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Calibration characteristics of a three-hole probe and a static tube in wet steam

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Abstract

Total pressure tubes, yawmeters and static probes can be used for measurements in droplet laden flows, e.g., mists and wet steam. But to be successful it is important when calibrating the instruments that the characteristics of the droplets be satisfactorily matched. Water droplets formed by nucleation in the wet stages of steam turbines are very small and difficult to reproduce under steady flow conditions. To produce wet steam with realistic droplet sizes requires a supply of supercooled steam which can be created under blow-down conditions by the equipment employed. The calibration characteristics of a three-hole probe and a static tube in superheated and in wet steam are presented. © 2001 Elsevier Science Inc. All rights reserved.

Keywords: Two-phase flow; Instrumentation; Wet steam; Probes; Steam turbines; Transonic cascades

1. Introduction

Total pressure tubes, yawmeters and static tubes are widely used in studies of high speed flows of gases. They can also be used in droplet laden flows e.g. mists and wet steam. When the fluid is single phase calibration of the probes does not present any particular problems but in the case of two-phase flows it is necessary that the characteristics of the droplets be satisfactorily matched between the calibration facility and the actual experimental conditions.

An important practical field where two-phase flows are encountered is the wet stages of steam turbines. The naturally nucleated droplets are extremely small and at low and moderate pressures the limiting supersaturation associated with the first reversion of steam is high. This combination presents practical obstacles to the generation of wet steam mixtures representative of those found in turbines. Although many studies of the performance of the wet stages of steam turbines have been reported in the literature (e.g. Barbucci et al., 1993; Haller et al., 1989; Hisa et al., 1991; Kleitz et al., 1989; Kreitmeier et al., 1979; Sakamoto et al., 1992; Walters, 1985; Yoshida et al., 1990), information about calibration arrangements and characteristics of probes in wet steam is scarce. Calibration characteristics of total pressure tubes in wet steam have been considered in theoretical papers by Crane and Moore (1972) and by White and Young (1995). Crane and Moore have considered the contribution of the droplets to the momentum change of the fluid on reaching the probe head in the high subsonic range of Mach numbers, but they have disregarded the effects of the thermal relaxation. White and Young have considered the correction to the probe reading due to both dynamic and thermal relaxation effects, particularly in supersonic flows where a standing shock wave develops in front of the probe. But no experimentally determined calibration characteristics are reported. The error due to thermal relaxation increases with decreasing droplet size and for droplet sizes associated with turbine flows is substantial. In a review of experimental development of blading for large steam turbines Cox (1980) has included some typical calibration charts for a five point probe in a Freon–air mixture and in wet steam.

In the course of investigations of the characteristics of turbine blading in nucleating and in wet steam in two-dimensional cascades, the present authors have performed flow traverses downstream of the blades (Bakhtar et al., 1997a,b). For this purpose a combined total pressure tube and yawmeter with a separate static pressure tube was used. Although the details of the equipment, the probe and its calibration were given in connection with earlier measurements (Bakhtar et al., 1994), the calibrations have subsequently been repeated over a wider range of conditions. A set of calibration graphs is presented in this paper in the hope that it will be of value to other investigators.

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Notation

P	pressure
T	temperature
$T_S(P)$	saturation temperature corresponding to pressure P
α	probe angle relative to the flow

Subscripts

0	Stagnation condition
L	left-hand tapping
R	right-hand tapping
S	static (pressure)
TD	Total pressure tube
1,2	station numbers

To produce wet steam with small droplet sizes in subsonic flows requires a supply of supercooled steam which can be generated under blow-down conditions by the equipment employed (Bakhtar et al., 1991). Before considering the probe and its calibration, the general features of the equipment will be briefly described.

2. Main features of the equipment and principle of operation

The general features of the equipment are illustrated diagrammatically in Fig. 1. The steam receiver is a tank of 28 m^3 capacity. Valve 1 is a quick-acting valve with a typical opening time of 70 ms and releases the flow to the test section. The spent steam is discharged to a condenser with a condensing surface area of 60 m^2. The test section is essentially a stainless steel fabrication which holds two cover plates 76 mm apart. The blades forming the cascade or other profile blocks forming the configuration to be investigated are mounted on circular supporting plates which fit into the test section. The opening of the quick-acting valve is followed by transients which decay in less than 1 s. A quasi-steady flow is then established in the test section which can be studied.

