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Bin Rusli, IH, Aleksandrova, S, Medina, H & Benjamin, S 2018, 'Using single-sensor hot-wire anemometry for velocity measurements in confined swirling flows' *Measurement*, vol 129, pp. 277-280.

https://dx.doi.org/10.1016/j.measurement.2018.07.024

DOI 10.1016/j.measurement.2018.07.024

ISSN 0263-2241

Publisher: Elsevier

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# 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.

*Keywords:* hot-wire anemometry, swirling flow, velocity measurement

## 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 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.

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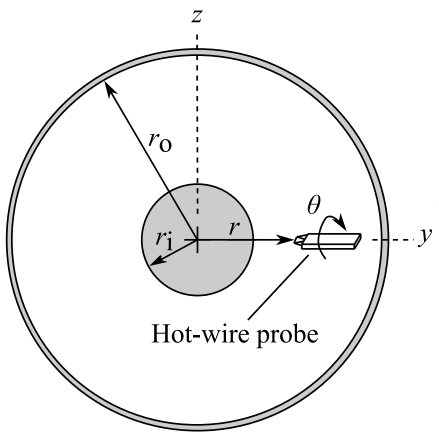


Figure 1: Schematic showing the positioning of the hot-wire probe within the annulus. The angle $\theta$ represents the angle of rotation of the probe about its axis in the local coordinate system. The flow is normal to the page.

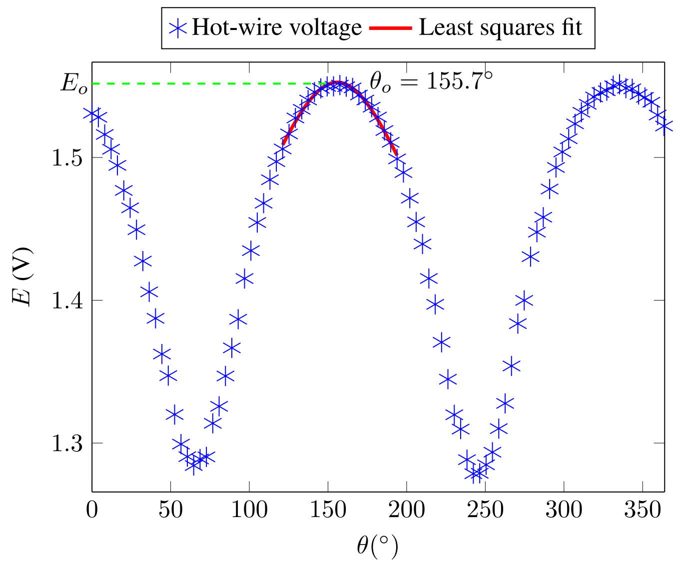


Figure 2: Time-averaged, temperature-corrected hot-wire probe response with rotation about its axis. A least squares fit curve is fitted about the peak to obtain $E_o$ and $\theta_o$.

## 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 $E_\text{o}$ and $\theta_\text{o}$ 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 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 $E_\text{max}$ and $\theta_\text{max}$, analogous to $E_o$ and $\theta_o$, respectively.

Values of $E$ obtained from the least squares fits are converted into velocities using the probe calibration coefficients. $\theta$ 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 $\Delta\theta \leq 4°$ resulted in $E_o$ and $\theta_o$ 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

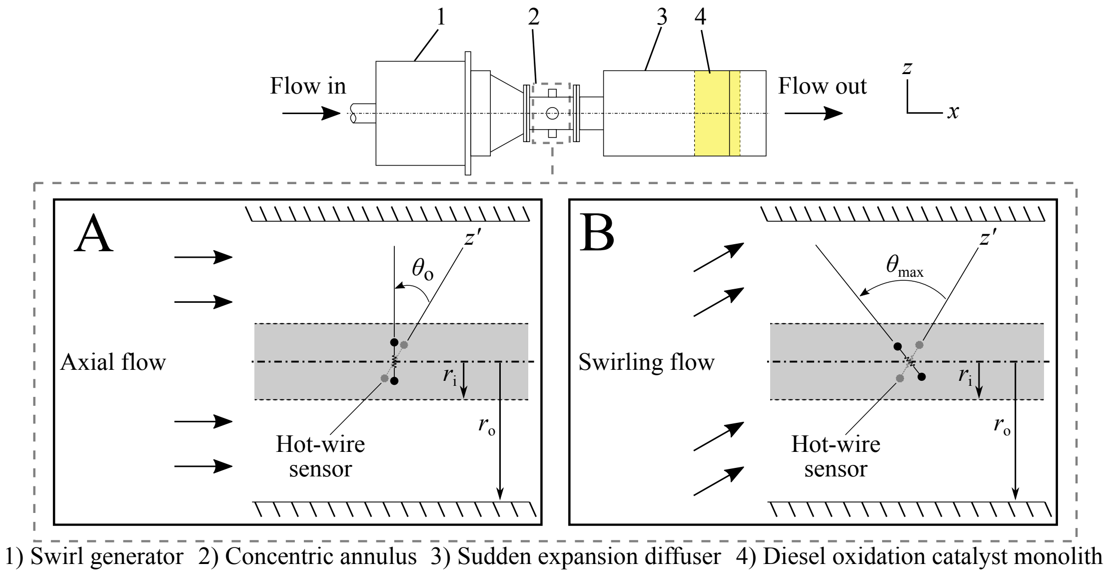


Figure 3: Schematic of the experimental flow rig and the flow in the local coordinate system. The sensor is rotated from the $z'$-axis as shown. $\theta_o$ and $\theta_{\max}$ are the angles when the sensor is perpendicular to axial (A) and swirling (B) flows, respectively. Radial traverse of the probe is normal to the page.

