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An Investigation of the Response of Temperature Sensing Probes to an Unsteady Flow Field

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ABSTRACT

The response of temperature measuring devices to pulsating flow fields has been a source of concern to compressor designers. A conventional temperature sensing device is known to respond to the highly energetic wake flow leaving a rotor and due to the long thermal time constant of the probe a temperature lying between the hot wake temperature and the relatively cooler main stream temperature tends to be indicated. This indicated temperature can be in serious error if included in a calculation to define the energy flux.

This work is concerned with a theoretical and experimental examination of temperature sensor response to an unsteady pulsating flow typical of that occuring in a compressor.

NOTATION

Cp	Specific heat of air at constant pressure
hc,h	Heat transfer coefficient (air to sensor)
Q	Heat transfer rate
T	Total temperature,
t	Time
U	Velocity, blade
V	Velocity, air
V'	Velocity, axial component
X	Biasing factor due to sampling
X'	$X_w h_w / H_j h_j$
α, β	Angles defined in figure 1
ΔT_{MA}	Difference in temperature between the sensor and mass averaged temperature
ΔT_{TA}	Difference in temperature between the sensor and time averaged temperature
ΔT_{SP}	Difference in temperature between the sensor and upstream plenum chamber temperature
ε	Proportion of blade pitch occupied by the wake
ρ	Density

Subscripts

A	Air
j	Jet
MA	Mass averaged
R	Relative to rotor
S	Sensor
TA	Time averaged
W	Wake

INTRODUCTION

The response of temperature measuring devices to pulsating flow fields has been a source of concern to compressor designers. In the majority of thermal power systems the variable of interest is the fluid enthalpy flux as this can be used to give a direct indication of the efficiency of the energy exchange process. A prerequisite for this calculation is the mass averaged temperature but it has been observed in compressor tests that conventional temperature measurements taken close to a rotating blade row can provide misleading results when used in this context. This has been attributed to blade wake interaction with the sensor.

Concern about this phenomena led to the initiation of a study to investigate the response of temperature sensing probes to unsteady flow. This report provides details of the response of several sensor types to an unsteady flow field typical of those in axial compressors and also provides an analysis of the flow sampling process produced by the installation of a stagnation shield around an open bead. The results of this theoretical analysis are compared with experimental measurements made using a rig developed for the experimental evaluation of sensors.

This problem has received some attention in the technical literature, Moffat and Dean (1), but probably the most positive proposal was that suggested by Mikolajczak and Kerrebrock (2) who suggested moving the measurement station downstream to the stator trailing edge where, so long as the stator wakes were avoided (the stator pressure surface tends to 'collect' the hot rotor wakes), more representative temperatures appeared to exist. Such a solution was not eagerly adopted because stator leading edge instrumentation is attractive because radial migration within the stator row can easily confuse any streamline analysis.

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Although measurement of temperature at the stator exit, in the manner prescribed, could well give a more representative result, it is not apparent to the authors that the correct 'mass weighted temperature' should necessarily be obtained; also, recent laser anemometer results taken at Cranfield and DFVLR (3) suggest that in a high speed machine only partial mixing of the rotor wake will take place in the stator passage and therefore instrumentation at the stator exit will still be subjected to a fluctuating flow.

THEORETICAL ANALYSIS

The objective of the present analytical approach was to define the response of various temperature sensors to unsteady flows typical of those occurring behind a rotating blade row.

In order to achieve this objective various significant factors such as the definition of the flow field, heat transfer effects, internal conduction and others have to be considered. In the following sections an attempt to achieve this is described.

Specification Of The Flow Field Downstream Of The Rotor

To achieve a realistic simulation of the flow field behind the rotor, appropriate velocity triangles have been defined for flow situations at the hub, mid-height and tip of a fan. The rotor outlet velocity triangles involved are shown in figure 1.

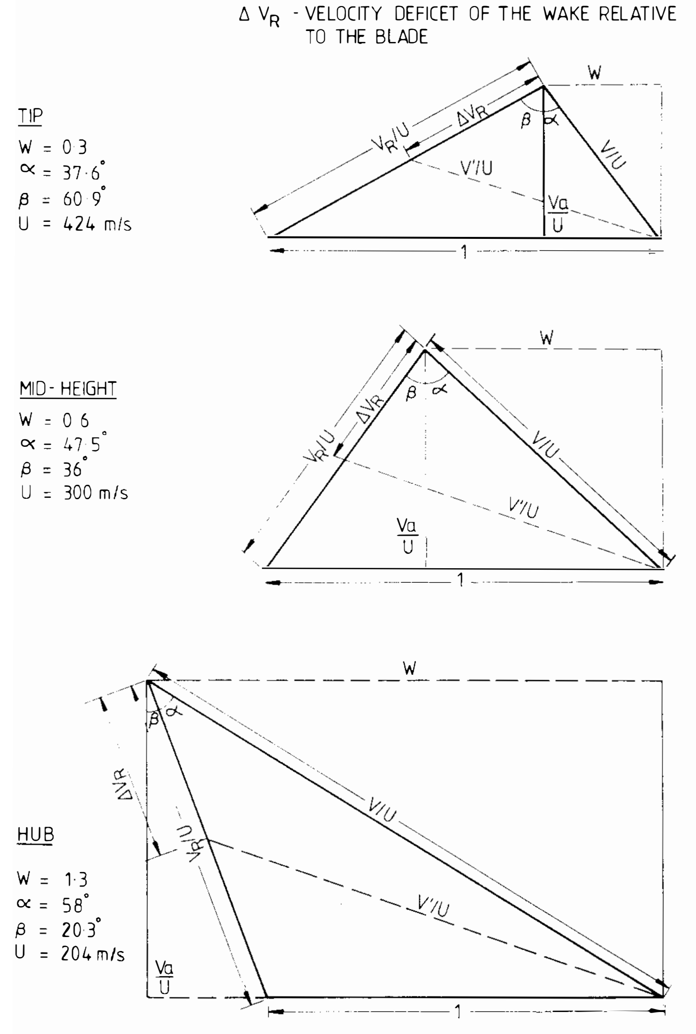

FIG. 1 OUTLET VELOCITY DIAGRAMS FOR HUB, MID HEIGHT AND TIP OF BLADE

The unsteady flow effects have been introduced by defining perturbations in velocity, relative to the rotor (ΔV_R in figure 1), which were thought to be typical. With the velocity so defined, the instantaneous values of the other dependent flow parameters downstream of the rotor can be obtained if the static pressure field is assumed to be uniform and various relationships defining thermal conductivity, Kreith (4), are assumed.

