of thermal expansion on calibration

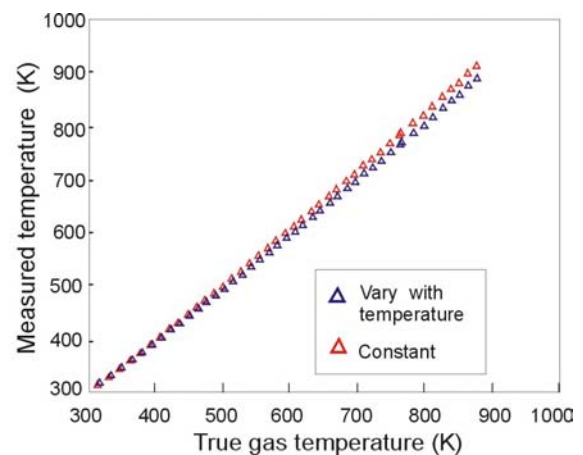


Figure 7 Effects of gas property variation with temperature

temperature is raised and the value of  $\gamma$  falls. These two effects opposed each other, one causing a fall in the measured temperature and the other a rise. The combined effect of variation in both  $c_p$  and  $\gamma$  on the temperature measured by the probe is shown in Figure 7.

In real engines, in addition to variations in gas properties with temperature, the gas properties vary with gas composition. During operation the air/fuel ratio of an engine is typically changed from 80:1 to 120:1. The effect of changing air/fuel ratio on the gas properties at combustor exit and thus the probe calibration is shown in Figure 8. In engine tests the gas composition is unknown and so cannot be calibrated for. At engine representative temperatures (2000K), variations in air/fuel ratio of between 80:1 and 120:1 at combustor inlet result in a probe measurement error of  $\pm 6\text{K}$ . The variation in probe measurement error with operating

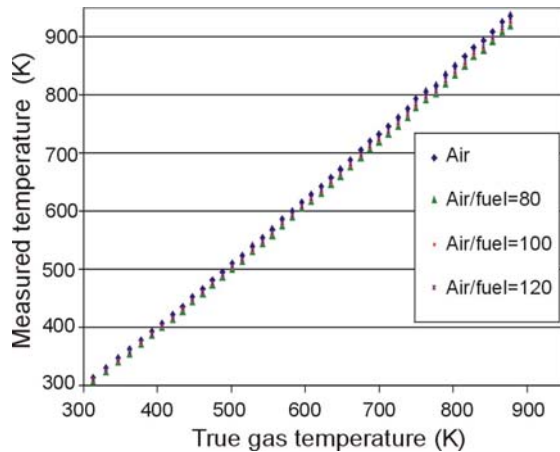


Figure 8 Effect of air/fuel ratio on probe calibration

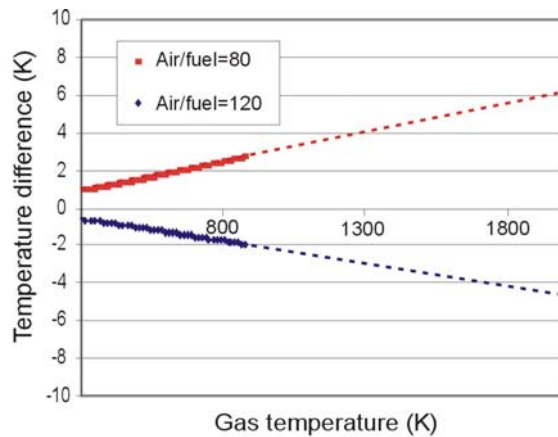


Figure 9 Variation of probe accuracy with temperature due to varying air/fuel ratio

temperature caused by variations in air/fuel ratio is shown in Figure 9. The graph shows the error that would be incurred if the probe was calibrated at the exit of combustor with an air fuel ratio of 100:1 but was used at the exit of a combustor with an inlet air fuel ratio of either 80:1 or 120:1.

### AERODYNAMIC CALIBRATION

To determine the sensitivity of the probe to variations in Mach number and flow angle tests were undertaken in an aerodynamic calibration facility. The facility allows the temperature of the gas to be raised by 40K above ambient conditions while the Mach number of the jet and probe mounting angle are changed. The aerodynamic test facility is shown in Figure 3.

The probe was tested at two Mach numbers (0.2 and 0.7) and six flow angles (0°, 5°, 10°, 15°, 20° and 30°). During the testing the true total temperature of the gas was measured using a thermocouple mounted in a low Mach number region of the flow upstream of the calibration jet.

