FIBRE OPTIC INTERFEROMETRIC HEAT TRANSFER SENSORS FOR TRANSIENT FLOW WIND TUNNELS

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ABSTRACT

A new type of heat transfer sensor has been developed in which the sensing element is a short length (~3mm) of single mode optical fibre acting as a Fabry-Perot interferometer. The reflected light intensity follows a periodic transfer function, and the phase change is proportional to the sensor's spatially averaged temperature. We present results from three optical fibre sensors embedded as calorimeter gauges in a ceramic nozzle guide vane end wall model exposed to a transient heat flux of ~100 kWm⁻² in the Isentropic Light Piston Facility at DRA Pyestock Farnborough, and validated by comparison with previous data from platinum thin film resistance gauges. The optical sensors exhibit high spatial resolution (~5µm), high heat transfer resolution (~1kWm⁻²), and wide temperature measurement bandwidth (100kHz) with intrinsic calibration. No electrical connections to the measurement volume are required and multiplexing is possible.

NOMENCLATURE

C Specific heat capacity of optical fibre core
D_t Thermal diffusion depth
I Optical intensity
I_M, I_MAX, I_MIN Mean, maximum and minimum optical intensities returned from the optical sensor
T Temperature (time dependent)
T_o Ambient temperature
V Optical interference fringe visibility
l Length of fibre optic Fabry-Perot cavity
n Refractive index of optical fibre core
q Heat energy per unit area
t time
α Coefficient of thermal expansion of optical fibre core
β Thermo-optic coefficient of optical fibre core, β=dn/dT
λ Optical wavelength
ρ Mass density of optical fibre core
φ Optical phase
γ Thermal diffusivity of optical fibre core

1. INTRODUCTION

1.1 Objectives

Improvements in the efficiency of gas turbines tend towards operation in which the component materials are subject to high thermal stress. For optimum design of blade cooling systems it is necessary to understand the heat transfer from combustion gases to turbine components over a range of operating conditions. While numerical codes are accurate in predicting the aerodynamics of complex flows, their success in prediction of heat transfer rates is limited. Thus determining heat transfer rates by experiment continues to be important. Data are needed to validate and improve the accuracy of predictive techniques. The development of the optical fibre sensor described in this paper has been driven by the need to acquire high resolution high bandwidth heat flux data.

Optical fibre sensors have potential benefits of high spatial resolution (approximately 5 µm), immunity to electro-magnetic interference (EMI), intrinsic calibration and the ability to be multiplexed. Additional features of high measurand resolution, large dynamic range and high measurement bandwidth may be realised if an interferometric sensor is used. The performance specification is given in Table 1.

1.2 Current measurement techniques

Heat transfer measurement techniques using transient flow wind tunnels are well established. They include liquid crystal paints (Ireland & Jones 1986), mass transfer analogues (Heikal et al. 1991), swollen polymers (Roberts et al. 1991) and double sided...
thin film gauges (Epstein et al. 1986). In addition, platinum thin film resistance surface gauges (Schultz and Jones 1973, Dunn & Stodard 1979) continue to play an important role.

Liquid crystals are useful in obtaining heat flux data over extended areas and complex surface topologies, but are restricted in their temperature range. Mass transfer techniques are relatively simple to implement and can be applied to extended areas of measurement, but they cannot provide time resolved data. Platinum thin film resistance gauges can provide high bandwidth (approximately 90 kHz) spatially localised (approximately 1mm²) heat transfer data. However, they are difficult to manufacture, require substrate firing at high temperatures, are easily damaged, are susceptible to electromagnetic interference (EMI) and require individual calibration. The double sided gauges have the advantage over the thin film gauges in that they do not require high temperature firing. However, they still require individual calibration and are susceptible to EMI.

This paper describes a new type of heat transfer sensor and its evaluation in the DRA Pyestock short duration Isentropic Light Piston Facility (ILPF).

2. FIBRE SENSOR THEORY

Our sensor system consists of a fibre optic sensor head, a fibre optic addressing system, launch optics and detector optics; figure 1 shows the layout. The sensor head is a short length (~3mm) of optical fibre, that forms a fibre Fabry-Perot (FFP) interferometer.

2.1 Sensing Mechanism

The basis of the FFP as a sensor is that the single mode fibre from which it is constructed has an intrinsic optical phase sensitivity to temperature, pressure and strain. For the fused silica core fibre used in our experiments, the thermal phase sensitivity of the fibre dominates over the pressure and strain sensitivities in many practical situations (Hocker 1979).

The FFP can be used as a calorimeter by embedding it in a substrate such that its length l is perpendicular to the surface (figure 2). For a substrate with similar thermal properties as the FFP, the single mode fibre Fabry-Perot (FFP) interferometer is sufficient for operation in wind tunnels with a pulse duration of up to 0.5 s.