Model Of Heat Transfer Between The Airstream And Sensor

Conventionally the heat transfer at the gas/solid interface is governed by the following equation:

$$Q = h_c \, (T_A - T_s) \qquad (1)$$

As presented, Eq. (1), assumes a perfect recovery factor. It can be shown, Mahanta and Elder (5), however, that a similar relation holds when the recovery factor is finite and that the added complexity provides a near unity term outside of the temperature difference expression. In the calculations shown here this is neglected.

A more serious complication arises due to the probability that the sensor response, particularly when housed, could be biased towards high momentum flows. This is considered in more detail later where Eq. (1) is modified to include a biasing factor X, as shown in Eq. (2). For unshielded (not housed) sensors the sampling has been assumed to be non-discretionary, i.e. X = 1.

$$Q = h_c \, X \, (T_A - T_s) \qquad (2)$$

During the analysis presented here, Eq. (2) has been treated in a quasi-steady fashion, i.e. the amount of heat transferred from the fluid to the probe or vice versa at any instant is determined by the values of h_c, T_A and T_s at that instant. This implies a quasi-steady assumption about the boundary layer which controls the heat transfer coefficient.

The heat transfer coefficient bears a functional relationship with the Reynolds and Prandtl numbers which vary with the geometry of the system. In the present analysis, calculations have been attempted for both cylindrical sensors ('hot-wire' resistance probes) and spherical sensors (thermocouple beads); but only the results arising from the spherical sensor study are contained in this report.

Model of Heat Conduction Within The Sensor

The effect of internal conduction within the sensor on its response to the free stream temperature has been estimated by modelling the internal gradients of temperature. From this analysis it has been inferred that the internal conduction effects within the sensor can be ignored at either of the following conditions:

(i) At low frequencies where the sensor is sufficiently conductive to dissipate any internal temperature gradient, or,

(ii) At high frequencies (when it cannot be argued that the dissipation time is sufficient) where any fluctuation in the bead surface temperature is negligible.

For the study in question, where passing frequencies are typically 10-20 KHz, it is the second condition which is of interest and repeated tests have shown that, under such conditions, the fluctuation in sensor surface temperature is extremely small. Similar conclusions can be implied from the work of Eckert and Drake (6) in which a simplified linearised version of the heat transfer and conduction equations are used.

It is considered, therefore, that in the region of interest the internal heat conduction effects are negligible and that the sensor is almost without temperature gradients. This simplifies the analysis considerably because it is possible to exclude errors from local sensor heating caused by small eddy currents and it appears very probable that the thermal e.m.f. indicated by the sensor is associated with the bead temperature.

Model For The Thermocouple Response to Fluctuating Flows

The heat transfer relation, Eq. (2), may be integrated over one cycle, T, in the following manner:

$$\int_t^{t+T} Q \, dt = \int_t^{t+T} h_c \, T_A \, X \, dt - \int_t^{t+T} h_c \, T_s \, X \, dt$$

Following an initial transient the probes may be considered to have attained a quasi-steady state, so that

$$\int_t^{t+T} Q \, dt = 0$$

therefore

$$(h_c T_A X)_{TA} = (h_c T_s X)_{TA} \qquad (3)$$

If the sensor has a sufficiently fast response it can follow the air temperature so that the error between T_A and T_s is always small.
Substitution of this condition into Eq. (3) leads to a situation where the air and sensor temperature are equal at all times and, therefore, so are their time averaged values.

Sensors, however, are generally slow in response and studies made with various rates of flow change show that a frequency is soon reached where the sensor temperature is very nearly constant during the thermal cycle. This situation is represented by the equation

$$T_s = \frac{(X T_A h_c)_{TA}}{(X h_c)_{TA}} \qquad (4)$$

Thus the error between T_A and T_s varies from zero at frequencies where the sensor is comparatively highly responsive, to that defined by Eq. (4), at high frequencies where the sensor fails to respond to changes in the air stream temperature.

Response Of A Temperature Sensor To A Time Varying Flow

If a simple proportional analysis is used in which it is assumed that the blade wake (and ΔV_R in figure 1) is a square wave type function and extends for a fraction ε of the blade pitch then the time averaged sensor temperature, obtained from Eq. 4 can be expressed as

$$T_s = \frac{(X_j h_j \, (1 - \varepsilon) T_j + X_w h_w \, \varepsilon \, T_w)}{(X_j h_j \, (1 - \varepsilon) + X_w h_w \, \varepsilon)} \qquad (5)$$

where X is the biasing factor and h is the heat transfer coefficient and suffixes refer to the jet (j) and wake (w) flow. The format of the equation can be simplified if

$$X' = \frac{X_w h_w}{X_j h_j} \qquad (6)$$

$$\text{i.e.} \qquad T_s = \frac{(1 - \varepsilon) \, T_j + \varepsilon \, X' \, T_w}{(1 - \varepsilon) + \varepsilon \, X'}$$

Based upon similar arguments the true time averaged temperature of the flow is $(1 - \varepsilon) \, T_j + \varepsilon \, T_w$ and the difference between this and the sensor temperature is

$$\Delta T_{TA} = \frac{\varepsilon \, (1 - \varepsilon)(1 - X')(T_w - T_j)}{1 - \varepsilon \, (1 - X')} \qquad (7)$$

It is more useful, however, to examine the difference between the sensor temperature and the mass averaged temperature. The mass averaged temperature for such a flow can be expressed as

$$T_{MA} = \frac{(1 - \varepsilon) \, T_j \, V'_j \, \rho_j + \varepsilon \, T_w \, V'_w \, \rho_w}{(1 - \varepsilon) \, V'_j \, \rho_j + \varepsilon \, V'_w \, \rho_w} \qquad (8)$$

where the primed velocity indicates the axial component.

