UNSTEADY TOTAL TEMPERATURE MEASUREMENTS
DOWNSTREAM OF A HIGH PRESSURE TURBINE

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ABSTRACT
An experimental technique for the measurement of flow total temperature in a turbine facility is demonstrated. Two thin film heat transfer gauges located at the stagnation point of fused quartz substrates are operated at different temperatures in order to determine the flow total temperature. With this technique, no assumptions regarding the magnitude of the convective heat transfer coefficient are made. Thus, the probe can operate successfully in unsteady compressible flows of arbitrary composition and high free-stream turbulence levels without a heat transfer law calibration. The operation of the total temperature probe is first demonstrated using a small wind tunnel facility. Based on results from the small wind tunnel tests, it appears that the probe total temperature measurements are accurate to within ± 1K. Experiments using the probe downstream of a high pressure turbine stage are then described. Both high and low frequency components of the flow total temperature can be accurately resolved with the present technique. The probe measures a time-averaged flow total temperature that is in good agreement with thermocouple measurements made downstream of the rotor. Frequencies as high as 182 kHz have been detected in the spectral analysis of the heat flux signals from the total temperature probe. Through comparison with fast-response aerodynamic probe measurements, it is demonstrated that at the current measurement location, the total temperature fluctuations arise mainly due to the isentropic extraction of work by the turbine. The present total temperature probe is demonstrated to be an accurate, robust, fast-response device that is suitable for operation in a turbomachinery environment.

NOMENCLATURE

\[ c \] specific heat of the substrate (J.kg\(^{-1}\).K\(^{-1}\))
\[ C \] nondimensional constant in the lateral conduction correction
\[ h \] convective heat transfer coefficient (W.m\(^{-2}\).K\(^{-1}\))
\[ k \] conductivity of the substrate (W.m\(^{-1}\).K\(^{-1}\))
\[ N \] rotational speed (rpm)
\[ p \] pressure (Pa, bar)
\[ q \] surface heat transfer rate (W.m\(^{-2}\))
\[ q_i \] heat flux due to lateral conduction
\[ q_n \] heat flux in the direction normal to the probe surface
\[ R \] radius of the probe, radius of curvature
\[ R \] specific gas constant (J.kg\(^{-1}\).K\(^{-1}\))
\[ s \] entropy (J.kg\(^{-1}\).K\(^{-1}\))
\[ t \] time
\[ T \] temperature of the flow or substrate surface (K)
\[ \alpha \] thermal diffusivity of substrate material (m\(^2\).s\(^{-1}\))
\[ \gamma \] ratio of specific heats (\( \gamma = 1.4 \))
\[ \rho \] density of the flow or substrate material
\[ \omega \] frequency (rad.s\(^{-1}\))

subscripts
mean value averaged over the steady flow run time
\( t \) total or stagnation condition
\( w \) value at probe surface (stagnation point)
1 NGV inlet; first probe
2 NGV exit, turbine inlet; second probe
3 turbine exit

superscript
' fluctuating quantity
INTRODUCTION

Despite the development of advanced non-intrusive techniques, probes continue to play a key role in turbomachinery research and development due to their low cost and relative ease of operation in many situations. Relatively slow response total pressure and temperature probes which indicate time-averaged values have been used for many years (Smout and Cook, 1996). However, as turbomachinery flows are inherently unsteady, performance augmentation is better served though a detailed understanding of the unsteady physics of the flow. Computational techniques which capture aspects of the unsteady flow processes have been developed (Giles, 1988). However, such codes must be validated using experimental measurements of unsteady flow parameters such as the pressure and temperature before they can be reliably used in the design and development process.

Aerodynamic probes based on high frequency response semiconductor technology have been developed to measure the total pressure and other parameters such as the flow direction and Mach number (Ainsworth et al., 1994). Fast-response total temperature measurements are also possible, and the aspirating probe first developed by Ng and Epstein (1983) has achieved considerable popularity (e.g., Alday et. al, 1993; Van Zante et al., 1994; Suryavamshi et al., 1996). Nevertheless, the aspirating probe has a number of limitations (e.g., Van Zante et al.) including a restricted frequency response (the claimed bandwidths are generally lower than 40 kHz) which may not be sufficient in many applications.