The FFP optical phase is given by

\[ \phi = \frac{4\pi n l}{\lambda} \]  

where \( n \) is the effective refractive index of the fibre core and \( \lambda \) is the wavelength of the laser light illuminating the FFP. The phase change \( \Delta \phi \) of the FFP associated with a temperature change \( \Delta T \) from an ambient temperature of \( T_0 \) is

\[ \Delta \phi = \phi(T_0 + \Delta T) - \phi(T_0) \]  

where \( \alpha \) is the coefficient of thermal expansion, \( \beta \) is the thermooptic coefficient and \( \Delta T(x) \) is the temperature change of an elemental length \( dx \) of the FFP. If \( \Delta T \) is defined as the mean temperature rise integrated over the length of the FFP, then equation (4) becomes

\[ \Delta \phi = \frac{4\pi(n\alpha + \beta)}{\lambda} \Delta T \]  

The calorimeter equation in terms of \( \Delta T \) applied to the FFP is

\[ \Delta q = \rho C l \Delta T \]  

where \( \rho \) and C are the mass density per unit length and specific heat capacity of fused silica respectively and \( \Delta q \) is the heat energy gained by the calorimeter per unit cross-sectional area. The surface heat transfer rate is hence

\[ \dot{q} = \frac{\rho C l}{4\pi(n\alpha + \beta)} \frac{d\phi}{dt} \]  

Note that the determination of the heat transfer rate is achieved via the measurement of the mean temperature rise of the FFP. This avoids the problems of heat transfer determination via the surface temperature time history and its associated complicated integral equation.

Also note from equation (7) that the heat transfer calibration is independent of the sensor length. The constant parameters \( \rho, C, n, \alpha \) and \( \beta \) are all intrinsic properties of the FFP construction material: fused silica. This is a well characterised stable optical material, hence these parameters have accurately known values and are the same for all fused silica FFPS. The wavelength \( \lambda \) of the laser diode source is stable to better than 1 part in 780. Thus the principal uncertainty in the derived heat transfer rates is associated with the phase error of the FFP, discussed in section 5.2.

2.2 Fibre interferometry

If \( \Delta \phi \) is determined, then heat flux may be found using equation (7). The phase change is found by interferometry. Vaughan (1989) gives full details of the Fabry-Perot resonator. As \( \phi \) changes, the reflected and transmitted FFP intensity change periodically, corresponding to a series of interference fringes. For the case of low reflectivity at each end of the FFP, the return intensity \( I \) is

\[ I = I_M(1 + V \cos \phi) \]  

where \( I_M \) is the mean return intensity (averaged over one period of cos \( \phi \)) and \( V \) is the visibility of the fringe pattern, where
The optical phase was recovered using a technique based on signal digitization. Aliasing filtering was performed with 6th order Bessel filters prior to capture in the transient recorder. Anti-aliasing was used to condition the electrical signals before digitization and the reflected FFP intensity. Trans-impedance amplifiers were used to amplify both the laser output power and operating wavelength. A light free piston is forced along a tube by high pressure air and compresses and thereby heats the air ahead of it. When a predetermined level of pressure is reached, a fast acting valve opens allowing the heated air to flow through the working section and into the dump tank. This gives steady operating conditions. The Pyestock facility is described by Brooks et al. (1973). The Pyestock facility is described by Brooks et al. (1985). A schematic view of the ILPF is shown in figure 3.

3. SENSOR CONSTRUCTION

The simplest method to produce a reflective splice between two fibres is to coat one of the fibre ends with aluminium by vacuum deposition and glue it to the other fibre using mechanical alignment, such as a glass splice tube or ceramic connector tube. Very accurate alignment is required, with a tolerance of approximately 0.2 μm. The reflectivities of the two ends of the sensor were both about 10%. Higher reflectivities would have increased the return signal, but invalidate the assumptions underlying the transfer function of equation (8), and hence complicate the analysis of the data. We have also reported using a fusion splicing method (Indi et al., 1992) where one fibre end is coated with titanium dioxide and fusion spliced to the other fibre, yielding a very compact and rugged sensor, in which the minimum diameter is only 125 μm.

4. SENSOR EVALUATION

4.1 Test Facility

Testing was carried out in the Isentropic Light Piston Facility at DRA Pyestock. This is a short duration facility designed to allow high quality heat transfer data and aerodynamic measurements to be taken for a full size annular cascade of turbine vanes. The use of this technique for turbomachinery measurements was pioneered by Schultz et al. (1973). The Pyestock facility is described by Brooks et al. (1985). A schematic view of the ILPF is shown in figure 3.