If $\hat{V} = (V'_w \, \rho_w)/(V'_j \, \rho_j)$ then the above relation can be simplified to

$$T_{MA} = \frac{(1 - \varepsilon) \, T_j + \varepsilon \, \hat{V} \, T_w}{1 - \varepsilon \, (1 - \hat{V})} \qquad (9)$$

The difference between this relation and the sensor temperature represents the probe error i.e.

$$\Delta T_{MA} = \frac{\varepsilon \, (1 - \varepsilon)(\hat{V} - X')(T_w - T_j)}{(\varepsilon \, X + 1 - \varepsilon) \, (\varepsilon \, \hat{V} + 1 - \varepsilon)} \qquad (10)$$

The above equation suggests that if sufficient details are known about the probe and the flow regime such that estimates of X', $\hat{V}$ and ε could be made, it should be possible to correct sensor readings to obtain the mass averaged temperature. In practice, however, it is not usual to know such details about the flow although the compressor aerodynamicist may be able to provide estimates of the parameter to give an approximate correction term.

One of the largest difficulties is the definition of the sampling parameter X. This will cearly depend on the details of any stagnation shield and involves the complexities of the flow surrounding the sensor. In the results shown here a very simple model has been used in that it has been assumed that the probability of a particular sample of flow reaching the sensor is related to the ratio of its total pressure to the average total pressure.

$$X = P_T/\overline{P}_T$$

This formulation has been used in the subsequent analysis of shielded sensors and is shown below. No such discretionary sampling has been assumed for the non-shielded thermocouple bead.

The model previously described has been used to investigate the response of both shielded and unshielded sensors for perturbations in the flow about the hub, mid-height and tip conditions shown in figure 1 The perturbations considered have taken various forms but the most informative was a jet/wake formulation where the conditions oscillate between the design flow and those represented by a much reduced or zero flow relative to the rotor.

In figure 2, the model predictions of the following factors are compared for a situation in which the wake is assumed to extend for 10% and 20% of the blade pitch and, in the wake, the relative velocity at the trailing edge is zero:

(i) the difference between the mass averaged temperature and the time averaged temperature.

(ii) the difference between the mass averaged temperature and the modelled response of an unshielded thermocouple.

(iii) the difference between the mass averaged temperature and the modelled response of a shielded thermocouple.

Clearly, the response differs significantly along the span of the blade because of the very different flow conditions associated with each station and before discussing the response at the various stations it is probably worth describing the effect of various flow conditions on the above parameters;

(i) a wake temperature above the jet temperature tends to make the time averaged higher than the mass averaged temperature (and vice-versa).

(ii) where the wake has a higher heat transfer coefficient than the jet (due to a higher velocity) the sensor tends to be biased towards the wake temperature (away from the time averaged temperature).

(iii) As a consequence of the biasing model used, if the wake has a higher total pressure than the jet the shielded sensor tends to be biased towards the wake temperature (away from the time averaged temperature).

The conditions at the various stations are as follows:

(i) Hub: in this region the wake temperature is below the jet temperature (-12.4C°), the heat transfer coefficient of the wake flow is lower than that of the jet and the total pressure of the wake region is lower than that of the jet. This gives a time averaged temperature which is below the mass averaged temperature; the unshielded sensor temperature is close to the time averaged flow but biased towards the jet temperature and the temperature of the unshielded sensor is further biased towards the jet temperature.

(ii) Mid-height: in this region the wake temperature is higher (+35.3C°) than the jet temperature; the heat transfer coefficient of the wake flow is higher than that of the jet and the total pressure of the wake region is higher than that of the jet. This provides a time averaged temperature which is higher than the mass averaged temperature; the unshielded sensor temperature is biased (from the time averaged temperature) towards the jet temperature and the temperature of the unshielded sensor is further biased towards the jet temperature.

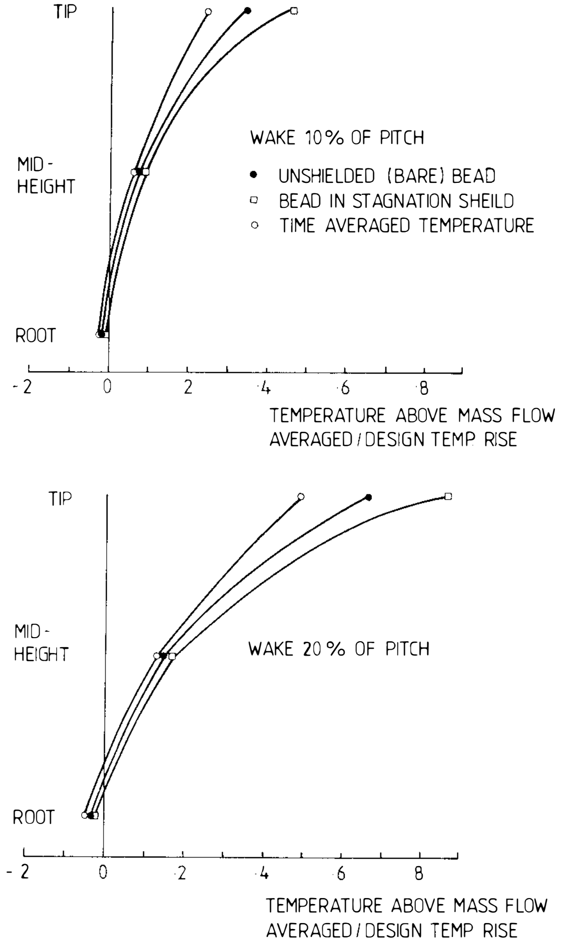

FIG 2 TYPICAL PREDICTED SENSOR ERRORS FOR THE FLOWS SHOWN IN FIG 1

(iii) Tip: in this region the wake temperature is considerably higher (123C°) than the jet temperature; the heat transfer coefficient of the wake is significantly higher than that of the jet and the total pressure of the wake region is higher than that of the jet. These conditions are similar to those at blade mid-height but the difference between the jet and wake is much greater leading to larger divergences from the mass averaged temperature.