$f(\theta) = A\cos(\theta + B) + C$ 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 $\theta_o$ (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 $\theta$.

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

Figures 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.,

$$S = \frac{\int_{r_i}^{r_o} \rho V_x V_z r 2\pi r dr}{r_o \int_{r_i}^{r_o} \rho V_x^2 2\pi r dr} \tag{1}$$

where $\rho$ is the air density and $V_x$ and $V_z$ are the axial and tangential velocities, respectively.

At $S \sim 0.23$, the discrepancies in the tangential velocities between the two techniques range from 8 to 15% while at $S \sim 0.65$ the discrepancies range from 1 to 9%. These discrepancies are attributed to uncertainties in flow rate prescription and probe alignment during the experiments. Measurements using the X-probe at both locations were within 5% of each other at the two locations for both swirl levels indicating symmetry of the flow.

The uncertainty in the flow rate prescription is investigated by integrating the axial velocities across the annulus radius to verify the flow rate prescribed by the flow meter (Table 1). Two near-wall velocity profiles were considered for the integration. The first profile assumes a linear relationship between the wall zero velocity and the measurement point nearest to the wall. The second profile assumes a hypothetical non-zero wall velocity linearly extrapolated from measurements nearest to the wall. Of the two velocity profiles, the former underestimates the flow rate while the latter overestimates it and thus lower and upper bounds of the errors are obtained (Table 1).

| $S$ | SN-probe | | X-probe | | | |
|---|---|---|---|---|---|---|
| | Location 1 | | Location 1 | | Location 2 | |
| | LB | UB | LB | UB | LB | UB |
| 0.23 | -5.7% | 1.5% | -4.0% | 1.3% | -2.9% | 2.1% |
| 0.65 | -9.7% | -3.1% | -2.1% | 0.4% | -1.3% | 2.9% |

Table 1: Percentage error in flow rates compared to flow meter prescription. The lower bounds (LB) and upper bounds (UB) are shown.

From Table 1 the error in measurements made using the SN-probe at $S \sim 0.65$ is seen as the most severe hence causing the discrepancy in the tangential velocity profile in Fig. 5. Despite the discrepancies in the flow rate prescription, the swirl numbers calculated using the different hot-wire techniques varied by only ±0.02 and ±0.04 for $S \sim 0.23$ and $S \sim 0.65$, respectively. This suggests that a good agreement is achieved between the two techniques.

Turbulence intensity, $I$, in the flow direction was also calculated from the measurements as $I = V_{rms}/V_{mean}$, where $V_{rms}$ and $V_{mean}$ are the root-mean-square (rms) and mean of the instantaneous velocities, respectively. For the SN-probe, an average was taken of the turbulence intensities calculated at the three points nearest to the peak in the $E - \theta$ plot (Fig. 2). For the X-probe, $V_{rms}$ and $V_{mean}$ were taken from the streamwise

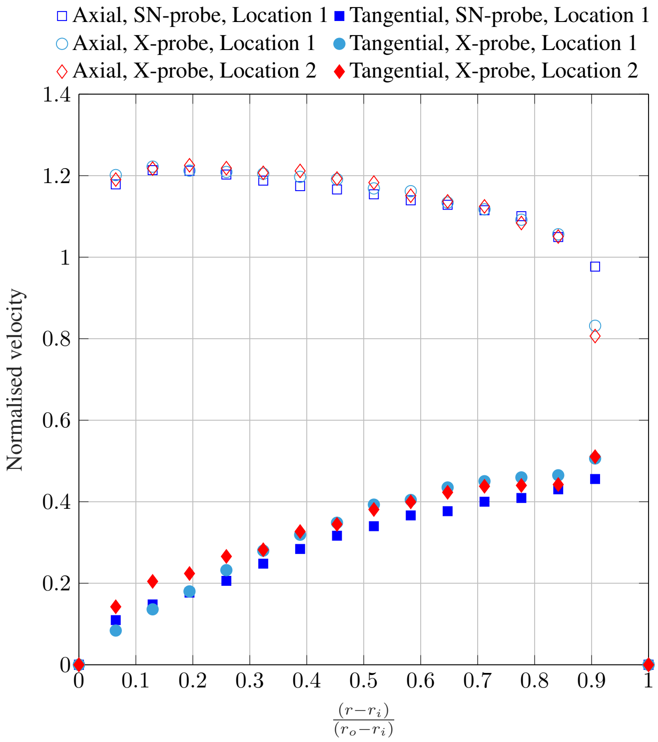


Figure 4: Normalised mean velocities at $S \sim 0.23$.