This paper describes a new fast-response total temperature probe that has a bandwidth significantly higher than that of the aspirating probe. Furthermore, it offers a number of other advantages including ease of operation and robustness. It is not necessary to calibrate the present probe to determine its heat transfer law (in contrast to devices based on hot wire anemometry). The new probe is a versatile device that offers a measurement of the total temperature that is independent of the gas composition and other flow parameters. An earlier version of the probe has already been successfully operated in a number of high speed flow situations (Buttsworth and Jones, 1996). The present work represents the first application of the new fast-response total temperature probe in a turbomachinery environment.

PROBE OPERATION

Theoretical Background

The operating principles of this probe have been discussed previously (Buttsworth and Jones, 1996) so only a brief description will now be given. Fast-response total temperature measurements are obtained by operating two thin film transient heat transfer gauges at two different temperatures. In the present investigation, platinum thin films were painted onto fused quartz substrates as shown in Fig. 1. The thin films are located close to the stagnation point of nominally identical hemispherical probes. Therefore, the convective heat transfer between the flow and the probes is proportional to the temperature difference between the flow total temperature and the probe surface temperature. That is,

\[ q = h (T_f - T_w) \]  

(1)

The surface temperatures are measured by monitoring the voltage across each of the thin films (which are powered with a constant current supply). The convective heat fluxes are obtained from the film temperature history using either electrical analogues of the transient one dimensional heat diffusion process (Oldfield et al., 1982), or numerical methods (Buttsworth, 1997) which similarly model the transient heat diffusion within the quartz substrate of the probes. Since it is assumed that the two nominally identical probes are exposed to the same flow, the values of \( h \) for each probe will be...
virtually the same. Thus, it is possible to write two equations in two unknowns,

\[ q_1 = h(T_1 - T_{w1}) \]  
\[ q_2 = h(T_1 - T_{w2}) \]

which can be solved to obtain the flow total temperature,

\[ T_1 = T_{w1} + q_1(T_{w2} - T_{w1})/(q_1 - q_2) \]

and the convective heat transfer coefficient,

\[ h = (q_1 - q_2)/(T_{w2} - T_{w1}) \]

The probe measures the flow total temperature irrespective of the flow Mach number because stagnation enthalpy is conserved as the flow decelerates to the stagnation point and there is virtually no viscous dissipation in the stagnation point boundary layer. Thus, even in flows where an immersed body would eventually reach a recovery (or adiabatic wall) temperature somewhat lower than the flow total temperature, the probe accurately detects the flow total temperature. This is because the thin films measure the transient heat flux close to the stagnation point which is driven by the flow total temperature as described in Eq. (1).

Total temperature measurements are made without reference to other flow parameters such as the Mach number, pitot pressure, and the flow composition. Thus, the probe offers a measurement of total temperature without needing to know the probe heat transfer law, and therefore many of the calibration issues associated with hot wire devices are avoided. Because the probe operates through the measurement of transient heat flux, the device can in principle be injected into high temperature environments such as combustors (temperatures around 1800 K), provided it is retracted again before the probe surface temperature exceeds the quartz softening point (around 850 K).

**Design and Practical Operation**

Details of the present implementation of the total temperature probe concept are given in Fig. 1. Both fused quartz probes were hollow, and a small heating element was inserted into the hot probe. The heating element had a resistance of around 12 \( \Omega \), and, during the turbine experiments, the heater was driven with approximately 4.6 V (from a battery supply). A temperature increase was experienced at the cold probe due to the heating of the hot probe. To maximize the temperature difference between the hot and cold probes, the heater power supply was only switched on approximately 10 seconds before the run commenced. This gave an initial temperature difference between the two films of approximately 50 °C at the start of the flow. Immediately prior to the start of the flow, the temperature of the hot and cold probes was still increasing slightly (however, the rate of change was very small relative to the temperature changes experienced during a run). Such pre-run variations can easily be accounted for when determining the convective heat flux during the run (Buttsworth and Jones, 1996). The heater remained on during the run so that additional transient temperature changes (which would accompany switching the heating power off) did not complicate the interpretation of the temperature changes associated with the convective heating.