To generate supercooled steam the receiver is filled with saturated steam to predetermined conditions. The steam is then vented to the condenser via the test section through the quick-acting valve as well as through by pass lines. This has the effect of expanding the receiver content, thus causing it to supercool, without the penalty of giving it kinetic energy. With the flow through the test section established, once the desired upstream conditions have been reached in the receiver the data acquisition system is triggered.

To take pressure measurements during the short run times each tapping point is connected by a hypodermic tube to a separate pressure transducer. To prevent formation of vapour bubbles and protect the transducers from exposure to steam, the connecting lines are kept full of oil and purged when necessary. Recording of data is controlled by a microcomputer. For this purpose the signals from the instruments after individual processing are connected each to a separate sample and hold module. To take a set of readings all the sample and hold units are signalled from the processor simultaneously and subsequently scanned. The signals are then converted to digital form and stored in the computer memory. Having completed a set of readings the sample and hold units are signalled again and the procedure repeated. Generally the average of 100 readings at each point was adopted as the value at that point.

3. The probe

Based on the experience of Cox (1980) the probe arrangement adopted is illustrated diagrammatically in Fig. 2. This was a three-holed yaw type instrument with a separate static tube. The tubes were of 0.5 mm bore and 0.8 mm outside diameter. The central tube was the total pressure probe and faced the flow. To minimise blockage of the flow the outer tubes of the yawmeter, which were chambered at 45° in opposite directions were placed above and below the central tube. To minimise stem effects the sensing heads of the tubes were 19.9 mm from the stem. The static pressure tube was placed 17 mm above the total pressure tube and had a 20° cone at its tip. To sense the static pressure only one tapping point was drilled into this tube 7.3 mm from its tip, positioned vertically above its axis and in line with the tip of the total pressure tube. With the cascade flow two-dimensional, the variations of pressure in the spanwise direction were negligible and the static tube was taken to indicate the static pressure at the probe tip accurately.

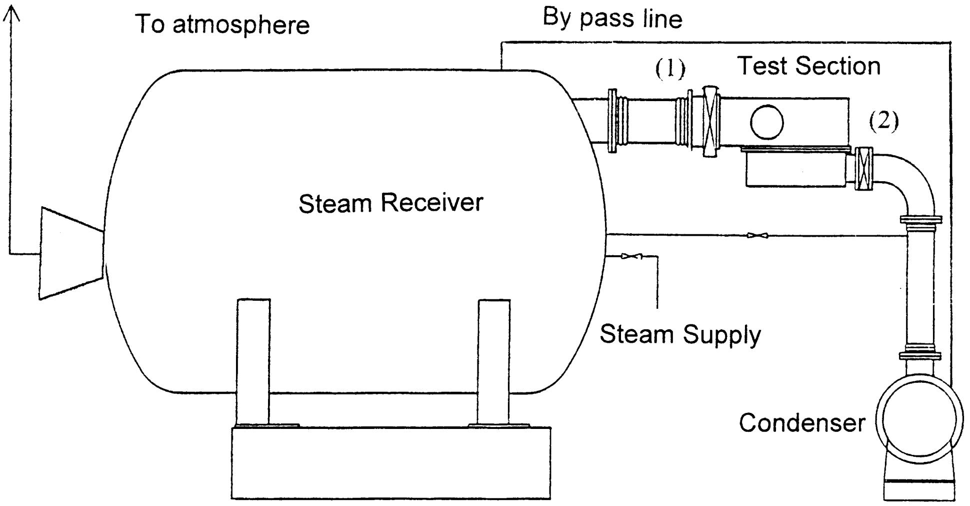

Fig. 1. General arrangement of the blow-down steam tunnel.

