ON DIRECTIONAL SENSITIVITY OF THERMO-ANEMOMETER SPLIT-FIBER PROBES

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ABSTRACT

Hot-wire thermo-anemometer probes are extremely fragile devices, and therefore they are used mostly in clean flows with neither debris nor small particles to prevent sensor destruction. Consequently, application of hot-wire probes is limited mostly to clean laboratory environments, their employment in semi-industrial research is extremely rare, and not always successful. Film probes with deposited thin metallic sensors on cylindrical fibers are more rugged and can be successfully employed for research tasks in semi-industrial applications. Surprisingly the potentials of these probes are not yet fully utilized. Detailed investigation of direction characteristics of a split-fiber probe was carried out during the course of this work. Several interesting outcomes resulted from this study. First, it has been shown that the split-fiber probe direction sensitivity rises with the increasing velocity contrary to the decrease of the velocity sensitivity, which is a common hindrance to application of single-sensor thermo-probes to high-speed and transonic flows. Second, the analysis of the acquired data indicates that the transition of the laminar vortex street into the turbulent one occurs in the probe wake at Reynolds number values between 900 and 1000, which is markedly higher than the usually reported range between 150 and 300 for a cylinder in cross-flow. Finally, the resilience of split-fiber probes to impairment by in-flow debris has been demonstrated proving the probe ability for effective use of these probes in semi-industrial or even industrial research tasks.

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NOMENCLATURE

X, Y, Z		coordinate axes
ΔV	[V]	voltage difference
δ	[deg]	effective zero incidence angle
η	[deg]	probe incidence angle
ψ	[deg]	fiber angular station
σ	[mV/deg]	probe directional sensitivity
Ma	[1]	Mach number
Nu	[1]	Nusselt number
Re	[1]	Reynolds number.

INTRODUCTION

Thermo-anemometry is a well-established experimental technique used in fluid dynamics investigations for more than 70 years. Thermo-anemometer technique is predominantly applied to research in the field of turbulence and low speed flow interactions. Principles of this experimental technique are well described in an open literature and will not be repeated here [Bruun, 1995; Perry, 1982; Tropea, 2007]. Sensors used for most of the thermo-anemometer probes are extremely thin wires of a diameter between 3 to 5 μm. The undisputable advantage of wire probes is above all very high sensor frequency response to flow unsteadiness, relatively little flow disturbance due to very small size of sensors, and continuous analog output signal. On the other hand, the heated wire thermo-anemometer sensors are extremely fragile and require clean flow with neither debris nor small particles to prevent sensor destruction. Application of hot-wire probes is limited mostly to clean laboratory environment. Employment of these probes in semi-industrial research is extremely rare, not always successful, and generally not recommended.

There are many industrial or semi-industrial research tasks demanding reliable measurements of velocity unsteadiness and varying flow directions, that could be efficiently resolved providing that suitable more rugged thermo-anemometer probes were available for reliable and efficient measurements. There are other types of thermo-anemometer probes, employing thin metallic films as sensors instead of thin fragile wires, which can be used for such purpose [Andreas & Murphy, 1986; Helle, 1993]. Surprisingly, the potentials of these probes are not yet fully utilized. Thin film sensors are deposited on firm support elements of various shapes using metallic sputtering method. Very effective sensor support is a slim ceramic cylindric fiber of a diameter between 50 to 200 μm as shown in Figs. 1 and 2. Cylindrical film probes have restricted frequency range, compared to the wire probes. Frequency range of fiber probes is affected by the sensor size, property, and shape of the support elements. The frequency response range of cylindrical fiber probes is limited to 25 kHz;

however, such frequency range is still sufficiently high for most of the semi-industrial applications. The most valuable properties of fiber probes are rigidity, longevity, and their resiliency to in-flow damages. At present, the probes are available in a single or dual sensor arrangement. A probe with two deposited film sensors, shown in Fig. 3, called a split-fiber probe, is the main topic of the investigation reported in this paper. There were limited attempts in the past to deposit three metallic sensors on a single fiber support. There are practically no known successful applications of the triple sensor thermo-anemometer probe to semi-industrial research, and it seems that use of these probes is no longer considered.