**Suction Tunnel Experiment**

A usual condition for the accurate operation of transient thin film heat transfer gauges is that the heat penetration depth must be small relative to the width or depth of the substrate. For the present geometry, this condition could be written, \( a/R^2 \ll 1 \) (where \( t \) is measured relative to the start of the heat transfer process). However, in order to maximize the number of rotor blade passing events (maximizing the run time, \( t \)) while maintaining a reasonable level of spatial resolution (minimizing the probe size, \( R \)), it is possible, with the appropriate thermal modelling, to relax this requirement. In the present section, the thermal modelling required to successfully operate the gauges for relatively long periods is demonstrated with specific reference to a preliminary experiment that was performed to verify the probe operation.

**Figure 2. Illustration of the suction tunnel experiment.**

Measurements were obtained using the total temperature probe within the suction tunnel illustrated in Fig. 2. Initially, the duct was evacuated to around 1 kPa and the hot probe was heated to approximately 140 °C. Atmospheric air was drawn into the duct after
the mylar diaphragm at the entrance to the duct was ruptured. The Mach number of the flow approaching the probe was approximately 0.38 (Fig. 2b). The air flow was terminated after approximately 0.5 s by releasing the shutter which sealed the duct from the atmosphere. Figure 3a shows the static pressure measured on the wall of the duct at a location 10 mm upstream of the probe (in the row 1 pressure tappings, Fig. 2a), and Fig. 3b gives the surface temperature histories for the hot and cold probes. After the shutter isolated the duct from the air flow, the actual heat transfer from the probe would have quickly returned to the pre-run level (which was close to zero on the scale in Fig. 3c) due to the rapid flow break-down (see Fig. 3a).

Figure 3. Results from the suction tunnel experiment.

Heat transfer data (e.g., Fig. 3c curve i) was obtained by analysing the temperature histories (Fig. 3b) using a finite difference routine (Buttsworth, 1997) which incorporates radius of curvature and variable thermal property effects. Although the quartz probes have a nominal radius of 1.5 mm, the actual radius of curvature close to the probe tip can vary significantly due to the glass blowing technique that was used to construct the rounded quartz probes. For example, from the measurements in Fig. 4, it can be seen that the rounded tip of the hot probe closely follows that of a hemisphere with \( R = 1.3 \) mm over the majority of the curved profile. In contrast, the cold probe initially has a very tight radius of curvature near the stagnation point (\( R = 1.1 \) mm), but the overall shape of the probe tip more closely resembles that of a hemisphere-cone than a perfect hemisphere. Since the surface curvature at points well away from the stagnation point can influence the heat diffusion process if the condition \( \alpha R^2 \ll 1 \) no longer applies, it is not immediately clear (from the profile measurements alone) what radius of curvature should be used in the transient heat conduction analysis, particularly in the case of the cold probe.

Figure 4. Profiles of the hot and cold heat transfer probes.

To determine the radius of curvature that should be used in the heat diffusion analysis, an empirical approach was adopted. An effective radius of curvature of each probe was selected so that the apparent post-run heat flux (determined using the finite difference routine) remained constant (see curve i, Fig. 3c). The actual post-run heat flux was essentially zero, but a constant (non-zero) apparent post-run heat flux is the appropriate condition at this stage because a finite amount of lateral heat diffusion has taken place. In the case of the hot probe, where the probe tip was reasonably hemispherical, the empirical approach indicated a value of \( R = 1.37 \) mm which is within approximately 5% of the measured physical radius of curvature (which was around 1.3 mm, Fig. 4).

A first-order lateral diffusion analysis gives the correction,

\[
q_l = 4C \frac{\alpha \tau}{R^2} \int_0^\tau q_n \, dt
\]

for a hemispherical probe (Buttsworth, 1997). The constant \( C \) depends on the gradients of the convective heat flux around the probe tip. Again, adopting an empirical approach, the value of \( C \) was selected so that the post-run heat flux \( q_n + q_l \) was brought to zero (see curve ii, Fig. 3c). (Note that \( q_n \) is the heat flux inferred from the finite difference routine prior to lateral conduction correction, e.g., curve i, Fig. 3c.) For further details of the lateral diffusion correction, see Buttsworth (1997). The fact that the apparent post-run heat flux level remains at zero after the correction is applied suggests that the heat diffusion modelling is accurate.