For heat transfer measurements the nozzle guide vanes are manufactured from machinable ceramic (Corning Macor) which has a low thermal diffusivity, on which thin film resistance gauges are painted. For aerodynamic measurements, surface static pressure tappings are measured.

4.2 Experiment

The objectives of the evaluation experiment were:

(a) demonstration of suitable sensor mounting arrangements for a vane model in a standard ILPF cassette;
(b) evaluation of performance with a quadrature switched laser;
(c) comparison with thin film heat transfer data obtained under similar run conditions;
(d) measurement of incident heat flux under varying ILPF run conditions.

\[ V = \frac{I_{MAX} - I_{MIN}}{I_{MAX} + I_{MIN}} \] (9)

and where \( I_{MAX} \) and \( I_{MIN} \) are the fringe intensity maxima and minima. Thus by measuring changes in \( I \), \( \Delta \phi \) is determined.

2.3 Components

Single mode fused silica optical fibre has been used throughout the system, except for a length of multi-mode fibre spliced to arm 3 of the directional coupler. The single mode fibre has a lightly germanium doped fused core of diameter 5 μm, which is surrounded by a cladding of fused silica with a diameter of 125 μm. A flexible buffer coating is used to protect this structure. By using single mode fibre, the spatial coherence of the laser is maintained. The multi-mode fibre had a core diameter of 50 μm with cladding and buffer dimensions the same as that of the single mode fibre, and was included to suppress unwanted reflections.

The directional coupler is the fibre optic equivalent of a bulk optic beam splitter. Couplers, like beam splitters can have an arbitrary (fixed) splitting ratio, in our experiments 50/50. Light arriving at the coupler in arm 1 is split into arms 2 and 3. Similarly, light reflected from the sensor and arriving back at the coupler on arm 3 is split between arms 1 and 4.

The optical source was a GaAlAs laser diode, which had a mean output power of 20 mW at an injection current of 70 mA and operated at a wavelength of 780 nm. The laser housing was a standard TO 18 transistor can. The injection current modulates the laser output power and operating wavelength.

Silicon photo-diodes were used to detect the illuminating and the reflected FFP intensity. Trans-impedance amplifiers were used to condition the electrical signals before digitization (with a 12 bit ADC) and capture in the transient recorder. Anti-alias filtering was performed with 6th order Bessel filters prior to signal digitization.

2.4 Signal processing

The optical phase was recovered using a technique based on quadrature switching the laser diode wavelength by controlling its injection current (Dandridge & Goldberg 1982). This effectively generates two wavelengths (\( \lambda_1 \) and \( \lambda_2 \)) of illumination of the FFP, each wavelength being used alternately. The wavelength difference \( \lambda_2 - \lambda_1 \) is chosen so that the FFP phase (given by equation (1)) shifts by \( \pi/2 \) as a result of the change in wavelength. The reflected signals can then be described as

\[ I_1 = I_{MAX}(1 + V \sin \phi) \] (10)

\[ I_2 = I_{MAX}(1 + V \cos \phi) \] (11)

From \( I_1 \) and \( I_2 \), a value of \( \phi \) is obtained without signal fading. We have demonstrated switching rates of up to 90 kHz (Anderson et al. 1991).
Three ceramic tube FFP sensors, each approximately 3mm in length, were embedded in the endwall casing of a nozzle guide vane (ngv). Figure 4 depicts the ngv, the endwall casing and the location of the three fibre optic sensors. A close up of one of the FFP sensor endfaces, which is flush with the endwall surface is shown in figure 5. The vane was from a research turbine designated the High Temperature Demonstrator Unit (HTDU) 4X. Thin film thermometers were not available for simultaneous use with the optical sensors, but comparison heat flux data had previously been obtained on the same model in a systematic series of runs, Chana, (1992).

The launch and detection optics, situated in the ILPF control room, were mounted on an optical rail supported by a pneumatic ring for vibration isolation. One optical fibre downlead per sensor, about 8m in length and protected by flexible sleeving, ran from the optics board to the ILPF cassette in the tunnel's working section. There were no electrical connections between the sensors and the control room.

A series of 14 ILPF runs was made. In runs 1 - 12 the ILPF run conditions were nominally constant, while for runs 13 and 14 run times were shorter and longer respectively, to investigate systematic changes in the heat flux. Data captured in each run were sensor signal, reference signal and ILPF working section pressure.

4.3 Results

The sensor signal was normalised to reference level variations and converted to an optical phase change $\Phi(t)$; calibration (section 2.2) was applied to convert to heat flux into the sensor. Figure 6 shows a typical $\Phi(t)$ together with the ILPF pressure signal over the 530 ms run time.