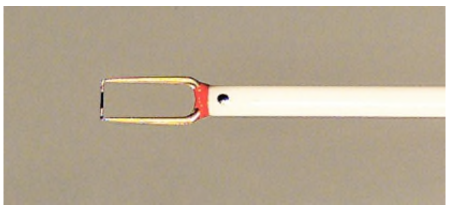

Fig. 1 Straight cylindrical fiber thermo-anemometer probe.

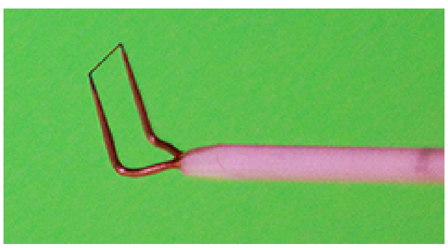

Fig. 2 Right-angle cylindrical fiber thermo- anemometer probe.

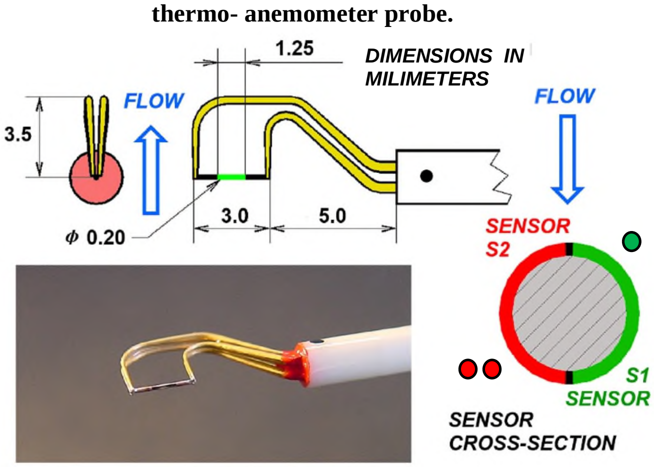

Fig. 3 Split-fiber thermo-anemometer probe.

WORK OBJECTIVES

The main objective of the reported work was to explore applicability of split-fiber probes (Fig. 3) for reliable measurements in highly three-dimensional flows with velocities peaking up to Mach number 0.6 level. The work emphasis was focused above all on determination of probe direction characteristics for measurement of sharp direction changes in three-dimensional velocity flowfields. The experiments were carried out under semi-industrial conditions with no provisions for air filtering at the test facility intake.

BRIEF NOTES ON THERMO-ANEMOMETER EXPERIMENTAL TECHNIQUE

The thermo-anemometer experimental technique is based on detection of convective heat transfer rate from a heated sensor into surrounding fluid [Collis & Williams, 1959]. In short, suffice to say that the voltage level required to maintain a constant, preselected sensor temperature is related to the incoming flow velocity (more precisely to the through-flow density).

The heat transfer rate from a heated cylindrical sensor in a cross-flow of fluid depends on several parameters. This dependency can be summarized into a relation between Reynolds and Nusselt numbers [Beale, 2011]. Velocity characteristics of single-wire or single-film probes are well discussed and documented in the open literature [Bruun, 1995; Perry, 1982; Tropea, 2007], and will not be presented here. The main thrust of this work has been focused on reliability of flow direction measurements using split-fiber probes.

It is the nature of any thermo-anemometer wire or fiber cylindrical sensor that the detected signal in regions of three-dimensional flows represents the magnitude of the effective flow velocity and not the absolute velocity vector magnitude. It means that these probes are competent in measuring only the velocity vector components projected onto the plane perpendicular to the cylindrical sensor centerline. The situation is depicted in the sketch in Fig. 4. The fiber centerline is identical with axis X. The depicted fiber cross-section is in plane YZ, which is hence the plane of measurement. In a three-dimensional flowfield the probe will always detect the effective velocity vector only. Aside from one exception the measured vector is always smaller than the three-dimensional absolute velocity vector. The only exception is the case when the entire velocity vector lays in the YZ plane, and then the absolute and measured effective velocity vectors are identical.