Further justification for the above heat diffusion modelling is obtained from the values of the convective heat transfer coefficient and the flow total temperature indicated by the individual hot and cold probes. The convective heat transfer coefficients of the hot and cold probes and the flow total temperature remained essentially
constant during the run. Thus the indicated flow total temperature and the convective heat transfer coefficients can be obtained from the individual hot and cold probes by fitting Eq. (1) to the experimental heat flux data using the measured surface temperatures. Results from this line fitting exercise are shown in Fig. 5. For the hot probe, the line fit gave $T_i = 293.5$ K, and $h = 1.55$ kW.m$^{-2}$.K$^{-1}$; for the cold probe, $T_i = 292.0$ K, and $h = 1.57$ kW.m$^{-2}$.K$^{-1}$. The ambient temperature (which is the flow total temperature in this suction tunnel experiment) was measured at 293.0 K (using a mercury filled glass thermometer, with an estimated accuracy of ± 0.2 °C). Thus, it is concluded that in the present configuration, total temperature measurements to an accuracy of within ± 1 K are certainly possible.

Considering the excellent agreement between the curve fits and the experimental data (Fig. 5), the accuracy of the individual probe total temperature measurements, and the consistency of the values of $h$ for the hot and cold probes (these were within ± 1 % of the mean value), it is concluded that the current thermal modelling is indeed valid. It is of interest to note that for the current flow conditions, the slightly different shape of the hot and cold probe tips appears to have had little influence on the values of $h$ for the hot and the cold probes. Thus, the key assumption in the operation of the present total temperature probe, which is that both probes have the same value of $h$, is certainly valid in this steady uniform flow.

TURBINE EXPERIMENTS

Facility and Instrumentation

Total temperature measurements were made in the Isentropic Light Piston Facility (ILPF) at DRA Pyestock. Currently, the ILPF has a high pressure turbine stage with film cooling on both the nozzle guide vanes (NGVs) and the rotor. However, for the runs presented in the current paper, no film cooling was utilized. Details of the facility are give elsewhere (Hilditch et al., 1994) and various measurements including high frequency pressure and heat flux measurements on the NGV and turbine blades have already been obtained (e.g., Hilditch et al., 1995).

![Figure 6. Illustration detailing the instrumentation and its relative location in the turbine experiments (not to scale).](http://example.com/figs/TurbineExperiments.png)

![Figure 7. Photograph of the total temperature probe (left) and wedge probe (right) downstream of the turbine blades.](http://example.com/figs/TurbinePhotograph.png)
For the present work, the total temperature probe (Fig. 1) was located approximately 2.5 mm behind the rotor at mid-height of the flow annulus as shown in Fig. 6. A photograph of the probe located behind the turbine blades is given in Fig. 7. A fast-response wedge probe was also located at the mid-height and at the same distance downstream of the rotor, but was offset in the circumferential direction (relative to the total temperature probe) a distance of one NGV pitch in the direction of rotation (Figs. 6 and 7). Thus, both the total temperature probe and the wedge probe should experience a similar flow, however, the phase of the wedge probe signal will lead that of the total temperature signal because the number of rotor blades was not a whole number multiple of the number of NGV blades.

Figure 8. Example of the NGV inlet total pressure.

An example of the total pressure measured at the NGV inlet (using a relatively slow response pitot tube) is given in Fig. 8 for a typical ILPF run. The high frequency results presented in this paper were obtained during the period shown in Fig. 8. The relevant flow parameters given in Table 1 are based on the average conditions measured during the period shown in Fig. 8. The variations given in Table 1 correspond to the maximum and minimum values measured during the current series of experiments. Piston oscillations within the pump tube are responsible for the observed temporal variations in the pressure measurements (Jones et al., 1993). The oscillations amount to a variation in NGV inlet total pressure of approximately ± 4 % over the period indicated in Fig. 8. During this period, the turbine speed was typically held constant (to within ± 0.06 %) by a turbo-brake located downstream of the rotor (Goodisman et al., 1992).