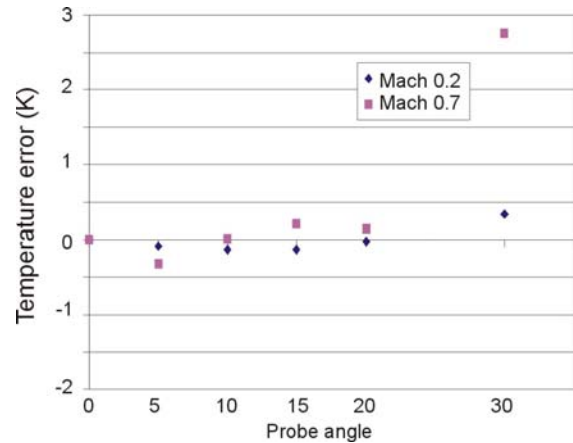


Figure 10 Probe angle sensitivity test at two different Mach number

The difference between the upstream temperature and the temperature measured by the probe for each of the tests is shown in Figure 10. At a Mach number of 0.2 the measurement error of the probe was found to be below 0.27K at incident angles of up to 20°. At 30°, the error was found to rise slightly to 0.35K. It should be noted that these measurement errors are well within the measurement accuracy of the technique. At a Mach number of 0.7 the measurement error of the probe was found to be below 0.3K at incidence angles of up to 20°. At 30° the error was found to rise sharply to 2.76K. The cause of this suddenly rise in measurement error is not yet known, however, it seems likely that the rise in error is caused by an aerodynamic change that results in an alteration of the effective inlet throat area of the probe. This will alter the mass flow rate through the probe and thus change its calibration.

The design of inlet nozzle chosen for the test probe is shown in Figure 11a. The nozzle was designed to be insensitive to flow angle and to have a firmly fixed throat location. Any change in throat area changes the calibration of the probe. The aim of the upstream nozzle in the final design of probe is to maintain a throat area that is insensitive to

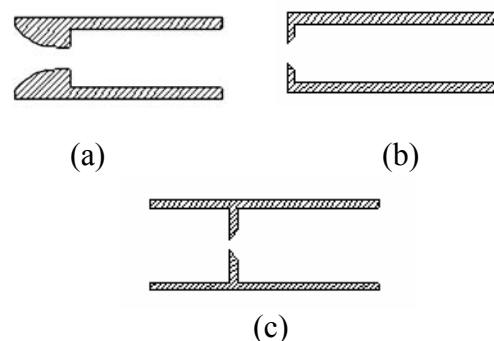


Figure 11 Different designs of inlet nozzles

changes in external flow conditions (flow angle Mach number and Reynolds number). Examples of two further designs of inlet nozzle are shown in Figures 11b and 11c. These designs of inlet nozzle are likely to be more insensitive to Reynolds number but their angle and Mach number sensitivity is at present not understood. Optimization of the geometry of the inlet nozzle is the subject of future work.

## CONCLUSIONS

This paper describes the design and testing of a probe for measuring temperature in the high temperature regions of jet engines (combustor exit and the high pressure turbine). A test probe was shown to have a random measurement error of  $\pm 2.90\text{K}$  (95%) at 900K. The error analysis indicated that the major source of error in the test probe was the accuracy of the pressure measurement made across the downstream orifice plate. The analysis showed that this error could be reduced to  $\pm 1\text{K}$ .

The systematic measurement error was shown to be caused by three effects. The change in the area of the upstream throat with temperature, the change in the gas properties with temperature and the variation of gas properties with gas composition. It was shown that the probe could be calibrated to remove the first two of these but that the third could not be removed by calibrated. In aeroengines the variation of air/fuel ratio at 2000K was shown to cause a measurement error of  $\pm 6\text{K}$ . It should be noted that a second probe that is at present under development will allow gas composition to be determined and thus removes this error.

The inlet nozzle is a key component of the final design of the probe. This is due to the requirement for it to operate at engine conditions. A possible material for the manufacture of the final inlet nozzle for the probe is Platinum/Rhodium which exhibits excellent material behaviour at temperatures over 2000K. The sensitivity of a basic design of inlet nozzle has been investigated and it was shown to be insensitive to flow incidence angles of up to  $20^\circ$  and of Mach number up to 0.7.

Three major advantage of the probe over existing thermocouples for use in jet engines are: The probe can be used to measure pressure and temperature at the same location, saving instrumentation space; The wall thickness of the probe does not affect its measurement accuracy and this allows the robustness of the probe be improved; Radiation and conduction error are of second order compared to measurements made by thermocouples.

## REFERENCES

1. Mannik and Brown, *'Temperature: Its Measurement and Control in Science and Industry'*, American Institute of Physics, New York, 1992, p1244-p1249.
2. Michalski, L., Eckersdorf, K., Kucharshi, J., and McGhee, J., *'Temperature Measurement'*. Second Edition, John Wiley & Sons, Ltd., 2000.
3. Childs, P. R. N., *'Practical Temperature Measurement'*, Butterworth-Heinemann, 2001, p241-242, p296-p297.
4. Tina, Y. M., Lawn, C. L., Mellor, A. M., and Taylor, A. M. K. P, *'Instrumentation For Flows with Combustion'*, Academic Press Limited, 1993, pp53-p64.
5. Kaye, G. W. C., Laby, T. H., *'Tables of Physical and Chemical Constants'*, 14<sup>th</sup> Edition, Longman Group Limited, 1973, p39.