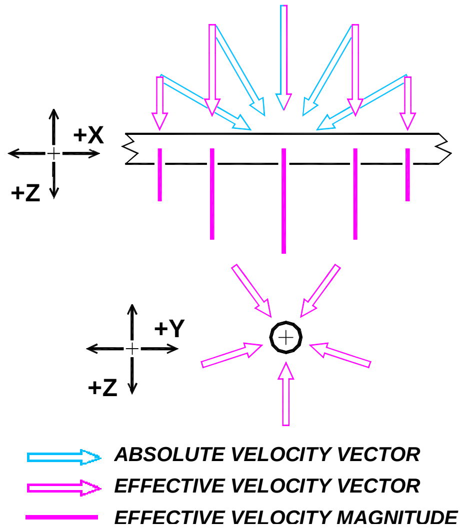

Fig. 4 Relation between absolute and effective flow velocities.

SPLIT-FIBER PROBE DESIGN

The principle instrument for the reported experiments was the split-fiber probe. The probe was already shown in Fig. 3. The probe consists of a single quartz cylinder with deposited two independent nickel thin-film sensors halving the fiber cylindrical surface along its axis. The diameter of the quartz cylinder is *200 μm*, the nickel films are 5 *μm* thick, and their active length is *1.5 mm*. The fiber cross-section is circular, whether it supports one or two sensors. Therefore, the overall cross flow pattern is always the same regardless any incoming velocity vector direction. The effective velocity vector components are projected onto plane YZ. This why a probe with a single sensor, like a wire probe, is insensitive to flow direction in plane YZ, because the probe signal is always represented by a single same voltage value regardless of the incoming flow direction. However, the distribution of the Nusselt numbers around a cylinder circumference is not uniform; on the contrary it varies significantly as shown in Fig. 5 [Eckert & Soehngen, 1952]. As the heating electric energy is fed to the wire or film sensor only in a single point inlet, there is no way for a single element probe to detect the depicted Nusselt number distribution around the fiber circumference. Consequently, the recorded electric voltage is always an indication of the average Nusselt number regardless of the incoming flow direction in plane YZ, as indicated in the plot in Fig. 5.

For a split-fiber probe the situation for the same flow conditions is different. As mentioned above, the split-fiber probe consists of two independent films deposited on a single fiber, as shown in Fig. 3. Each film sensor is an independent unit with its own source of electric voltage to maintain a constant, preselected temperature level for both sensors regardless the magnitude or direction of the incoming flow. Of course, the Nusselt number distribution over the fiber circumference does not depend on a number of film sectors deposited on the fiber, and the effective velocity influence is not altered either. Therefore, the overall heat transfer pattern is the same for a split-fiber probe as well as for any single-film fiber probe (see Fig. 5). Consequently, as far as the overall heat transfer rate from the sensors is concerned, its dependency on flow velocity (through-flow density) is governed by the same fashion as for a single-sensor thermo-anemometer probe.

SPLIT-FIBER PROBE DIRECTION SENSITIVITY

The difference between a single-sensor probe and the split-fiber probe is in the fact that the convective heat transfer, on the latter one, will be averaged separately on each of the film sensors deposited on the fiber. The average partial heat transfer rate value for each sensor will then depend directly on the particular distribution of the

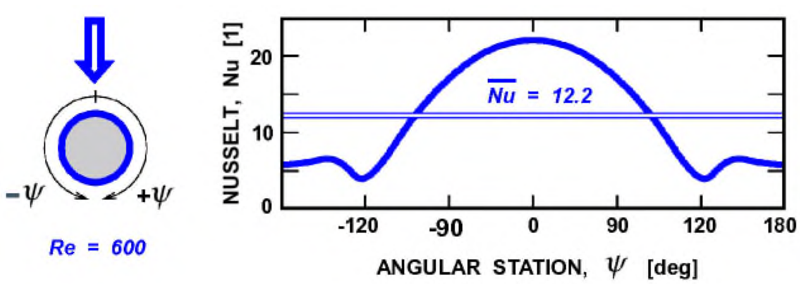

Fig. 5 Distribution of local Nusselt number on a cylinder in cross flow.