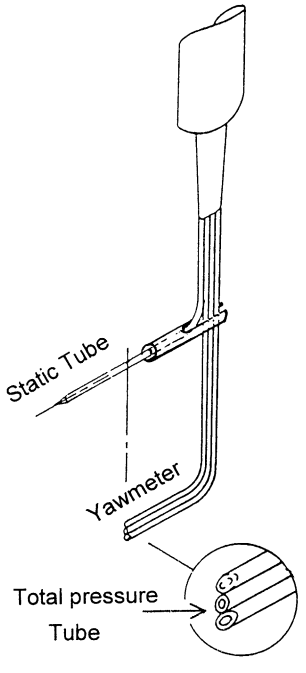

Fig. 2. Probe.

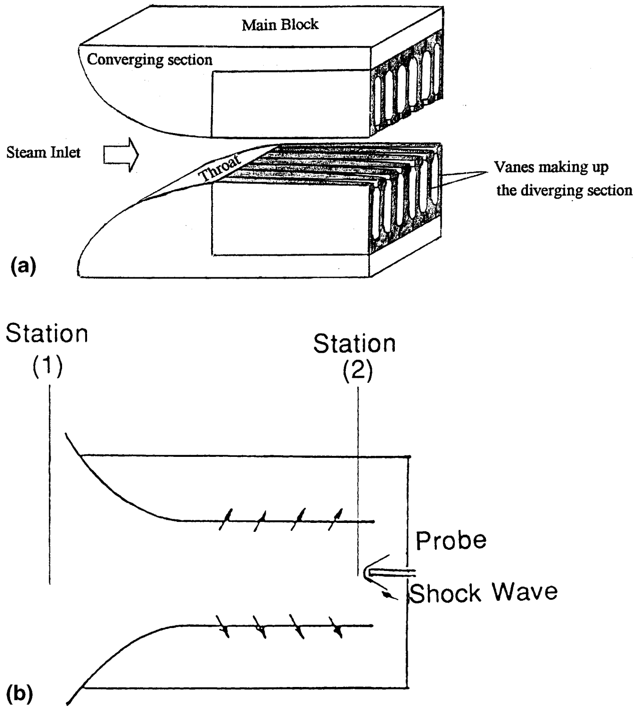

Fig. 3. (a) Schematic diagram of the slotted nozzle. (b) Calibration nomenclature.

To increase the rigidity of the static tube and prevent it from oscillating in the flow, it was stiffened by a closely fitting sleeve for the first 6 mm of its length.

4. The slotted nozzle

To calibrate the probe using the test section a slotted nozzle was designed and constructed. As described by Knight (1957) these nozzles are capable of inviscid expansion of the flow over a wide range of outlet Mach numbers. The outlet Mach number can be varied simply by changing the pressure ratio across the nozzle. A schematic diagram showing the features of the nozzle is shown in Fig. 3(a). The nozzle was constructed with a rectangular section to fit inside the test section in place of the cascade. The converging section reduces the flow area from the outlet of the contraction liners to a throat width of 25.4 mm. There are then seven vanes in each block constituting the parallel section downstream of the throat. The vanes are shaped to form slots in the sides of the parallel section to allow for some fluid to escape, thus reducing the mass flow rate per unit area of the parallel section and causing it to act as a diverging section. As the pressure ratio across the section and with it across the slots is increased there will be a larger flow through the slots and thus greater effective expansion of the flow. The dimensions of the slots relative to the width of the passage provide for a maximum outlet Mach number of 1.6.

A further sketch illustrating the position of the probe relative to the nozzle and the notation adopted is given in Fig. 3(b). The station upstream of the nozzle is designated as (1), the position in the nozzle near the exit and just upstream of the probe as (2) while the reading of the total pressure tube is given suffix TD. When the nozzle is fed with steam at sufficiently high temperature for the flow to remain superheated throughout, the expansion to the exit plane is isentropic. When the nozzle is fed with supercooled steam, the fluid nucleates just downstream of the throat and results in wet steam with small droplet sizes at the downstream plane. With this arrangement calibration of the instrument for all flow characteristics in superheated steam and the calibration of the yawmeter and the static tube in wet steam was straightforward. But the calibration of the total pressure tube in wet steam in supersonic flows presented a problem.

To calibrate the tube it is necessary to establish the relation between the tube reading, P_{TD}, the static pressure P_{S2} and the total pressure at station (2), P_{02}. In the absence of phase change the total pressure at (2) can be taken to be the same as that at (1) which can be measured. But if the fluid nucleates in the passage, the flow in the core of the nozzle will no longer be isentropic, as the reversion process involves internal heat transfer and hence increase of entropy and loss of total pressure between stations (1) and (2).

