Using single-sensor hot-wire anemometry for velocity measurements in confined swirling flows

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ABSTRACT

This short communication presents a novel technique for measuring the velocity of a confined swirling flow using a single-sensor hot-wire probe. Unlike conventional hot-wire techniques, directional calibration of the hot-wire probe is not required. The technique has been applied to a swirling flow in an annular pipe. Comparisons are made with measurements obtained using a dual-sensor X-probe. A non-dimensional swirl number was used to characterise the swirl intensity obtained using both techniques. A good agreement was attained wherein a ± 0.04 difference was obtained between the two techniques.

1. Introduction

Measurements of internal flows are important in many applications. Laser measurement techniques such as laser Doppler velocimetry (LDV) and particle image velocimetry (PIV) are often preferred because of their non-intrusive nature and their capability in providing directional information. These techniques require the measurement section to be optically accessible and for the flow to be seeded by tracer particles. In many applications, seeding of the flow may be undesirable, for example when this can change the flow characteristics downstream. With certain types of seeding strategies, regular cleaning of the optical surface may be required, which can be difficult, if not impossible, in some cases. In the presence of these limitations, hot-wire anemometry offers a much simpler measurement system when there is no ambiguity regarding the flow direction.

Hot-wire anemometry is an intrusive measurement technique wherein a probe is introduced into the fluid stream to be measured. A typical hot-wire probe consists of a thin cylindrical sensing element soldered onto two stems. The sensing element is heated by an electrical circuit and acts as a resistor. As the sensing element is exposed to a fluid flow, heat is transferred from it to the flowing fluid. In a constant-temperature anemometer, the electrical circuitry has the task of ensuring a constant temperature of the sensor as heat is convected from it to the fluid flow. A relationship can thus be established between the rate of heat transfer and flow velocity from calibration of the hot-wire probe.

A calibrated single-normal (SN) probe is typically used to measure a single-component velocity lying either in, or orthogonal to, the stem-

sensor plane and orthogonal to the sensing element. If these criteria are not met the so-called effective velocity measured by the probe is a function of the pitch and yaw angles. This effective velocity concept [1] can be used to determine flow direction and is typically employed in the measurement of multi-component flows.

Multi-component swirling flows have previously been measured by using multi-sensor probes [2–6], SN- [7,8] or single-yawed (SY) probes [9] or by rotating an SY-probe [2,10]. Measurements have also been made by combining two or more of these techniques [3,11]. In these studies, the effects of pitch and yaw angles on the velocity measurements are determined from directional calibration of the probe [12–14]. Directional calibration, however, imposes a limitation on the approach angle of the flow relative to that of the sensing element axis.

This limitation has been demonstrated by Champagne and Kromat [4] and Skusiewicz [15] for measurements using X-probes. In these studies, the authors resorted to yawing of the X-probes to overcome this limitation thus introducing additional uncertainty to the measurements. Limitations imposed on X-probes also extend to their relatively inferior spatial resolution for near-wall measurements. Measurements of low velocities using X-probes are also prone to cross-flow and "dropout" errors [16].

For any measurement using hot-wire anemometry, proper alignment of the probe is indispensable for reducing uncertainties. Probe alignment can be a challenge especially if visual access to the probe area is limited as is in confined flows. The confining geometry also inhibits the use of multi-positioning techniques [7,9].

This paper discusses a technique for measuring the velocity of a confined swirling flow using a relatively inexpensive SN-probe without
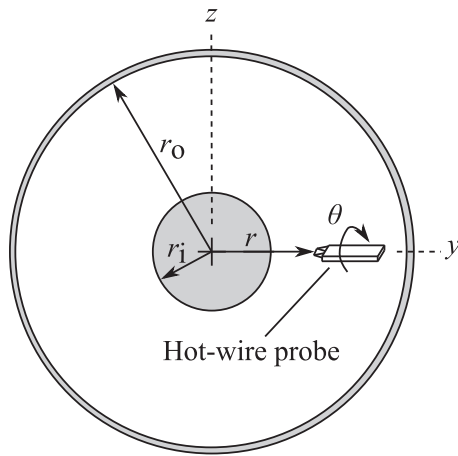
Fig. 1. Schematic showing the positioning of the hot-wire probe within the annulus. The angle θ represents the angle of rotation of the probe about its axis in the local coordinate system. The flow is normal to the page.

the need for directional calibration. The proposed technique also eliminates the uncertainty associated with probe alignment during data acquisition and offers the more favourable spatial resolution provided by the SN-probe.

2. Methodology

In this technique an SN-probe is introduced into the flow such that the probe's stems are normal to the bulk flow velocity. Swirling flow in a concentric annular pipe with inner radius, r_i, and outer radius, r_o, is used to illustrate the technique. The radial component of the flow is considered to be small and is therefore neglected.

Consider a hot-wire sensor placed in an annulus at a radial distance, r, as shown in Fig. 1. With axial flow through the annulus, a typical time-averaged voltage output, E, of the sensor as it is rotated at discrete angular positions about its axis is shown in Fig. 2. The peaks in Fig. 2 correspond to perpendicularity between the sensor and the flow and hence with the pipe axis. A least squares curve is fitted to the points around the peak of the $E-\theta$ plot from which E_o and θ_o are obtained (Fig. 2).