circumferential Nusselt number spread over the given sector of the fiber circumference occupied by the particular sensor. This situation is illustrated in Fig. 6. If the incoming flow is in the split-plane of both films (the graph upper diagram), then the probe acts as a single film probe. The signal voltages for the left (Sensor 2) and for the right (Sensor 1) films are equal. When the flow direction turns into the negative angle zone ($\eta < 0$), then consequently the flow stagnation point moves toward the center of the left film (Sensor 2), as indicated in the middle diagram in Fig. 6. The same outcome, although in the opposite direction, happens when the flow direction turns into the positive angle zone ($\eta > 0$). In that case the flow stagnation point moves toward the center of the right film sector (Sensor 1), as evident in the bottom diagram of the same figure. It is obvious, from the Nusselt number distribution, that now each sensor experiences convective heat transfer of a different rate. Consequently, the corresponding voltage levels are diverging, which indicates flow direction changes.

EFFECTIVE FLOW INCIDENCE ANGLE

The variable difference between two signals of a split-fiber probe determines the effective flow incidence angle respectively to the probe split plane orientation. The split-fiber plane orientation with respect to the probe setting angle then determines the absolute flow angle value with respect to the coordinate system of the test article. For an ideal split-fiber probe, all the properties will be exactly symmetrical about the split plane. In such a case, an effective zero flow incidence will be identical with the split-plane angle orientation and the signals of both sensors will be equal.

A graph of effective flow angle values versus probe setting angle for three flows of different Mach numbers is in Fig. 7. Presented data were acquired for an incoming flow of Mach numbers of 0.016, 0.123 and 0,568, which was for velocities of 5.4 m/s, 42.4 m/s, and 183.9 m/s, respectively. The equivalent probe Reynolds numbers were 70, 538, and 1908 in the same order. The plot contains data for a full 360-deg range of probe rotation about the fiber axis. As seen here, the signal is of a sine wave nature.

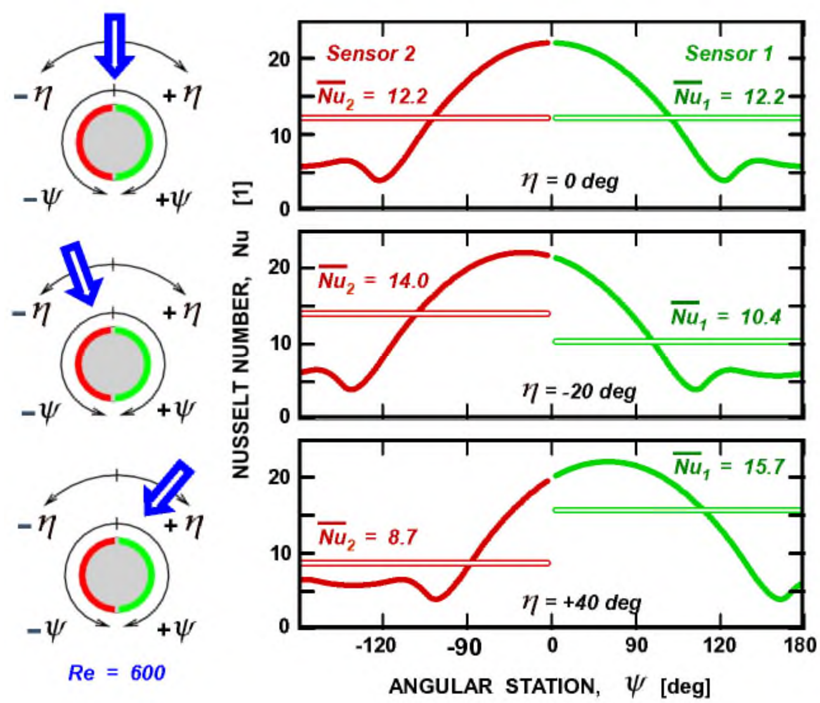

Fig. 6 Distribution of local Nusselt number along the circumference of a split-fiber probe.

In theory a full 360-deg probe angle range could be used for flow angle measurements, e.g. in zones of separated or reversed flow. However, an extreme caution would need to be exercised to avoid confusion due to the signal ambiguity past angles of ± 90 *deg*. Thus, a supplemental probe must be used to prevent the data misinterpretation. Rather, it is more than practical to restrict the probe range to ± 90 *deg*, or even down to ± 60 *deg* where the signal can be sufficiently well approximated by a fitted straight line. The probe directional sensitivity within the angular range of the probe linear response can be expressed as the fitted line gradient (steepness), as indicated in Fig. 8 The zero-incidence angle is the intersection of the direction characteristic with the zero-voltage line (dark dashed line). As seen in this figure, the zero-incidence angle values are spread over a small angular range, which was not actually expected and demanded an explanation.