In the original investigation, it was estimated theoretically that the loss of total pressure due to nucleation in the slotted nozzle over the range of pressures considered was approximately 3% of the absolute value of the total pressure. With this correction included the estimated values of P_{02} matched the readings of the total pressure tube in subsonic flows very closely. This was taken as evidence that both the estimates of the loss of total pressure due to nucleation had been of the right magnitude and that in subsonic flows the total pressure tube measures the total pressure with negligible error directly.

In a subsequent investigation to study the behaviour of a profile in wet steam two venturis were constructed. When supercooled steam is admitted to a venturi expansion in the converging part will cause the fluid to nucleate. Careful diffusion of the flow in the diverging section allows the droplets to be retained. Naturally nucleated steam thus generated could then be admitted to the cascade of the blades. The venturis were designed for rates of expansion of 1000 and 5000 s^{-1} to generate droplets of 0.3 and 0.1 μ m diameter, respectively.

With the venturis available it was thought possible to place them upstream of the slotted nozzle in the test section,to nucleate the steam prior to admission to it. This would have minimised the thermodynamic losses incurred by the flow in the nozzle. However, preliminary measurements showed evidence of dissipation in the diverging sections of the venturis. It was not certain that at entry to the slotted nozzle the fluid was completely mixed and the fluid condition could not be regarded as uniform. The loss of total pressure due to nucleation was, however, measured in the venturis directly (Bakhtar et al., 1997a,b). With the flow in the venturis sub-sonic throughout and the outlet Mach number relatively low, the drop in total pressure in the core of the flow between the inlet and outlet sections could be measured and taken as the loss due to nucleation. The average of the loss in a series of measurements in both nozzles was approximately 3% of the total pressure wi th an experimental uncertainty of ±0.5%. But the corresponding theoretical solutions underestimated the measurements by a greater margin. On the other hand in the case of the slotted nozzle, as already stated the losses have been both measured and predicted to be 3% of the total pressure.It was, therefore, reasoned that in subsonic flows the total pressure tube reads the true pressure accurately and that the measurements in subsonic flow in the slotted nozzle provide direct observation sof the loss, are more extensive and are of a similar magnitude to those obtained in the venturis. The loss of total pressure due to nucleation in the slotted nozzle was, therefore, taken tobe 3% of the absolute value of the total pressure.

5. Calibration graphs

The three point probe and the static tube were calibrated with steam superheated and 8, 13, 17 and 21 K supercooled at inlet to the nozzle with probe angles of −20°, −10°, 0°, +10° and +20° relative to the flow. Over the range of conditions used in the measurements the calibration data for the tests with steam supercooled at inlet were independent of the supercooling. Consequently in the results presented the majority of the measurements have been recorded at 17 K supercooling.

5.1. Characteristics of the yawmeter

The calibration characteristics of the yawmeter in superheated and in wet steam are shown in Figs. 4(a) and (b), respectively. Using P_{L}, P_{R}, and P_{TD} to denote the pressures indicated by the left-hand, right-hand and total pressure tubes, respectively, values of $(1 - P_{\mathrm{R}}/P_{\mathrm{TD}})$ are plotted against $1 - P_{\mathrm{L}}/P_{\mathrm{TD}}$ in these figures. It is seen that the relationship is linear and the mean line connecting the points at each angle passes through the origin. The slight departure of the two measurements in wet steam at +10° angle near the origin is attributed to reduced resolution of the system at very low velocities. It will also be noted that the two sets of results are similar but in fact the differences between the two sets were sufficient to warrant distinguishing between them.