EXPERIMENTAL STUDY

The objective of this study was to examine an experimental situation and ascertain if the phenomena described in the previous section were realistic. Also, to establish an experimental rig which could be used to study the response of various sensors to distorted flows.

After careful consideration of several design schemes for a machine capable of producing a pulsating flow field, an axial flow turbine was chosen as being the most suitable. In this design, a free running axial air turbine generates, in its working section, a relatively cool mainstream flow accompanied by a highly energetic blade wake travelling with the turbine. The turbine was designed to rotate at a speed of 8,000 rpm and was supported upon two angular contact ball bearings lubricated by oil mist. This whole arrangement was supported in a cylindrical fabrication consisting of the bearing housing and the exhaust ducting. The measurement section was located in the exhaust duct running from a point immediately behind the turbine to a point 0.35m along the duct.

The flow downstream of the rotor was intended to approximately simulate the conditions found at the tip of an axial flow compressor (operating with some tip stall) where the measurement errors had been predicted to be greatest. In this respect the blade loading was light, being comprised of windage and bearing friction losses only, and the blade wake was severely overheated having a greater absolute velocity than the mainstream flow. The width of the blade wake was determined by the width of the blade trailing edge, which was blunt. The repeatability of the flow field was a function of the accuracy of the disc manufacture and the steadiness of the inlet air stream.

The overall size of the turbine was dictated by consideration of the minimum height of the working section into which the probes could be inserted. The turbine unit was designed to have significant wake velocities and blade passing frequencies on the one hand with reasonable turbine speeds on the other. The outcome of these requirements was a turbine of 0.476m diameter with 37 blades of 25.4mm axial chord, 12.7mm in height and rotating at 8,000 rpm. The rotor design and blade profiles are shown in figure 3. To create a reasonable wake the blades have a blunt trailing edge which occupies 33% of the blade pitch.

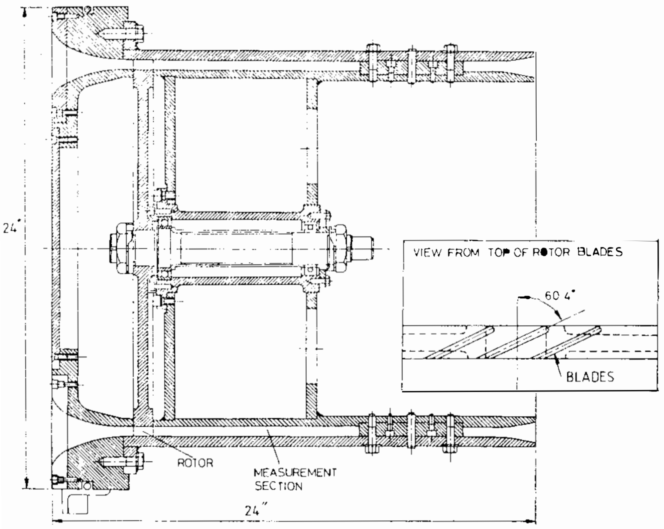

FIG. [illegible] GENERAL ASSEMBLY OF BLADE WAKE SIMULATION RIG

Low pressure air was supplied to the turbine which was placed downstream of a plenum chamber. The plenum chamber of 1.2m diameter was 1.8m in length and was fitted with damping screens to eliminate any disturbance, created by the regulating valves, propagating into the working section. The temperature of the air supply was measured in the plenum chamber using an array of ten chromal/alumel thermocouples mounted from the damping screens. The plenum chamber pressure was monitored using a mercury manometer.

The initial task was to define the flow conditions downstream of the turbine using hot wire anemometry. (In the mode used this instrument had a frequency response far in excess of the blade passing frequency). These measurements were taken at axial stations which were 12.5%, 25%, 50% and 100% of the rotor axial chord. Following this task various probes were to be operated behind the rotor (in the previously defined flow field) and their response compared.

The measurement of the velocity field downstream of the turbine using constant temperature hot wire anemometers was performed using a technique similar to that developed by Whitfield et al (7). In this technique a slant wire probe was located at a position in the measuring zone. The wire was orientated about its major axis and several velocity components in the plane normal to the wire were recorded. These velocities were then transposed into the components in the frame of reference relative to the turbine axis. During the analysis, the effect of changes in the wire overheating ratio was accommodated using the local air temperature calculated from the measured whirl velocity and using the Euler equation. This process was completed iteratively as initially both whirl velocity and local temperature were estimates. A check was made on the calibrated values of the gas temperature downstream of the turbine using a purpose built (fast response) hot wire anemometer working in the constant current mode.

The results obtained from the anemometry study are shown in figures 4 and 5 (the 100% of rotor axial chord measurements are omitted because they show very little evidence of a blade to blade flow structure). The velocity components are only illustrated for the blade mid-height position although other measurements were taken. There is clearly a distorted flow field immediately downstream of the rotor with somewhat larger perturbations in the tangential than axial direction. In the wake region, close to the rotor, the axial component of the flow is almost brought to rest whereas the tangential component is accelerated in the direction of rotation. Between the wakes, the flow has a high axial component and a tangential component which is in the opposite direction to the rotation of the rotor inferring that work is being taken from this flow region. Measurements were taken at various axial stations but by one axial chord length downstream, the perturbations had effectively disappeared.

These measurements indicate that the proportion of the blade passage area occupied by the wake fluid at blade mid-height is approximately 40% at the 12.5% (of rotor axial chord) downstream measuring station. This is larger than is normally the case for axial compressors, but close to the 33% blockage presented by the blunt blade trailing edge. The fluctuation in temperature at the 12.5% chord station is $25C^{o}$, figure 5. This degree of temperature difference would, according to the work of Moffat and Dean (1), produce a reading from an unshielded probe mounted close to the rotor approximately $15C^{O}$ higher than the value it would have read if it had been placed far enough from the turbine to sense the mixed fluid temperature.