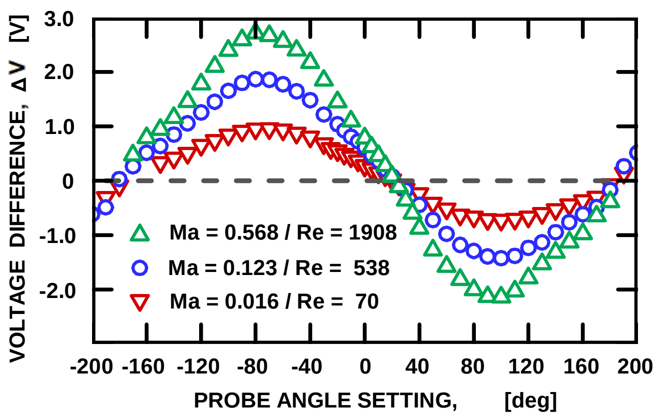

Fig. 7 Differential direction calibration characteristic of a split-fiber probe (full angular range).

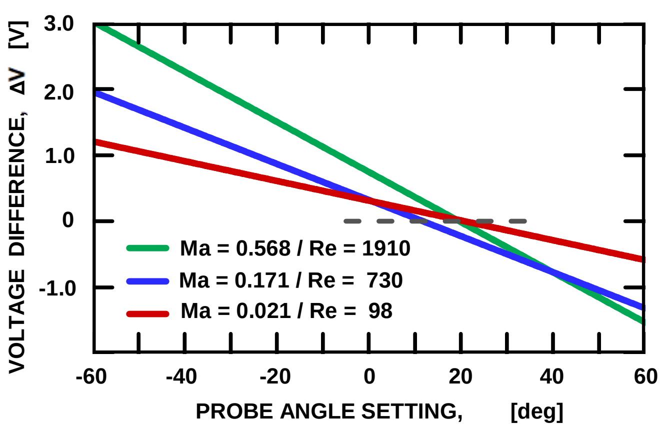

Fig. 8 Spread of effective zero incidence angles.

SPLIT-FIBER PROBE ASYMMETRY EFFECTS

Both film sensors of an ideal split-fiber probe would be equal and mutually mirror symmetrical (Fig. 5). For an ideal probe the supply voltage to both sensors will be equal, provided the flow stagnation point on the fiber circumference is in the split plane (Fig. 6). Unfortunately, it is practically impossible to manufacture the ideal probe due to the sensor's miniature dimensions. An obvious sign of any split-fiber probe asymmetry is the measured difference in resistance of both sensors. For example, the resistance difference of both sensors of the probe used in this investigation was *0.7 Ohm*. The measured sensor resistance at an ambient temperature of *20 C* was *5.60 Ohm* for the left sensor (#2) and *6.33 Ohm* for the right sensor (#1). For some split-fiber probes of the same kind such difference can be even over *1 Ohm*. The sensor resistance is nearly always detected in spite of the fact that the deposited film material (nickel) is the same for both sensors. There are two possible explanations for such sensor resistance asymmetry; first, the thickness of the deposited film might be different for each sensor; and second, the circumferential extents of the sensors might differ. It is probable that in reality both of these effects are involved. However, an experience shows that the thickness of the sputtered film can be controlled relatively well, at least for sputtering on flat surfaces [Lepicovsky et al, 1995]. Assuming the thickness of both film sensors is approximately the same, it follows then that the main reason for the resistance difference is the sensor shape asymmetry. In other words, the sensor with the lower resistance (#2) is circumferentially wider than the sensor with the higher resistance (#1), as indicated in Fig. 9.

Fine details of probe manufacturing process are not available in the public domain. However, it is not difficult to imagine that it is not an easy matter to divide the surface of a fiber only *200 μm* in diameter exactly in the middle. As it was shown in Figs. 5 and 6, the value of the convective heat transfer coefficient rapidly decreases on a cylindrical fiber side in the direction away from the flow impact (stagnation) point.