5.2. Characteristics of the total pressure tube

The calibration characteristics of the total pressure tube in superheated and in wet steam are plotted in Figs. 5(a) and (b), respectively. Because of the uncertainty in the speed of sound in wet steam, pressure ratios are more readily quantifiable and are used in preference to Mach numbers. Thus, using P_{02} to denote the true stagnation pressure just upstream of the probe and P_{S} (tube) the reading of the static tube, the calibration graphs are plotted in general form as P_{02}/P_{TD} against $1 - P_{\mathrm{S}}(\mathrm{true})/P_{\mathrm{TD}}$. Although in actual application it would be more convenient to plot P_{02}/P_{TD} against $1 - P_{\mathrm{S}}(\mathrm{tube})/P_{\mathrm{TD}}$. The measurements at flow angles of −10°, 0° and +10° relative to the probe are also shown on the graphs.

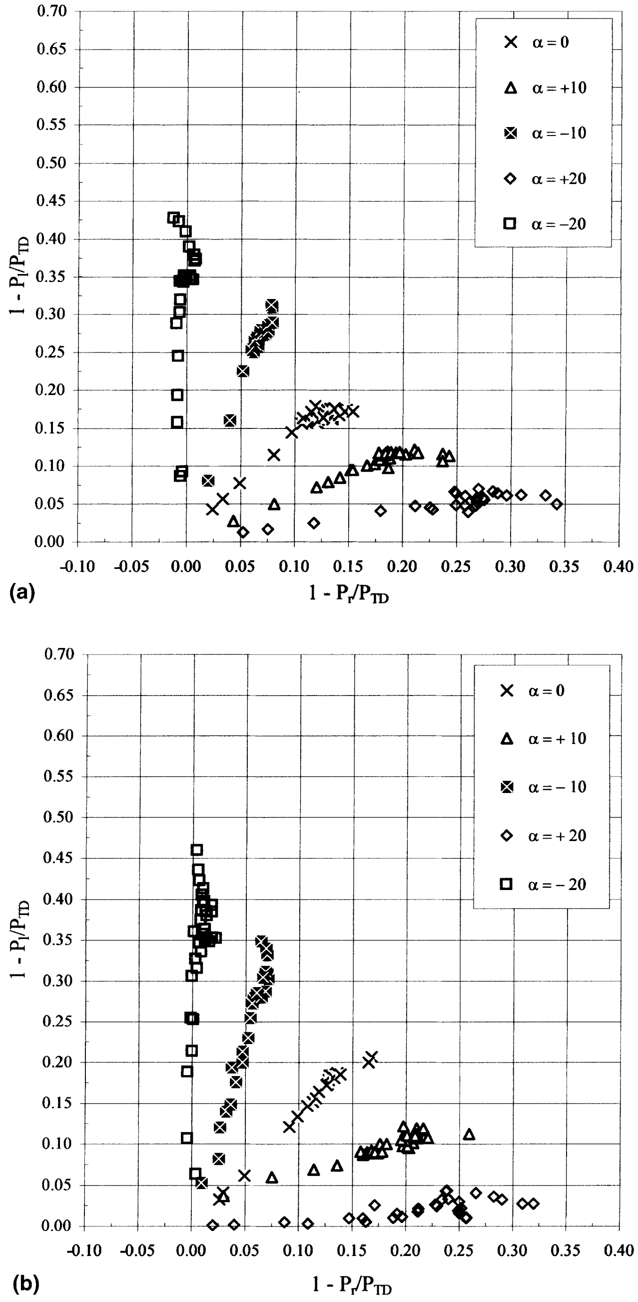

Fig. 4. (a) Characteristics of yawmeter in superheated steam. (b) Characteristics of yawmeter in wet steam.

It should be noted that despite the similarity of the two graphs, the difference between the two fluid conditions is considerable. Because of the enthalpy of phase change associated with two-phase flows a given pressure ratio P_{S}/P_0 represents very different actual fluid velocities in superheated and wet calibration curves. Calculation of the flow velocity from the measurements when the fluid is superheated is straightforward but one fluid temperature needs to be determined.