The heat fluxes averaged over the complete run times are given in Table 2, together with averaged data from thin film surface temperature measurements on the same vane model in previous experiments. Agreement between the optical fibre and thin film gauges is clearly within random error limits, both sets of data showing the systematic changes of heat flux with sensor position on the vane model.

Time-resolved heat flux data $q(t)$ are shown in figure 7, by numerical differentiation of the phase signal $\Phi(t)$ and bandwidth limiting the signal to 100 Hz. Also plotted are the thin film heat transfer data. The heat flux is highest at the start of the run, when the gas-to-vane temperature difference is largest.

5 DISCUSSION

5.1 ILPF Data

The data obtained from the ILPF evaluation show that the fibre optic calorimeter gauges operate successfully in a transient wind tunnel, giving time resolved heat flux data comparable with thin film gauges. The calibration of the optical gauges is intrinsic, depending only on the thermal properties of the fused silica fibre material, which match the thermal properties of machinable ceramic. The resulting one-dimensional heat transfer in the vane surface adjacent to the gauge simplifies the data reduction. The optical gauges are not electrical in operation, so could be used to measure heat flux in metal vanes, provided the two-dimensional nature of the heat flow field in this case was allowed for in data processing.

5.2 Fundamental performance limits

The resolution of the optical sensor is noise floor limited. Noise arises in the optical source and detector as a result of scattering and unwanted reflections in the optical fibre, and because of environmental effects on the optical system. We have taken measures to reduce system noise to an equivalent temperature noise (of the FFP calorimeter) of 300 $\mu$K Hz$^{-1/2}$. The corresponding noise in $q$ is bandwidth dependent. The lowest attainable system noise floor is set by the shot noise limit of the photodetectors, which represents a temperature noise of 1 $\mu$K Hz$^{-1/2}$. This corresponds to a heat transfer rate noise of $< 1$ kWm$^{-2}$ in a 1 kHz bandwidth. We have demonstrated (Kidd et al. 1992) that the temperature bandwidth limit of the sensor is $> 100$ kHz.

6. SUMMARY AND CONCLUSIONS

A new type of heat transfer sensor has been developed in which the sensing element is a single mode optical fibre, configured as a Fabry-Perot interferometer. The optical sensor exhibits high spatial resolution (5 µm), calorimetric operation, intrinsic calibration and good sensitivity (1 kW m$^{-2}$) over a wide bandwidth (100 kHz). The technique requires no electrical connections to the measurement volume, and is capable of being multiplexed.

The optical sensor has been demonstrated in a realistic application, in the measurement of heat flux on the end wall of a nozzle guide vane deployed in a transient wind flow tunnel. The operation of the sensor was validated by comparison with data obtained from conventional platinum thin film resistance gauges.

The demonstration was intended to be illustrative, and the sensor is applicable to a range of other heat transfer measurement problems, over a temperature range of up to at least 500 °C. Furthermore, with alternative sensor lengths and mounting arrangements, the sensor is suitable for high resolution temperature measurement. The principle of fibre optic interferometry is generic, and sensing element designs for the measurement of parameters including pressure (Culshaw & Dakin, 1989) and strain (Lee et al., 1992) are also feasible.

7. ACKNOWLEDGEMENTS

The authors wish to thank Mr. K Walton, Department of Engineering Science, University of Oxford, for his technical assistance in embedding optical sensors.
8. REFERENCES


TABLE 1: REQUIRED SENSOR PERFORMANCE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Resolution</td>
<td>1 kWm⁻²</td>
</tr>
<tr>
<td>Range</td>
<td>1 MWM⁻²</td>
</tr>
</tbody>
</table>

TABLE 2: AVERAGE HEAT TRANSFER RATES

<table>
<thead>
<tr>
<th>Location</th>
<th>FFP q (kWm⁻²)</th>
<th>Thin Film q (kWm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>154 ± 15</td>
<td>140 ± 21</td>
</tr>
<tr>
<td>2</td>
<td>110 ± 16</td>
<td>100 ± 19</td>
</tr>
<tr>
<td>3</td>
<td>132 ± 11</td>
<td>132 ± 21</td>
</tr>
</tbody>
</table>
FIGURE 3
SCHEMATIC OF ILPF

FIGURE 4
LOCATION OF SENSORS ON RIM CASING

FIGURE 5
CLOSE UP OF FFP END FACE ON RIM CASING

FIGURE 6
TYPICAL RESULT FROM FFP GAUGE SHOWING MEAN TEMPERATURE CHANGE WITH TIME

FIGURE 7
TIME RESOLVED HEAT TRANSFER DATA FROM FFP AND THIN FILM GAUGES