The decay of the wake downstream of the rotor, figure 4, is seen to be very rapid, and much quicker than one would expect from a 'free' wake theory. Aerofoil wake decay, however, has been observed to occur very quickly in turbomachinery, Lakshminarayana (8), and results taken at different radial heights clearly indicated migration of the wake towards the outer walls of the casing. (It is also appreciated that evidence of blade wake can be transmitted through an axial flow machine and identified using spectral techniques). The 'constant current' hot wire results are super-

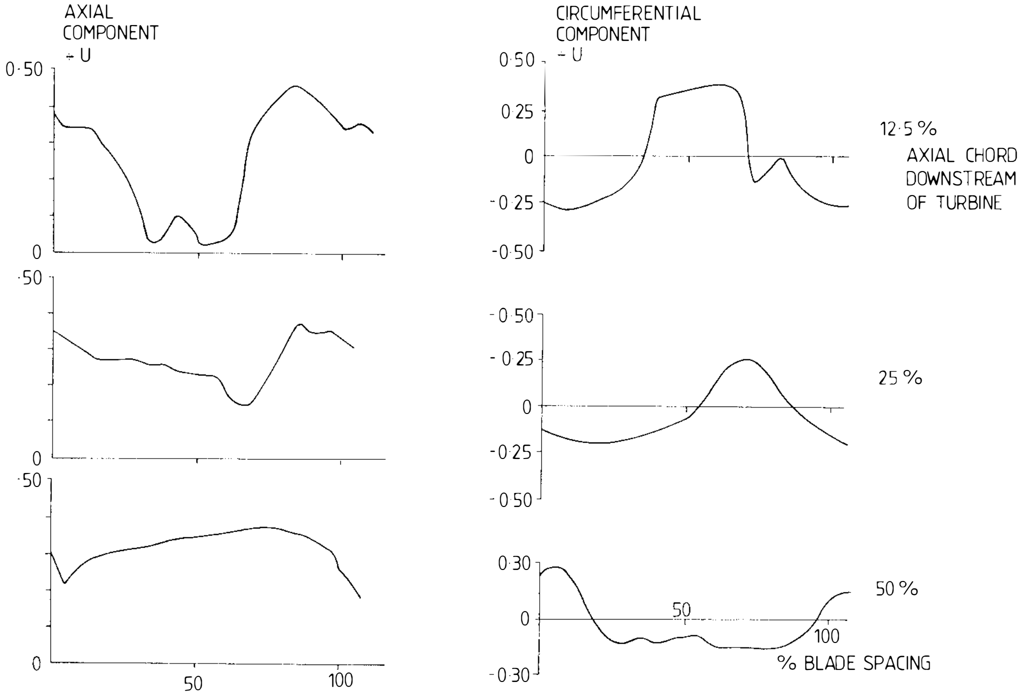

FIG 4 COMPONENTS OF VELOCITY DOWNSTREAM OF THE TURBINE

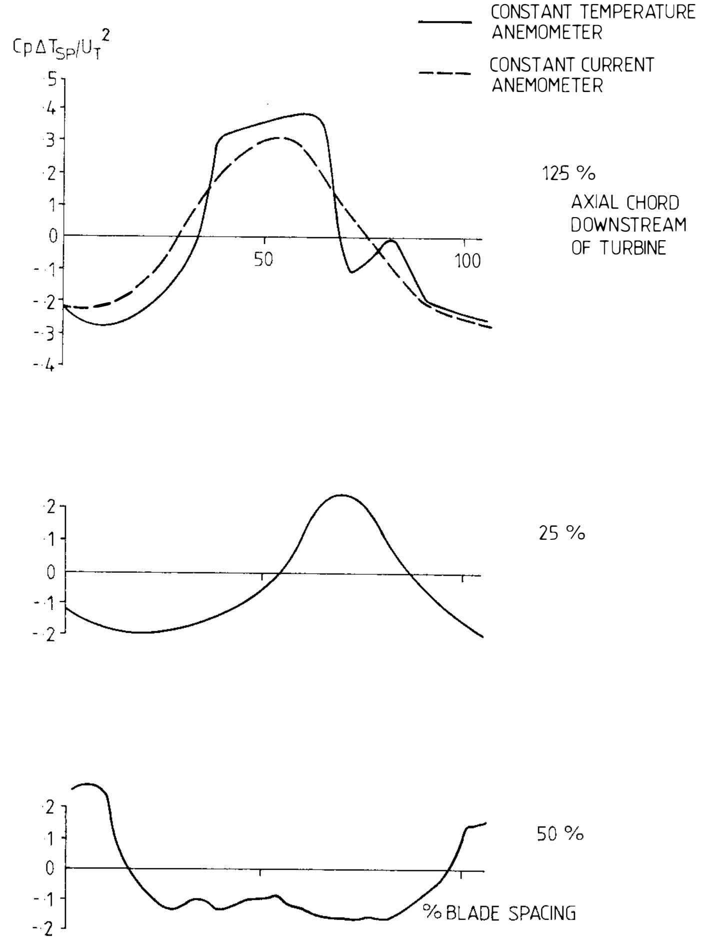

FIG 5 TEMPERATURE RISE AT MID-HEIGHT AND VARIOUS AXIAL STATIONS DOWNSTREAM OF THE TURBINE (HOT WIRE MEASUREMENTS)

imposed on the 'constant temperature' results in figure 5 for the 12.5% axial chord measurement station. The results are in fair agreement although the constant temperature bridge appears to detect a higher frequency component.

Figure 6 compares the mass averaged and time averaged hot wire results obtained at different axial distances from the rotor. Clearly there is good agreement sufficiently far downstream but close to the rotor there are considerable differences. As energy conservation considerations would suggest, the mass averaged hot wire results are very nearly constant (the small increase can be attributed to radial migration).

As suggested in the theoretical discussion, in cases where the flow is disturbed by a significant wake structure, the time averaged temperature is greater than the mass averaged value.