Table 1. ILPF operating conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (± Error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_t$ (Bar)</td>
<td>4.60 (± 1 %)</td>
</tr>
<tr>
<td>$T_t$ (K)</td>
<td>445 (± 1 %)</td>
</tr>
<tr>
<td>$N$ (rpm)</td>
<td>9564 (± 0.08 %)</td>
</tr>
</tbody>
</table>

Data Analysis

For each run, the film temperatures were amplified and low-pass filtered (~3dB point around 200 Hz) and then recorded at 500 Hz (referred to as the low sample rate). Heat transfer data from the analogues was low-pass filtered (~3dB point around 200 kHz) and recorded at 1 MHz (referred to as the high sample rate). Total pressure fluctuations from the wedge probe were also recorded at the high sample rate and later were processes with a digital low-pass filter having a ~3 dB point at 80 kHz to reduce the noise associated with the natural frequency of the transducer. A once-per-revolution signal was also recorded at the high sample rate to allow the high frequency total temperature measurements to be averaged over a number of revolutions (typically 30).

Figure 9. Example of the film temperature and heat flux measurements from the total temperature probe.

Using the low sample rate film temperature history (Fig. 9a), the time-averaged heat flux level was determined from the finite difference routine (which modelled the spherical probe geometry and variable thermal property effects) and the lateral conduction correction technique which was described previously. Time-averaged heat fluxes corresponding to the temperatures in Fig. 9a are shown in Fig. 9b. Time-averaged total temperature results (as given in Fig. 10) were then obtained using the time-averaged film temperature and heat flux results (Fig. 9a and 9b) using Eq. (4).

Figure 10. Comparison of the total temperature probe and thermocouple probe measurements.
The analogue heat transfer signals (recorded at 1 MHz) were later conditioned using a digital high-pass filter (having a -3 dB point at 1 kHz and virtually no attenuation at 10 kHz) and a variable sensitivity that was dependent on the thermal product ($\sqrt{\text{peck}}$) at the surface of the substrate (which was a function of the measured surface temperature). An example of the high frequency component of the heat flux processed in this manner is given in Fig. 11. (The spherical geometry and lateral conduction effects do not have a significant influence on the heat transfer fluctuations at such frequencies.) The total heat flux levels were determined from the sum of the heat fluxes obtained using the low and high sample rate data (as illustrated in Fig. 9c). Total temperature fluctuations (as given in Fig. 12) were then determined from the time-averaged film temperature (Fig. 9a) and the total convective heat flux results (Fig. 9c) using Eq. (4).

Results and Discussion

Time-averaged temperature results from the fast-response total temperature probe are given in Fig. 10 where a comparison is made with thermocouple measurements obtained using a shrouded thermocouple probe downstream of the rotor. The thermocouple probe consisted of a 0.0005" K-type bead junction located inside a 1.5 mm diameter hypodermic tube (at approximately 1 mm from the open tip of the tube). The hypodermic tube had two diametrically opposed vent holes (approximately 0.25 mm in diameter). In the present application, the accuracy of the thermocouple measurements is estimated at around ± 5 K.

There is good agreement between the overall level of the fast-response total temperature probe and the thermocouple probe measurements (Fig. 10). That is, both measurement techniques indicate a time-averaged flow total temperature during the facility run time of around 340 K. However, it may be noted (see Fig. 10) that the poor frequency response of the thermocouple has a significant influence on the temperature measurements even at the relatively low piston oscillation frequency (which is around 15 Hz).

