THE PERFORMANCE OF CROSSED-VANE SWIRL METERS

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ABSTRACT

Vortimeters consisting of vanes rotating about pipe axes are frequently used to indicate the swirl present in pump columns and feedlines from sumps and in piping networks. Since the design of such devices varies widely, the study described herein was undertaken to identify salient design parameters and to evaluate a device designed according to information available in the literature.

An apparatus which could produce known amounts of angular momentum in a pipeline was verified by direct measurement of axial and tangential velocity profiles. By using the assumption that a vortimeter, with vanes spanning only the rotational core, responded to an equivalent solid rotational core, an expression was developed relating the angular velocity to the angular momentum. Comparison of the angular velocity which the swirl generator should produce if angular momentum were conserved to that measured by the vortimeter showed excellent agreement.

NOMENCLATURE

A	area
d	pipe diameter
H	height of inlet
h	blockage width
in	inlet
K_u	velocity profile factor
$\underline{L}$	angular momentum flux
N	rotational speed
$\underline{n}$	unit surface normal
p	pipe
Q	volumetric flowrate
R	pipe radius
r	radius
r_v	outside radius of vortimeter blades
r_1	location of tangential velocity maximum
r_2	location of axial velocity maximum
$\underline{U}$	velocity
u	axial velocity
v	tangential velocity
w	channel width
z	axial coordinate
ϕ	swirl angle from axial
ρ	density
θ	vane angle

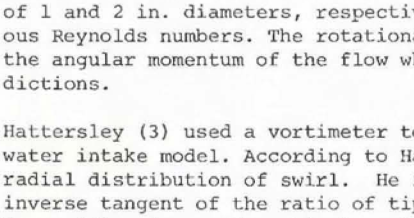
INTRODUCTION

Measuring devices consisting of axially aligned vanes allowed to freely rotate about an axial shaft are frequently used as indicators of the swirl in circular pipes. Such devices are often called crossed-vane swirl meters, or more simply vortimeters. They are widely used in experimental studies of sump exit lines as indicators of vortex activity in the sump and in pump approach lines to indicate pre-swirl.

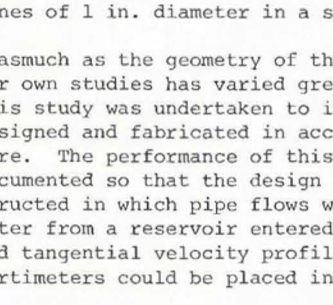
Hopkins and Sorensen (1) used a 1 inch diameter vortimeter to measure the rotational speed in free vortex cores associated with trailing vortices of air-foils. Kreith and Sonju (2) used vortimeters of diameters 0.74 and 1.48 in. in pipelines of 1 and 2 in. diameters, respectively, to study turbulent swirling flow at various Reynolds numbers. The rotational speed of the vortimeter was used to compute the angular momentum of the flow which compared well with their analytical predictions.

Hattersley (3) used a vortimeter to measure the swirl in the suction pipe of a water intake model. According to Hattersley, the vanes mechanically averaged the radial distribution of swirl. He introduced the "indicated swirl parameter" or inverse tangent of the ratio of tip speed to pipe average velocity. Baker and Sayer (4), also used vortimeters to measure the decay of swirling flow in pipelines of 1 in. diameter in a situation similar to that of Kreith and Sonju.

Inasmuch as the geometry of the devices used in the above studies as well as in our own studies has varied greatly depending upon the investigators' preferences, this study was undertaken to identify salient design parameters. A vortimeter was designed and fabricated in accordance with information available in the literature. The performance of this vortimeter was characterized and the flow field documented so that the design hypothesis could be tested. An apparatus was constructed in which pipe flows with adjustable amounts of swirl could be obtained. Water from a reservoir entered the pipes through adjustable guide vanes. Axial and tangential velocity profiles could be measured with directional probes and vortimeters could be placed in the pipelines.