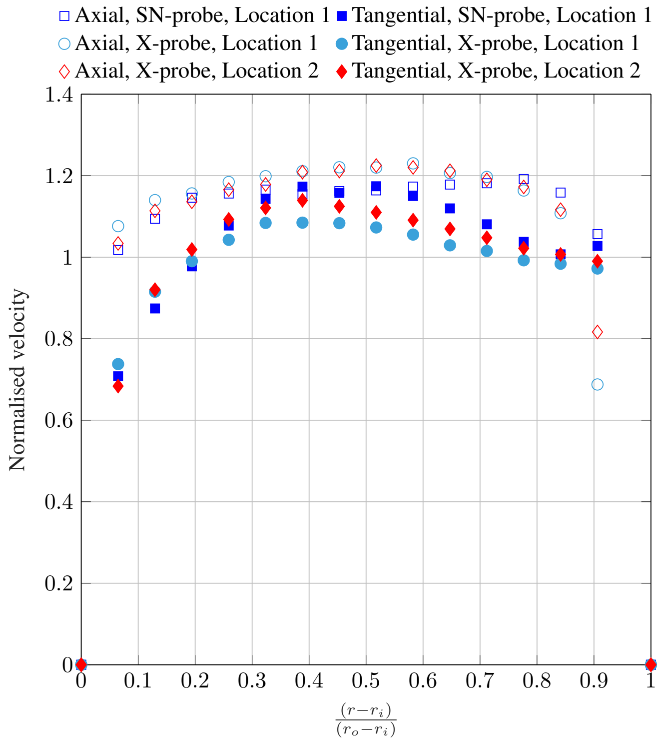


Figure 5: Normalised mean velocities at $S \sim 0.65$.

velocity component in the probe coordinate system. The agreement between the two measurement techniques is within 10% for $S \sim 0.23$ and 17% for $S \sim 0.65$ (Fig. 6), which is acceptable in most applications. The difference is higher near the walls, where the X-probe measurements are expected to be less accurate because of the spacing between the sensors in an area with high wall-normal velocity gradients.

## 5. Conclusion

A robust and relatively simple method of using a single-sensor hot-wire probe for measuring two-component flow has been presented. It has been successfully applied to measurements of swirling flow in a concentric annulus. Comparisons were made with measurements using an X-probe and a good agreement in the swirl number and turbulence intensity was attained.

The current method is advantageous because:

1. Only the use of single-sensor probes is required, incurring lower costs compared to dual-sensor X-probes,
2. The single-sensor probe used provides a more favourable spatial resolution compared to X-probes,
3. Only a simple velocity calibration in uni-directional flow is required,
4. The uncertainty associated with probe alignment during measurements is eliminated,
5. The transverse orientation of the probe relative to the main flow direction allows easier access for some flow configurations.

Although the method is applicable to other flows where there is no directional ambiguity it does require additional data in order to construct the $E-\theta$ plot.

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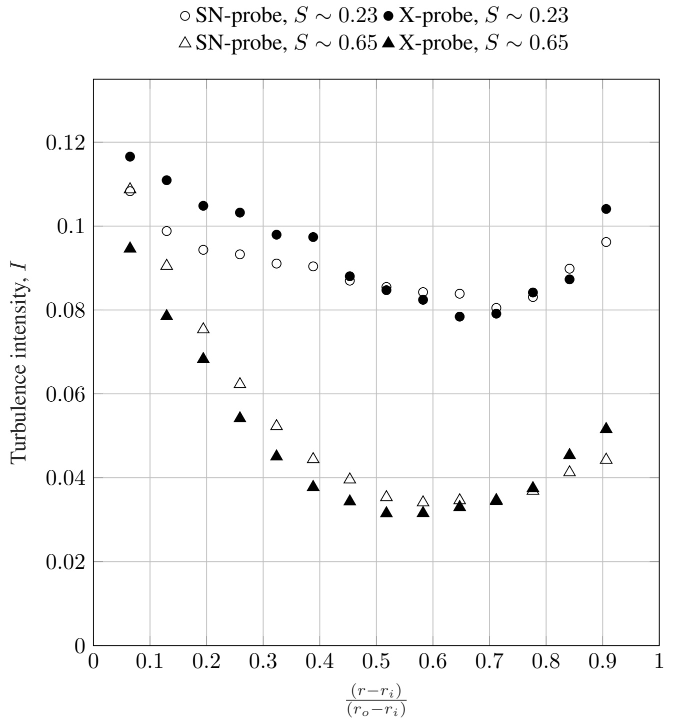


Figure 6: Comparison of turbulence intensities reported by the SN-probe and X-probe techniques.


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## Declaration of Interest

Declarations of interest: none


## Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.