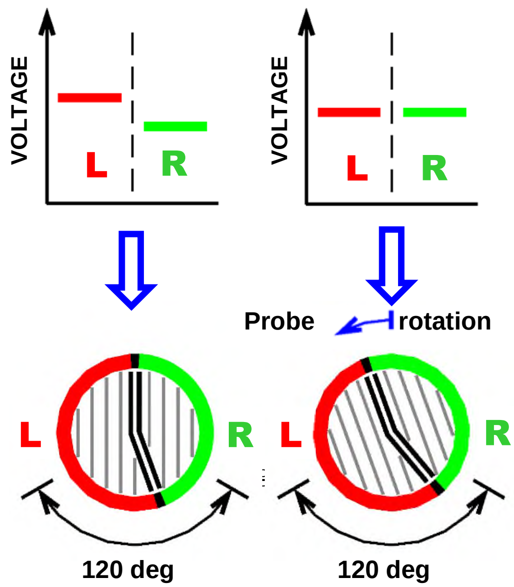

Fig. 9 Effects of probe asymmetry on detected signals.

Consequently, for a difference in sensor circumferential width, the average heat transfer rate for each sensor will be different. The heat transfer coefficient within the back-flow segment of the fiber is very low, practically constant, and has a very little impact on heat transfer rate of individual sensors.

STABILITY OF EFFECTIVE ZERO INCIDENCE ANGLE

When the upper fiber split point is in the flow stagnation point, then due to the sensor asymmetry, as indicated in Fig. 9, the overall heat flow rate from the left sensor (#2) is larger than from the right (#1) sensor. As the left sensor is cooled more intensely than the right one, the supply voltage into the left sensor (#2) must be higher than the one for the right sensor (#2) to maintain the same temperature of both sensors. In order to equalize the supply voltage to both sensors the probe must be turned a little in the direction of the wider sensor. Thus, the flow stagnation point moves away from the surface film partition (split plane). The amount of probe turning to balance the sensor signals is called the effective zero angle shift or offset.

A dependence of the effective zero angle offset on the flow Reynolds number for a clean split-fiber probe is shown in Fig. 10. For the probe used, this shift was about *12 deg* for the Reynolds numbers less than 1000 and then it was about *19 deg* for the Reynolds numbers higher than 1000. As seen in the graph in Fig. 11, there is no sudden change of the directional sensitivity value in the entire Reynolds number range contrary to the case for the zero-angle offset dependence on the flow Reynolds number shown in Fig. 10.

The reasons for the step change in the probe effective zero angle offset distribution are not quite clear. It is suggested that this change correlates with the transition of the wake laminar vortex street into a turbulent one as shown in Fig. 12. It is commonly accepted that the transition between laminar and turbulent vortex streets for a cylinder in cross flow occurs in the range of Reynolds number between 150 and 300 [Blevins, 1990; Mills, 1998]. However, the observed sudden change of the split-fiber probe characteristics occurs at a Reynolds number range from 900 to 1000, which is noticeably higher than the commonly accepted transitional range. Of course, the question is whether the free stream Reynolds number is the proper similarity parameter for the flow in the boundary layer of a heated cylindrical fiber. In thermo-anemometer applications it is customary to use the air film temperature value for similarity considerations instead of the free stream temperature. The air film temperature is defined as an average between the free stream and sensor temperatures. If the air film temperature is used to determine the air dynamic viscosity then Reynolds numbers in the graph scale

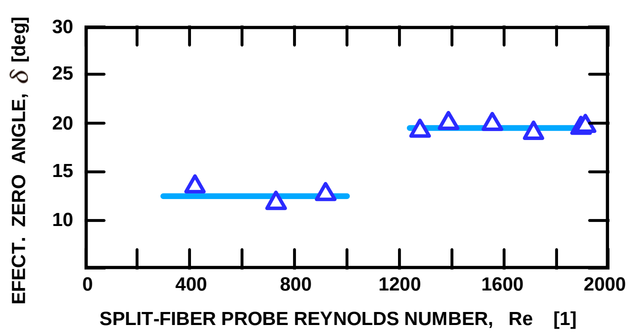

Fig. 10 Dependence of effective zero-angle offset on flow Reynolds number (clean probe).