In Fig. 13, the magnitude of the temperature variations associated with the piston oscillations are compared with isentropic predictions based on the measured NGV inlet total pressure variations. Both the temperature (from the fast response total temperature probe) and the pressure signals have been normalized using their respective mean values over the run time, and the pressure signal has been conditioned using the isentropic exponent, $(\gamma-1)/\gamma$. After the tunnel starting process is complete (i.e., for times > 200 ms on the scale in Fig. 13) there is good agreement between the measured total temperature variations and the isentropic predictions based on the measured pressure. This result indicates that while there may be temperature losses associated with the initial compression stroke, the subsequent piston oscillations give rise to variations in the flow conditions that are virtually isentropic. Furthermore, since the oscillations in the temperature measurement downstream of the rotor compare so favourably with the isentropic prediction based on pressure measurement upstream of the NGV, it is concluded that the piston oscillations do not have a significant influence on the stage performance.
Prior to examining the high frequency total temperature results in some detail, the frequency response of the probe is briefly discussed with reference to the power density spectrum results given in Fig. 14. These results were obtained using the high sample rate heat flux signal from the cold probe over the period shown in Fig. 8. The fundamental harmonic corresponding to the blade passing frequency is easily identified at approximately 9.5 kHz. Significant peaks in the spectrum right up to the 19th harmonic of the rotor blade passing frequency (corresponding to approximately 182 kHz) can also be identified. The significance of these results is that the potential bandwidth of the present fast-response total temperature probe is well beyond the capability of other techniques. For example, the highest claimed frequency response of the aspirating probe currently stands at around 40 kHz (Suryavamshi et. al. 1996) which arises mainly due to the time required to establish a steady flow in the duct upstream of the choked orifice. However, it should be noted that the actual bandwidth of the present total temperature measurements is restricted to around 85 kHz which is the -3 dB of the heat transfer analogues. Nevertheless, with the appropriate signal conditioning, it may be possible, in future applications to extend the bandwidth to well beyond 100 kHz.

By averaging the raw total temperature measurements (e.g., Fig. 12) over 30 rotor revolutions, rotor-averaged total temperature results were obtained for each rotor blade passing event, eight of which are shown in Fig. 15. The corresponding ensemble-averaged total pressure measurements from the wedge probe are given in Fig. 16. The location of the instrumentation relative to the rotor blades at the point given by a “rotor blade index” of 0 (in Figs. 15 to 18) is shown in Fig. 6a.

There exists good agreement between the scaled temperature and pressure results in Fig. 17 in terms of the magnitude and phase of the large scale fluctuations. Such agreement suggests that the fluctuations occurring at this location arise mainly because of isentropic processes associated with the work extracted by the rotor. This appears to be a reasonable result since these measurements were obtained at the annulus mid-height where it is anticipated that viscous and heat transfer effects are smallest.
CONCLUSIONS

In excess of 15 runs were performed using the total temperature probe in the present turbine facility without any noticeable change in the ambient resistance of the films, or degradation of the frequency response. It is concluded that the present total temperature probe is a robust device that is well suited to operation in the turbine facility. The expected life of the present total temperature probe far exceeds the life of hot wire probes (i.e., the time prior to recalibration) when operated in a similar environment. The present total temperature probe does not require calibration to ascertain its convective heat transfer coefficient, and thus it has further advantages over hot wire devices. Total temperature measurements are obtained without reference to other flow parameters such as the Reynolds number, the Mach number or the flow composition, and thus it offers ease-of-use without compromising its considerable versatility. The probe is relatively cheap to construct and easy to implement as it is driven with a constant current supply.

The current results indicate that the bandwidth of the probe is more than adequate for resolving the unsteady flow field associated with rotor passing events and it far exceeds the quoted bandwidth of the aspirating probe. Frequencies as high as 182 kHz have been detected in the spectral analysis of the heat flux signals from the total temperature probe. The accuracy of the present total temperature probe appears comparable with that of the aspirating probe. An accuracy of around ±1 K was indicated by a calibration experiment performed in a small wind tunnel facility. The probe is essentially a transient device which means that it cannot be operated in a continuous flow facility unless it is injected into the stream. With the appropriate modelling of the substrate heat diffusion, the probe can certainly operate for at least 0.5 s. At present, the spatial resolution of the total temperature probe is approximately 3 mm (which corresponds to the distance between the two films). Ideally, this resolution should be improved, although as it stands, the probe resolution is comparable with that of other probes commonly employed in turbomachinery research.

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