(A) AXIAL AND TANGENTIAL VELOCITIES



(B) VELOCITY PROFILES

Fig. 1 Swirling Flow in a Pipe

Flow Field

The nature of swirling flow in a pipe is indicated in Figure 1. The tangential velocity, v(r) increases, somewhat linearly, to a maximum at radius r_1 and then decays to zero at the pipe wall, R. The central region, or core, then is in nearly solid rotation about the pipe axis as pointed out by Baker and Sayer (4) and Kreith and Sonju (2). The axial velocity profile, u(r), is distorted from that of fully developed non-swirling flow because of the radial pressure gradient. A maximum value is reached at radius r_2 with the velocity at the wall being zero and the velocity on the pipe axis being less than the maximum and, on occasion, less than zero.

The swirl angle, ϕ, is the angle that the velocity, $\bar{U}$, makes with the axial direction*. In terms of the velocity components

$$\phi = \tan^{-1} v(r)/u(r) \qquad (1)$$

and, in general, ϕ will be a function of radial location.

*It is customary to use this definition rather than the momentum ratio.

Vortimeter Design

The purpose of using a vortimeter is to measure the rotation rate of the core of the tangentially swirling flow. Since the core is only nearly in solid rotation and, in many applications, might not be exactly centered, such a device will give some indication of the rotation rate only. In any event, it seemed clear that the vortimeter blades ought not extend to radii larger than r_1, because torque would then be transferred from the core region to the wall region, thus lowering rotational speed. On the other hand, the blades ought to cover most of the expected core region in order to respond to the average swirl and capture any slightly eccentric flows.

Measurements of Kreith and Sonju (2) and Baker and Sayer (4) indicated that the central core of pipe flow rotated more or less as solid rotation with a tangential velocity maximum at 70 to 80% of the distance from centerline to wall. Based on these values, a blade length of 75% of the pipe radius was chosen. Prior experience with this type of device indicated that the blade chord needed to be 1 to 2 times the pipe radius in order to consistently avoid the effect of bearing friction. In this case, however, we sought to minimize the chord in order to minimize the perturbation on the velocity profiles. To this end, a fully wetted ball bearing support system was fabricated and the chord chosen at 75% of the pipe radius, giving an aspect ratio of 1.0.

Analysis

The methodology employed to evaluate vortimeter performance utilized a swirl generator to produce known angular momentum in the pipeline. The ability of the swirl generator to produce known angular momentum was verified by measuring the velocity distributions.

Since the details of interaction of the vortimeter with the swirling flow were not known, it was assumed that the vortimeter rotated as if in a core solidly rotating with the net angular momentum of the swirling flow. By generalizing the measured velocity profiles as power law functions, it was possible to relate the angular speed of the vortimeter to the vane angle setting of the swirl generator.

The angular momentum flux, $\overline{L}$, across a control surface can be found by integrating the product of the angular momentum of a particle by the component velocity over the surface

$$\overline{L} = \int_A \rho \, \overline{r} \times \overline{U} \, (\overline{n} \cdot \overline{U}) \, dA \tag{2}$$

Experimentally, the swirling flows were generated using radial inflow and guide vanes at an angle of θ_{in} from the radial direction. Performing the integration and using the volume flowrate $Q_{in} = [U_{in} \cos \theta_{in}] \, 2\pi r \, H$ and the inlet area $A = 2\pi r_{in} \, H$ gives

$$L_{in} = \rho \, \frac{r_{in}}{A_{in}} \, Q_{in}^2 \, \tan \theta_{in} \tag{3}$$

which is easily evaluated for a given test setup.

The angular momentum flux in the pipe is similarly evaluated as

$$L_p = 2\pi \, \rho \int_o^R u(r) \, v(r) \, r^2 \, dr \tag{4}$$

and measured profiles will be incorporated before integration.

EXPERIMENTAL APPARATUS

The experimental apparatus consisted of 7 ft long, 4 in. or 6 in. (15.7cm or 23.6cm) diameter lucite pipes, which were connected to a constant head tank, Figure 2. The initial swirling flow was introduced by a swirl generator, Figure 3, with adjustable guide vanes at the inlet. A calibrated orifice meter ($\beta = 0.70$) and a control valve were located downstream of the test section. The vortimeters were placed at a distance of 4 pipe diameters from the flow inlet. Velocity measurements were made at a distance of 2 pipe diameters from the inlet.