It should also be noted that the time averaged temperature (obtained with the constant current anemometer) agrees more closely, near the rotor, with the mass averaged temperature (obtained with the constant temperature work) than with the time averaged temperature (again obtained from the constant temperature method). This is somewhat surprising and possibly associated with the orientation of the wire during the constant current work where it was aligned in a tangential direction making it more sensitive to the axial flow component than to the tangential component. Similar results had been obtained previously.

The Response Of Thermocouple Type Probes To the Flow Field Downstream Of The Turbine Disc

Having established the nature of the flow in the working section, the following work examines the response of some currently used temperature measuring probes in the turbine flow field. The probes were installed in their respective holders and positioned in the working section with the temperature sensing element at blade mid-height. The axial position of a probe was such that the extreme front of the probe, when aligned with the major axis of the turbine, was located at a reference point. These reference points correspond to the location of the position of the hot wire anemometer for the initial calibration tests, i.e. axial distances of 10%, 12.5%, 25%, 37.5%, 50% and 100% of rotor axial chord. In cases when the design of the probe head permitted, the probe was rotated about its own major axis.

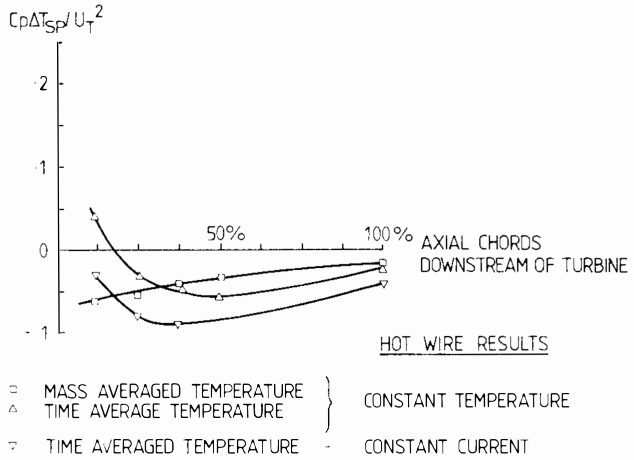

FIG 6 COMPARISON OF CONSTANT TEMPERATURE AND CONSTANT CURRENT HOT WIRE RESULTS DOWNSTREAM OF TURBINE DISC AT BLADE MID-HEIGHT

The temperature of the plenum chamber air and the output of the probe were measured at each of the axial positions. The temperature difference between the measured probe temperature and the plenum chamber temperature are discussed for the following probes, figure 7:

- An isolated bead thermocouple.
- A bead located in a combination type probe head.
- An open shielded type sensor.
- A Kiel "type" shielded sensor.
- A cylindrical type sensor.

All thermocouple heads were nickel-chrome/nickel-aluminium junctions (type k).

Figure 8 compares the response of the open bead thermocouple with the hot wire results. Now it would be expected, from the analysis presented in the previous section (Eq. (4)) that the bead would respond to the time averaged temperature but weighted by the heat transfer coefficient. For the experimental velocity fluctuations encountered, the weighting effect of the heat transfer coefficient is relatively small, therefore, the bead and time averaged hot wire results should be similar. This is not apparent in figure 8 but it should be remembered that although the bead results represent some response to an average flow, the hot wire results are for one blade passage only and during these studies differences between the flows emerging from different passages were noted. Therefore, the results from one blade passage would not be expected to compare with the average 'bead' response. (This was a disappointing result for this project and it is hoped to obtain more comparable results at a later date). It is interesting to note in figure 8 that the mass weighted temperature defined from the single blade passage is reasonably representative of the far down-stream condition. This suggests that the energy flux

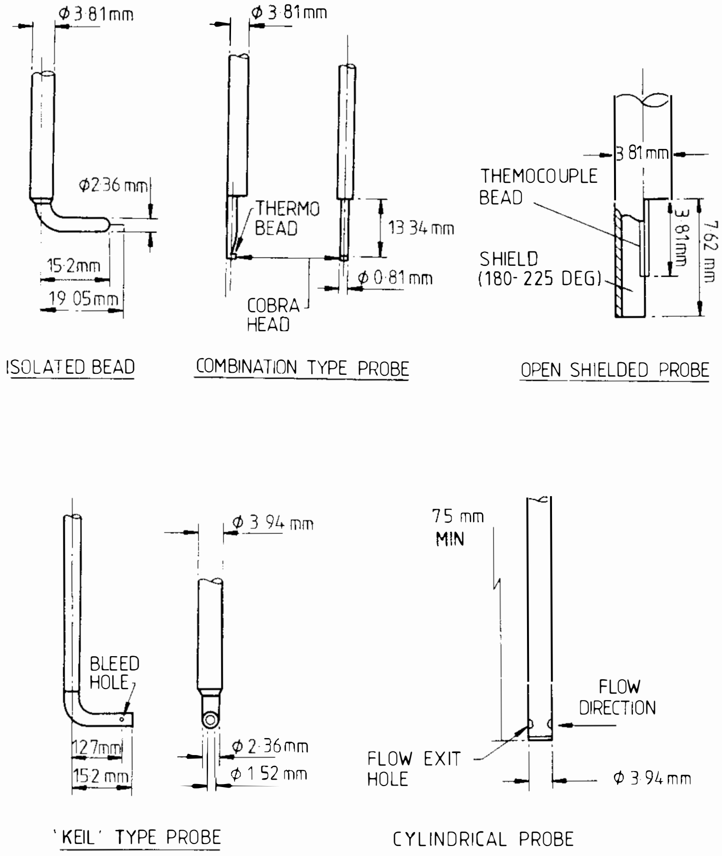

FIG 7 TYPICAL THERMOCOUPLE PROBES TESTED

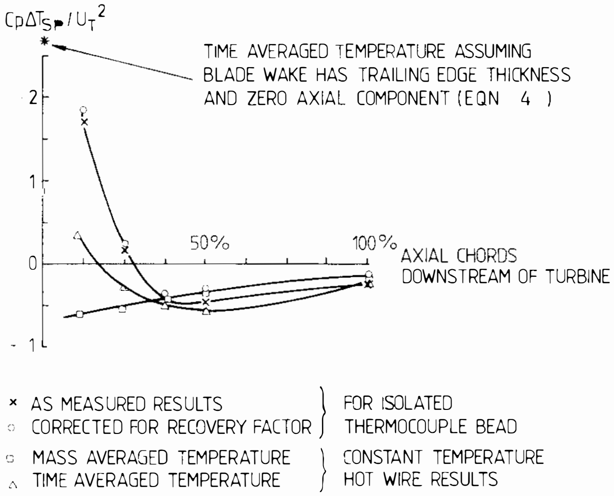

FIG 8 COMPARISON OF ISOLATED BEAD AND HOT WIRE RESULTS DOWNSTREAM OF TURBINE DISC AT BLADE MID-HEIGHT

through each blade passage is similar but that the wake structure (which largely defines the time averaged temperature) is not.