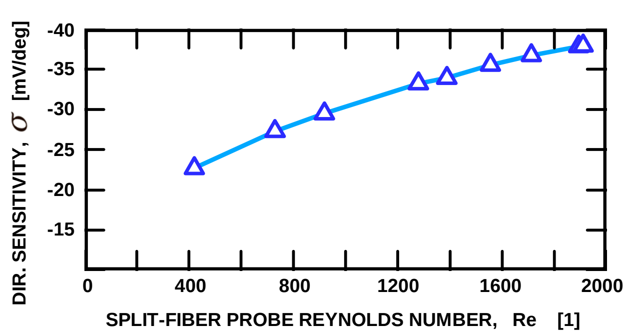

Fig. 11 Dependence of probe direction sensitivity on flow Reynolds number (clean probe).

on Fig. 10 drop to 78% of the presented values. Using the sensor temperature of *250 C* for the Reynolds number determination the drop would be even more dramatic down to 64%. In any case, it may be assumed that a thin layer of air adjacent to the heated sensor will most likely conform to lower Reynolds number behavior rather than to the value of the free stream flow Reynolds number.

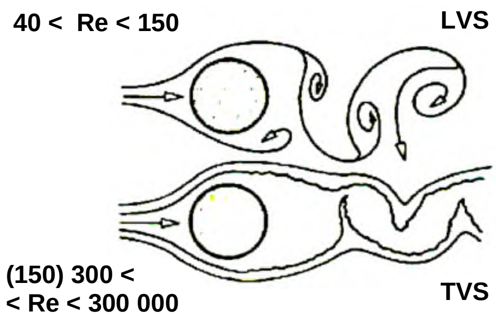

Fig. 12
Flow Reynolds number effects on fiber wake vortex street (LVS = laminar vortex street, TVS = turbulent vortex street) [Mills, 1998].

PROBE CONTAMINATION EFFECTS

There was an unintentional ingestion of soft clay debris, which happened during the course of testing. Some clay particles hit the split-fiber probe sensor and baked on the sensor as is evident in photograph in Fig. 13. This accident was not noticed at the moment of its occurrence. It was discovered later during the probe check after the test completion. Test data inspection revealed that the probe was contaminated at the very beginning of the long test period. In order to save the large amount of already acquired test data the contaminated probe was subjected to rigorous recalibration as presented below.

The results of the detail after-test probe recalibration are shown in Figs. 14 and 15. Surprisingly, effective zero-angle offset turned to be practically constant for the entire range of the test Reynolds numbers; there in no obvious sudden change of its value as it was the case for the clean probe in the vicinity of Reynolds number 1000 (Fig. 10). Similarly, as in Fig. 11, the probe direction sensitivity increases smoothly with the increasing flow Reynolds number. The direction sensitivity of the contaminated probe is practically identical with the values of the clean split-fiber probe for the entire investigated Reynolds number range.

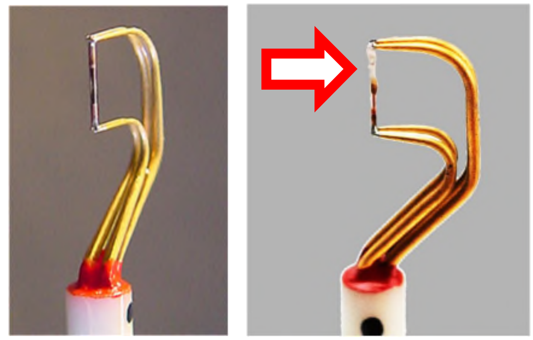

Fig. 13
View of clean and contaminated split-fiber probe.

It is an undisputable fact that the changes in the solid-body boundary layer, in particular the location of the boundary layer separation points, are markedly manifested by changes in the downstream wake pattern. The above presented findings strongly support the suggestion that the sudden change of the effective zero-angle offset observed for the clean probe (Figs. 10 and 14) is the result of the boundary layer transition on the cylindrical fiber surface.