Each swirl generator consisted of 16 adjustable vanes in a peripheral arrangement, which could be adjusted to inlet angles between 0° and 70°. The cover plate and center cone were designed to guide the inflow from the perpheral entrance into the test section.

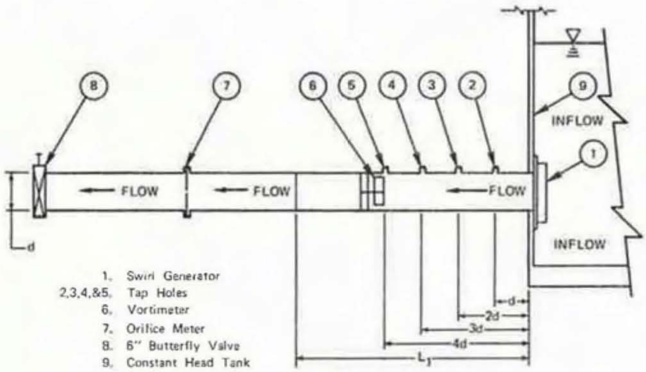


Fig. 2 Experimental Apparatus

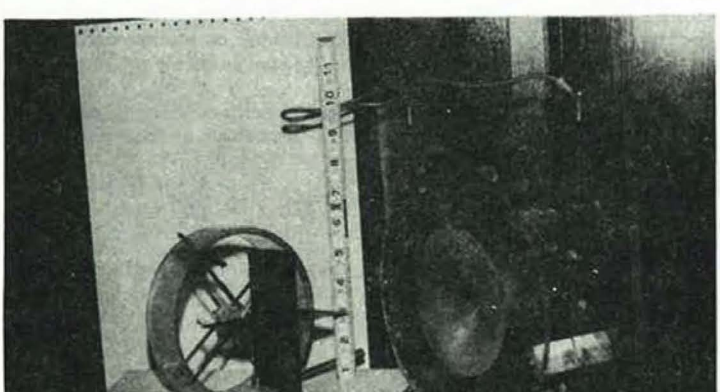


Fig. 3 Swirl Generator

Point velocities were measured using calibrated three-hole pitot probes to find both magnitude and direction. The probes were inserted into the pipe through a fitting on the pipe wall and traversed along radii. The probes could be rotated about their axes to align the center hole with the stream direction. The angle thus measured was what is commonly called the swirl angle at that point. Rotation of the vortimeter was detected using photo-electric cells and a digital counter. Additionally, dye could be injected at various locations for a flow pattern observation. Photographs of the flow patterns as well as further details regarding measured velocity profiles can be found in Lee (5).

EXPERIMENTAL RESULTS

Tests were conducted using both 4 in. and 6 in. diameter test sections with appropriate vortimeters over a range of flows such that the Reynolds numbers varied from 10^4 to 10^5 based on the measured average pipe flowrate while the inlet swirl angle was varied over the range from 0° to 50°.

The velocity profiles were found to be symmetric about the pipe centerline. The rotational core region extended from the center of the pipe outward to a variable distance, $r_1 < R$, where the maximum tangential velocity was reached. Because of the presence of the rotational core region, the axial velocity profile was distorted from the fully developed, non-swirling turbulent flow. In general, the axial velocity profiles were similar to the tangential velocity profiles inasmuch as the maximum velocity occurred between the pipe center and the pipe wall. At low swirl levels, the minimum axial velocity was at the center of the pipe, while reverse flow was observed for high swirl. The location of the maximum tangential velocity clearly defined the boundary between the rotational core within the inner flow region and the irrotational flow pattern at the outer region of the pipe cross-section. The area of the rotational core region was found to be strongly dependent on the amount of swirl present in the flow field; the core region encompassed about 30% of the pipe radius at a low swirl and 75% of the pipe radius distance at a high swirl. The tangential velocity profile was nearly linear with radius in the core region.

The radial distribution of swirl angle, found from the tangential and axial velocity measurements, is shown in Figure 4. The swirl angles increased as the pipe axis was approached and as guide vane angle was increased. Reverse flow occurred when the swirl angle reached a value of $\phi \geq 90°$. The onset of reversed flow was in proportion to the inlet swirl angle. The flow pattern was observed by injecting dye which showed that highly swirling flows suddenly exhibit vortex breakdown. When the inlet vane setting was greater than 40°, water vapor appeared in the reverse flow region. Under reversed flow conditions, the effective flow area was substantially reduced, highly distorting the axial velocity profile and reducing the flowrate.