The thermocouple bead response shown in figure 8 is typical of what previous sections would have suggested (reading high near the turbine disc and reducing to the mass meaned temperature as the flow becomes more uniform). If the thermocouple bead was stationed close to the rotor to provide energy flux information the sensor error would be very significant.

Figures 9 to 12 show results for the shielded thermocouple probes. Clearly the error produced by the shielded probes are very dependent on orientation. The requirement is a probe which provides an accurate measurement when facing some easily defined orientation and is insensitive to small changes in orientation about this position.

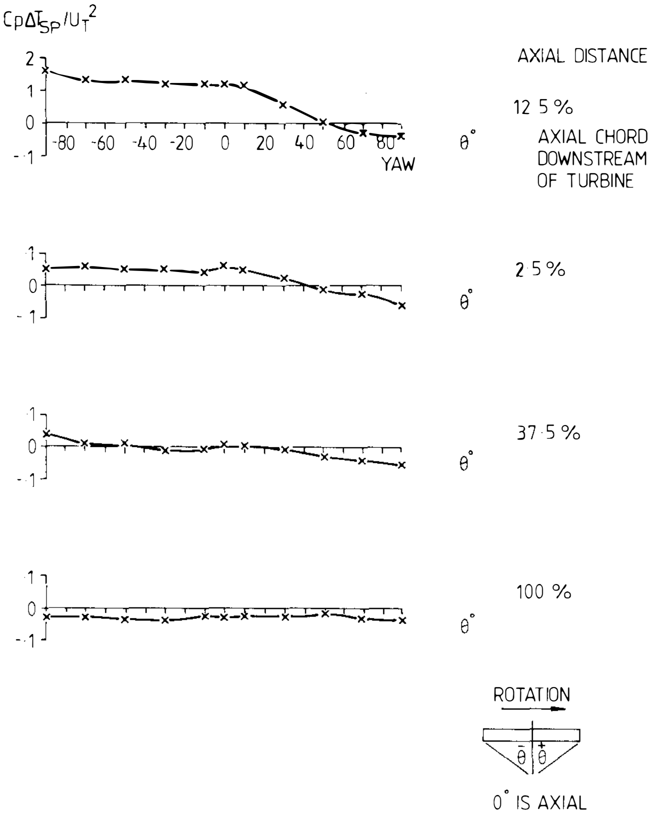

FIG. 9 RESPONSE OF COMBINATION TYPE PROBE AT VARIOUS ORIENTATIONS (BLADE MID-HEIGHT)

In all cases examined the shielded and non-shielded probes gave similar readings far downstream of the rotor (approximately -1C°) where the flow is essentially mixed. At close proximity to the rotor, however, the temperature indicated by the various shielded and non-shielded sensors differ considerably.

At close proximity to the rotor and when directed into the flow (0°) the combination type probe, figure 9, clearly tends to indicate a high temperature, and the error increases as the sensor is directed towards the direction of rotation (negative yaw) and the overheated wake. Conversly, the temperature response with this probe is reduced as the probe is directed away from the direction of rotation because in this situation the sensor is shielded from the wake by the probe shield.

The errors associated with the openly shielded thermocouple, figure 10, are of interest for two reasons. Firstly, the rotation of the shield exposes the thermocouple bead to fully wake flow and then fully mainstream flow at different angular orientations, Eckardt (9), and secondly, it should be noted that the extreme temperature difference, shown by these probes, compare very favourably with the peak to peak temperature difference indicated from hot wire measurements, figure 5. These probes would appear to be useful to ascertain the quantitative values of the wake and mainstream temperature, but in order to use the information to estimate the mass mean temperature, a knowledge of the proportion of the blade passage area occupied by the wake is required. (The method suggested by Eckardt (9) did not appear to apply). These probes also proved to have very complex recovery factors at large angles of orientation.

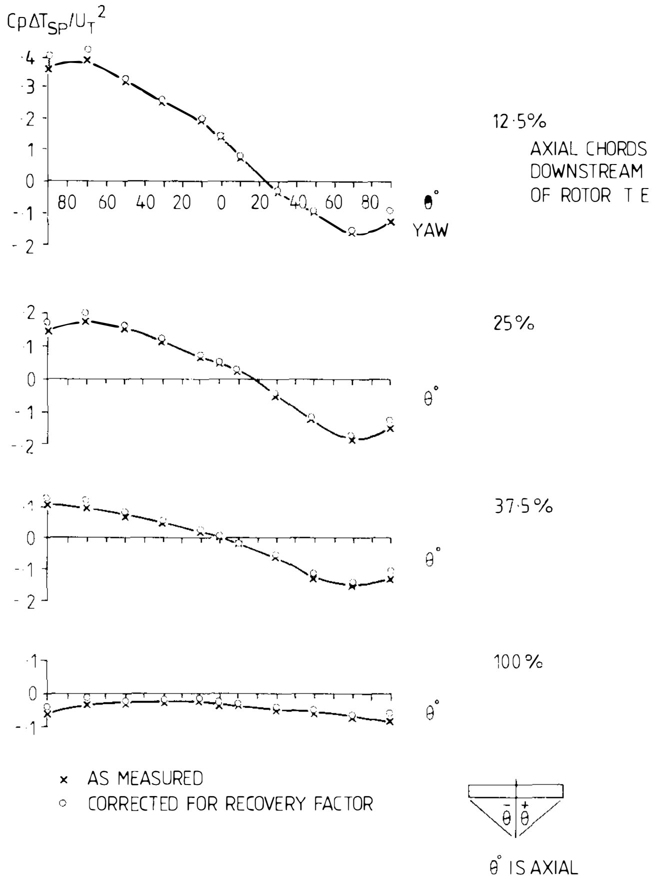

FIG 10 RESPONSE OF OPENLY SHIELDED TYPE PROBE AT VARIOUS ORIENTATIONS (BLADE MID-HEIGHT)

Figure 11 shows the error incurred with the Kiel type probe when placed axially. Clearly, the response is similar to that of the isolated bead. Again the agreement with the far downstream mass averaged temperature is good. This instrumentation is typical of that mounted on the leading edge of stators.