As already hinted the use of a similar procedure for a two-phase fluid is complicated by the need for using an apparent isentropic index. Calculated temperatures resulting from the use of apparent indices are unrealistic. The use of pressures in representing the results avoids all ambiguity. To deduce the flow velocity in wet steam, once the local static and stagnation

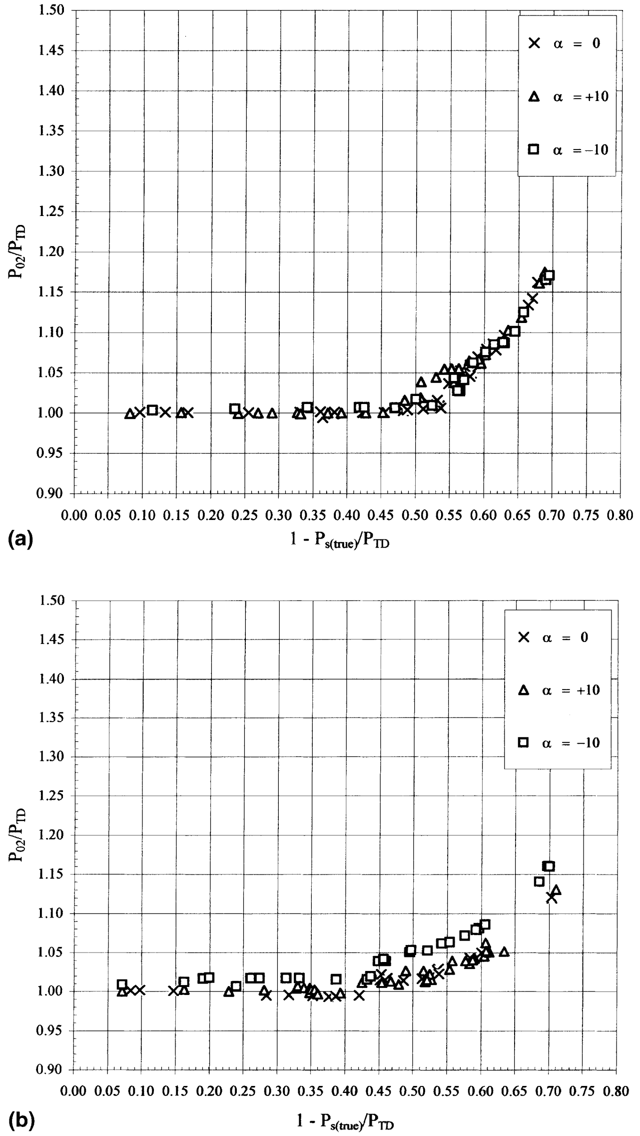

Fig. 5. (a) Characteristics of the total pressure tube in superheated steam. (b) Characteristics of the total pressure tube in wet steam.

pressures have been determined, one further fluid property needs to be known or determined. The measurements by the present authors were carried out in a stationary cascade where the inlet stagnation conditions were known and heat transfer between fluid layers could be assumed negligible. Thus stagnation enthalpy could be regarded as constant throughout the field. Hence, from the known stagnation enthalpy and measured stagnation pressure the fluid entropy could be calculated. Then with known entropy and static pressure the local enthalpy was calculated and the fluid velocity deduced from the difference between the total and static enthalpies.

5.3. Characteristics of the static tube

Using P_S (true) to denote the true static pressure read from wall tappings, the calibration results are plotted as $[P_S(\text{true}) - P_S(\text{tube})]/P_{TD}$ against $1 - P_S(\text{tube})/P_{TD}$ for superheated and wet steam in Figs. 6(a) and (b), respectively. The results at flow angles of −10° and +10° are also plotted on the same figures. The differences between the readings over this range of flow angle are generally within the experimental uncertainty. The dip in $[P_S(\text{true}) - P_S(\text{tube})]/P_{TD}$ over the range of $1 - P_S(\text{tube})/P_{TD}$ between 0.4 and 0.5 is a consequence of the cone angle and length of the probe tip. A smaller angle and longer tip would have reduced this effect but would have reduced the rigidity of the tube and its convenience in application.