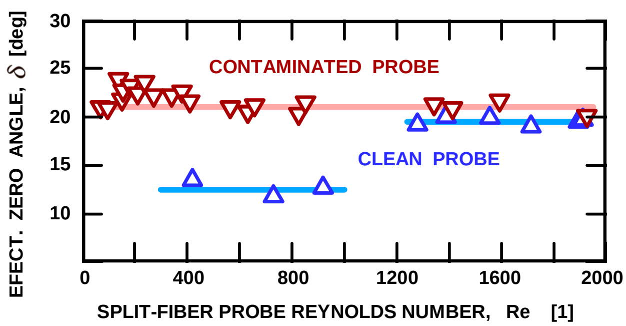

Fig. 14
Dependence of effective zero-angle offset on flow Reynolds number (clean & contaminated probe).

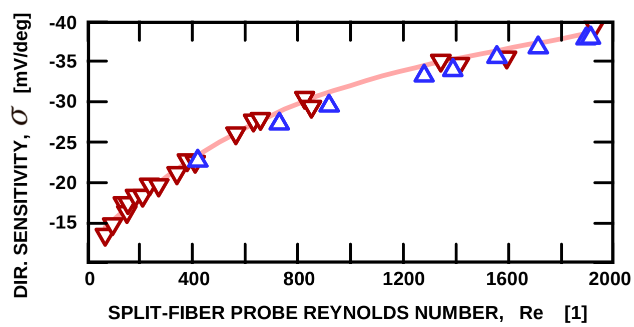

Fig. 15
Dependence of probe direction sensitivity on flow Reynolds number (clean and contaminated probe).

Results of a computational study of a cylinder in cross-flow [Mehdi et al, 2016] indicate noticeable change of the stream-line pattern behind the cylinder at the Reynolds number value of 1000 in comparison to the stream-line pattern at lower Reynolds numbers. It appears that this change in the stream-line patter indicates the change of the wake laminar vortex street into a turbulent one, which will modify the extent of the undisturbed heat transfer areas for each probe sensors. Such a change will increase the difference in the heat transfer rate between the sensors, which will be compensated by a larger effective zero incidence angle. The directional sensitivity seems to be affected very little or not at all by the changes in the backward sector of the cylindrical fiber.

It is conceivable to think that the accumulated debris on the probe sensor tripped the cylindrical sensor boundary layer, which therefore was turbulent from the onset of the flow Reynolds number range. Consequently, there was no starting laminar boundary layer to undergo any transitional effects. Of course, there was also no transitional change of the wake flow pattern. Instead, the convective heat transfer rate from the probe sensors into the flow was governed by the characteristics of wake turbulent vortex street in the entire Reynolds number range. This might be the explanation why there is no sudden change of the zero-incidence angle for the contaminated probe.

CONCLUSIONS

There are several conclusions resulting from this experimental investigation.

◆ The most important finding is the fact that directional sensitivity of the split-fiber probe smoothly increases with the increasing Reynolds number of the incoming flow. It is a very beneficial characteristic, as it means that the probe direction sensitivity rises with the increasing velocity, contrary to the decrease of the velocity sensitivity, which is a common hindrance to applications of single-sensor thermo-probes to high-speed and transonic flows. A split-fiber probe can be used with an advantage of its small size for reliable flow direction measurement under the high-speed flow conditions.

◆ An interesting observation is the appearance that the transition of the wake laminar vortex street into the turbulent vortex street occurs for the extremely small diameter cylinders in cross flow within the free stream Reynolds number range from 900 to 1000, as indicated in Fig. 10. Published computational results [Mehdi et al, 2016] imply that the transitional range is in the Reynolds number range between 500 and 1000. This observed critical range is rather higher than the generally reported range between 150 and 300 [Blevins, 1990; Mills, 1998]. When the probe Reynolds number is based on the cylinder surface temperature, rather than on the free stream temperature, then the transitional Reynolds number range would be between 600 and 650. Validity of this findings requires additional verification.

◆ The change of the effective zero incidence offset due to the wake vortex street transition must be accounted for in order to reliably measure flow-velocity direction changes using the split-fiber probes. Careful probe inspection and frequent recalibration of the probe effective zero incidence angle is strongly recommended.

ACKNOWLEDGMENTS

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