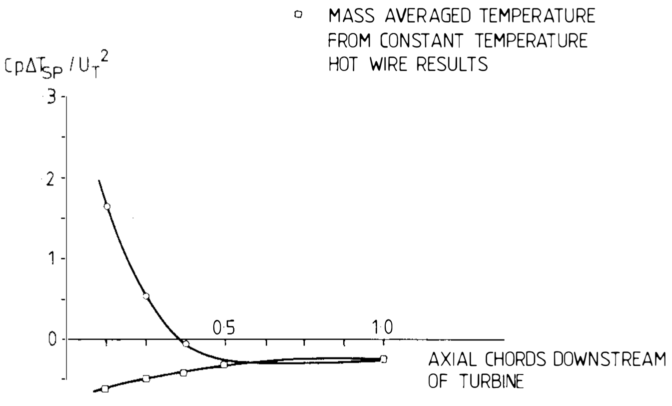

FIG 11 RESPONSE OF KIEL TYPE PROBE AT VARIOUS AXIAL STATIONS (BLADE MID-HEIGHT, AXIAL ORIENTATION)

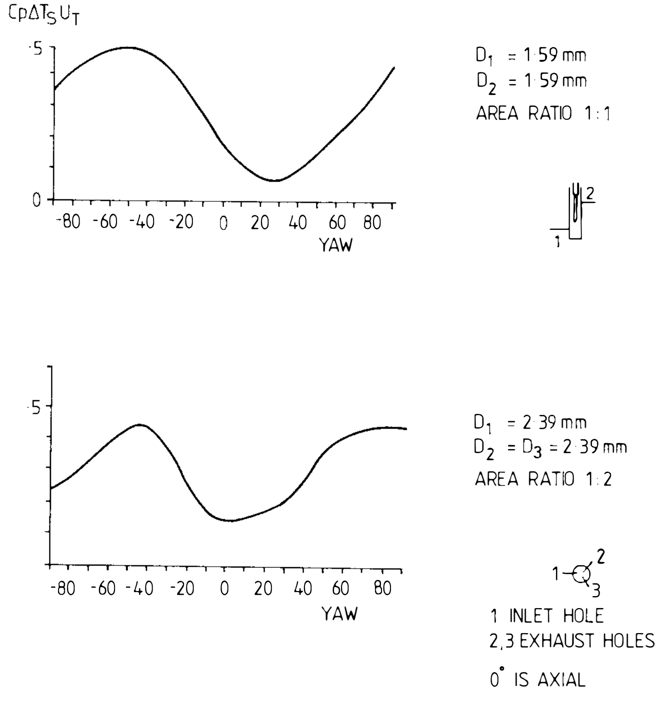

FIG 12 RESPONSE OF CYLINDRICAL PROBE WITH DIFFERENT CONFIGURATIONS (BLADE MID-HEIGHT)

The error, figure 12a, produced by the cylindrical closed shielded thermocouple probe (with single bleed hole) was the worst result obtained. Upon reflection, the cause for this is quite straightforward. Rotating the shield changes the duty of the inlet and outlet bleed holes as they in turn come in line with the wake. Rotating the shield centre anticlockwire exposes the lower inlet hole to the wake flow, thus increasing the temperature error. Rotation of the probe in the clockwise direction brings the upper bleed hole in line with the wake (the wake at the rotor tip is hotter than that at mid span) and the temperature error appears to be marginally increased in this case. Repositioning of the bleed holes on the same radial location of the shield showed little improvement although the indicated 'peaks' become more equal. The use of two bleed holes as indicated in figure 12b increased the number of lobes in a cycle which could also be explained using the qualitative model proposed above.

CONCLUSIONS AND RECOMMENDATIONS

From the work, the following conclusions can be drawn:

(1) The range of temperature sensing probes tested in the work exhibit an error effect produced by the interaction of the rotor wake with the probe. Generally, the sensor will attempt to provide a time averaged temperature whereas a mass weighted temperature is more useful. The matter becomes more complicated, however, due to biasing influences associated with any stagnation shield and heat transfer effects.

(2) The errors noted are very significant and are in general agreement with theoretical analysis which has indicated that different errors can be expected under different flow conditions. For example, at the hub of a fan the error may produce a slightly low reading whilst the tip of a fan can produce a significantly high reading of temperature.

(3) The size of error produced depends upon the probe design. If a simpler plain thermocouple bead is used as a standard, an improvement upon this result can be obtained by partly shielding the bead as in the case of the combination type probe. The error will be increased, however, if the shield is of such a construction so as to provide an unfavourable sampling process (e.g. the cylindrical probe).

(4) In general, most probes gave only small errors when more than half an axial chord downstream of the rotating blade row (in the test facility).

(5) It is considered that throughout this study a significant understanding of some of the probes involved has been gained. Further progress now should involve the testing of modified probes.

(6) It should be noted that dynamic sensors (hot wires in this case) were the only instruments capable of accurately defining the mean values of the variables required. Although such methods are unattractive, due to the fragility of sensor elements, their scientific merit cannot be denied. A suggested development, therefore, would be ruggedised dynamic (yawmeter) sensors possibly of the Drag Force Anemometer type, Krause (10), or dynamic transducer type instruments, Shreeve (11).

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