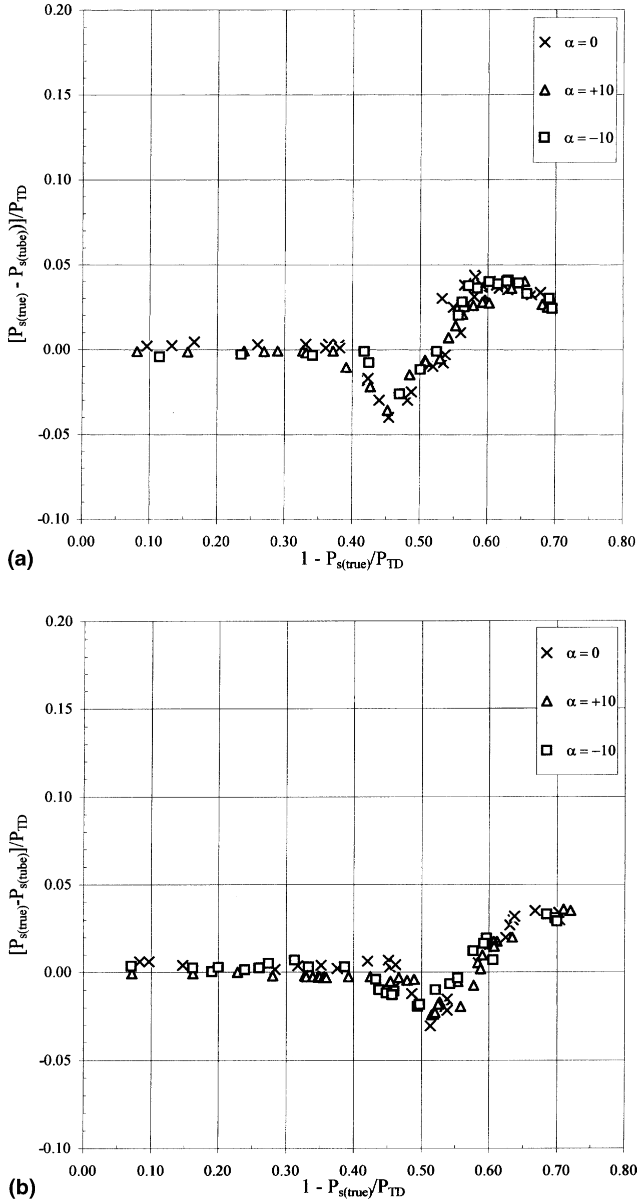

Fig. 6. (a) Characteristics of the static tube in superheated steam. (b) Characteristics of the static tube in wet steam.

6. Discussion and conclusions

For given steam conditions at inlet to the venturi, increases in the flow velocity just upstream of the probe are accompanied by increases in the wetness fraction. Over the range of pressure ratios used in this study the wetness fraction varied from 2% to 6%. For each setting of the inlet total pressure and the static pressure at the probe, the changes in the wetness fraction associated with the range of supercooling reasonably possible at inlet to the venturi have been about 1%. Surprisingly, over this range of conditions the calibration characteristics of the probe have been independent of the steam wetness.

To seek the reason for this observation the effect of the differences in steam wetness on the behaviour of the total pressure tube can be examined. Considering the example of steam at a pressure of 0.4 bar, carrying a population of very small droplets and moving at 400 m/s being brought to rest isentropically. For initial wetness fractions of 3.0%, 5.0% and 7.0%, the corresponding wetness fractions at stagnation will be 0.45%, 2.50% and 4.45%, respectively. Thus, the change in wetness fraction of steam on being brought to rest for these cases is 2.55%, 2.50% and 2.45%, respectively. This is a change of 0.1% in the wetness fraction for a difference of 4% in the initial moisture. Thus as a proportion of the moisture evaporated this represents a difference of 1% for each per cent of initial wetness. As the main influence of phase change on the behaviour of the flow is caused by the internal release (or absorption) of latent heat on the vapour phase, other things being the same the correction due to two-phase effects should be proportional to the change in wetness. As the correction for wetness effects is itself small, the effect of changes in the initial wetness of steam on the correction is very small. The only qualification is that the steam stagnation condition should not be superheated. It can thus be concluded that the results obtained represent the characteristics of the probe in steam with wetness fractions of 2–6% and very small droplets but extrapolation to slightly higher wetness fractions should still give reasonable results.

As can be seen from the results the changes in the calibration characteristics of the yawmeter and total pressure tube between superheated and wet steam flows are small when the flow is subsonic. But the characteristics of the static tube under all flow conditions and those of the total pressure tube in supersonic flows differ appreciably in superheated and in wet steam flows. The characteristics of the probes are typically as indicated by the graphs.

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