Consider now swirling flow in the annulus. The procedure described in the preceding paragraph is repeated, ensuring that the probe is
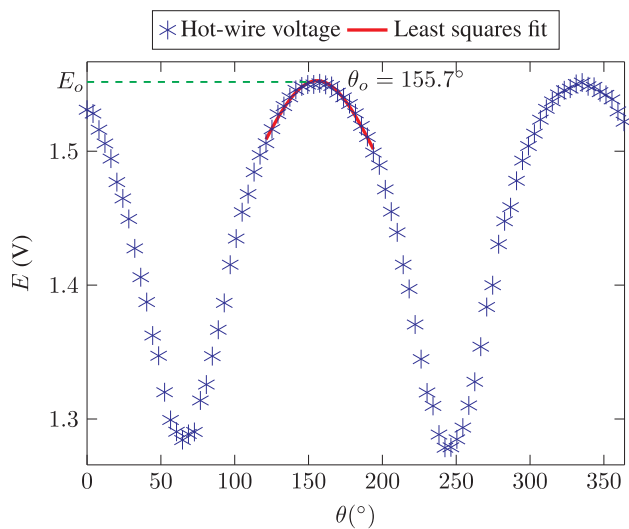

Fig. 2. Time-averaged, temperature-corrected hot-wire probe response with rotation about its axis. A least squares fit curve is fitted about the peak to obtain E_o and θ_o.

rotated from the same initial angular position as was performed for axial flow. A phase shift in the resulting $E-\theta$ plot is exhibited with respect to measurements made in axial flow. Least squares fitting of the peak of this newly-constructed $E-\theta$ plot yields values of $E_{\max}$ and $\theta_{\max}$, analogous to E_o and θ_o, respectively.

Values of E obtained from the least squares fits are converted into velocities using the probe calibration coefficients. θ values obtained from the least squares fits are used to decompose the velocities into the laboratory coordinate system.

3. Experimental application

To demonstrate the technique, velocity measurements were made of a swirling flow in an annular pipe with $r_o/r_i = 2.3$. The experimental setup and local coordinate system are shown in Fig. 3 and was used to determine the effect of swirling flow on flow uniformity in an automotive catalyst monolith [17]. Swirling flow from the swirl generator flows through the annular pipe and expands into a sudden expansion diffuser of diameter $2.6d_o$ (where $d_o = 2r_o$) before passing through a catalyst monolith $2.95d_o$ downstream of the expansion.

The mass flow rate was set to 63 g/s with $Re \approx 60000$ based on the mean axial velocity in the annulus and a characteristic length of $2(r_o - r_i)$ [18]. Variable swirl intensities were prescribed by adjusting the swirl generator angle.

Hot-wire bridge voltages were acquired using a TSI IFA 300 constant temperature anemometer. Sampling of the analogue signal was performed at 200 Hz to obtain 1024 instantaneous samples. Concurrent temperature measurements were made using a type-T thermocouple.

A Dantec 55P11 SN-probe was calibrated using a TSI 1129 calibrator. Eighteen calibration points were prescribed for velocities ranging from 0 to 140 m/s. A fourth-order polynomial was fitted to the calibration points allowing the acquired voltages to be converted into velocities.

Hot-wire bridge voltages were acquired along one radius of the annulus at 1 mm increments between r_o and r_i. Preliminary investigations revealed that rotation increments of $\Delta\theta \leqslant 4°$ resulted in E_o and θ_o variations of less than 1% and 3%, respectively. Thus a rotation increment of 4° was chosen to minimise the measurements needed.

To ensure repeatability in the probe's rotational motion, an in-house built probe positioning mechanism was manufactured. The probe positioning mechanism positions the probe with up to 0.2° resolution. Radial traverse of the probe across the annular cross-section was achieved using aluminium spacers inserted along the probe support between two datum points with 0.2 mm resolution.

The relative standard error of the time-averaged voltage measurements in Fig. 2 was calculated from the 1024 instantaneous samples with resulting values less of than 0.2%. The function $f(\theta) = A\cos(\theta + B) + C$ was fitted around the peak of the $E-\theta$ curve, where A, B and C are constants determined from a non-linear least squares fit. Pairs of E_o and θ_o (and $E_{\max}$ and $\theta_{\max}$) values were obtained from simulations using the Monte Carlo Method [19] resulting in a relative standard error of less than 0.1% for both E and θ.

For comparison, measurements were repeated using a TSI 1247A X-probe. The X-probe was calibrated for the same velocity range as used for the SN-probe. The necessary directional calibration was performed according to the manufacturer's recommendations [20]. Furthermore, a second set of measurements was made using the X-probe along another radii of the annular cross-section to analyse the symmetry of the flow.

4. Results and discussion

Figs. 4 and 5 show the mean velocity profiles obtained for the two swirl levels analysed. The results are presented in terms of the swirl number [21], S, i.e.,