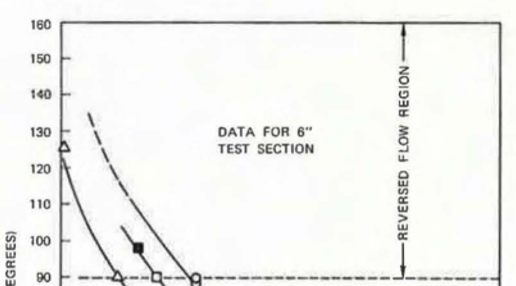


Fig. 4 Variation of Swirl Angle Along Pipe Radius

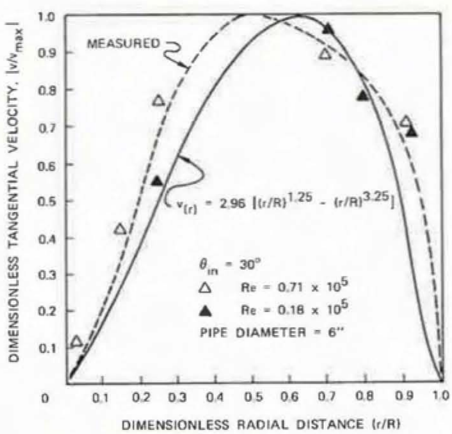


Fig. 5 Dimensionless Tangential Velocity Distribution of Swirling Flow in Pipe

In order to correlate vortimeter angular velocities with inlet guide vane settings, two velocity functions were generated from measured velocity profiles. Typical tangential profiles are shown in Figure 5 for a guide vane setting of 30° and pipe Reynolds numbers of 1.8×10^4 and 7.08×10^4. The tangential velocity profile was approximated by the power law function

$$V(r)=2.96[(r/R)^{1.25} - (r/R)^{3.25}]\, V_{max} \tag{5}$$

The maximum tangential velocity, V_{max}, was linearly related to the rotational speed, N, as $V_{max} = 2\pi N r_v$.

The axial velocity profiles were found to be similar to the tangential velocity profiles except that the velocity at the pipe center varied from positive to negative (reverse flow) depending on the swirl angle. For the axial velocity profile, the approximate function

$$u(r) = 2.96\,[(r/R)^{1.25} - (r/R)^{3.25}]\, u_{max} \tag{6}$$

was used.

This profile was verified by computing the ratio of the flowrate, Q_c, compared to the measured flowrate (Q_m). For all tests, this ratio was approximately 92.5% and seemed satisfactory for these purposes. The maximum axial velocity u_{max} was related to the average velocity as $K_u = u_{max}/u_{ave}$, which depended on the swirl angle, Figure 6, approximately as

$$K_u = 1 + 0.054\,(\theta)^{0.54} \tag{7}$$

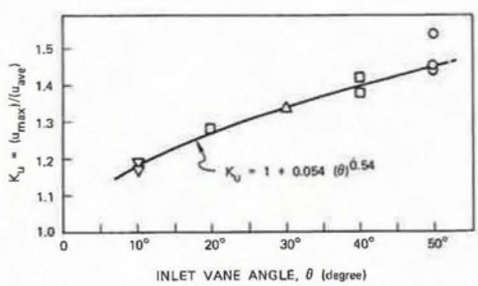


Fig. 6 Variation of Axial Velocity Coefficient (K_u)

Using Equations (3), (5), (6), and (7), the average rotational speed of the swirling flow core region can be predicted.

$$N = \frac{1}{1.4}\,\frac{Q\, r_{in}}{K_u\, r_p\, A_{in}}\,\tan\theta \tag{8}$$

The 45° straight line plot of the rotational speed, N_v, versus the vortimeter measured speed N_m, Figure 7, indicated that the vortimeter linearly responded to the rotational motion of the core region in the swirling pipe flow. This implies that the vortimeter correctly indicates angular momentum.

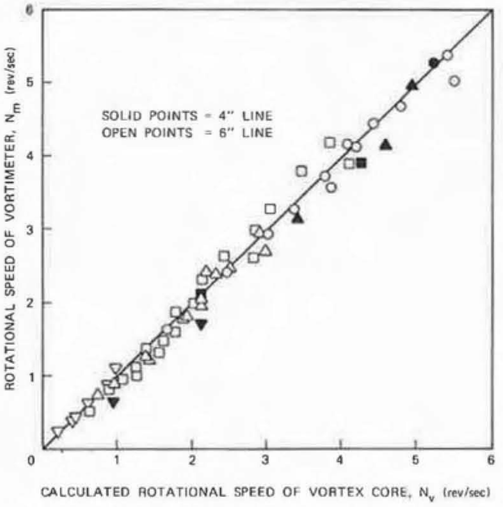


Fig. 7 Vortimeter Test Results

Additionally, the angular momentum of the swirling flow was calculated using the equations representing the velocity profiles within a distance of five pipe diameters. The results indicated that the circulation was conserved. The rotational motion of the core region dominated the flow field. Velocity retardation on and near the pipe wall did not significantly retard the axial circulation or angular momentum of the swirling flow in a pipe in the region of interest.

Example

Vortimeters are frequently used to indicate the swirl in the outlet conduits of hydraulic models. Swirl is associated with free surface and submerged vortex formation in containment sumps, pumped storage inlets, and circulating pump sumps. Figure 8 shows an experiment, Dharwadkar (6), designed to permit investigation of the effect of vorticity production in an approach channel on the swirl in a vertical pump column. Flow approached the inlet channel from a large tank so that, in the absence of any blockage, the vorticity flux was primarily due to boundary layers on the channel bottom and side walls. Despite efforts to ensure symmetry of the channel flow, Figure 9 shows that swirl was present in the pump column. This behavior is typical of outlets at the end of symmetrical channels in that the flow pattern is bi-stable due to an interaction of the vortex flow in the vicinity of the inlet with the approach flow. By temporarily blocking a portion of the channel, a steady rotational flow of either direction with resulting swirl in the outlet pipe can be set up. For a given configuration, slight geometrical asymmetries combined with background flows in the supply reservoir give rise to consistent bias in the swirl angle.

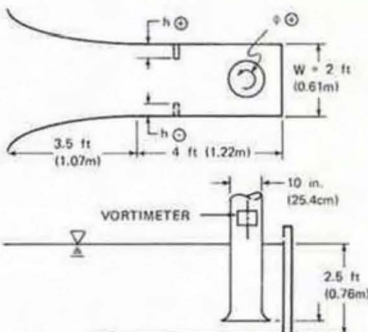


Fig. 8 Experimental Pump Sump

For the experiment shown, various blockages were added to the side walls of the approach channel to upset the velocity profile. Blockage of 20% of the channel width, from either side, caused only small changes in the swirl parameter as measured by the vortimeter. Increasing the blockage widths to approximately 40% of the channel width caused rapid increases in the measured swirl. The data are nearly symmetrical if the bias swirl with no blockage is removed indicating that the bias is caused either by background vorticity in the reservoir or by the boundary layer on the channel bottom.

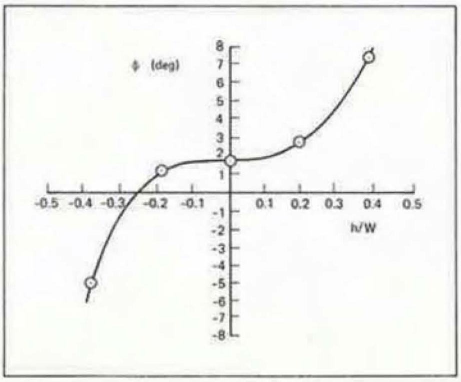


Fig. 9 Swirl Angle versus Blockage

CONCLUSIONS

Vortimeters which span approximately 75% of a pipe are good indicators of the angular momentum present in pipe flow at least when the flow is symmetric about the centerline. Equivalently, they are good indicators of the average swirl angle. For most of the measurements, the extent of the core region turned out to encompass significantly less than 75% of the pipeline. Nonetheless, the vortimeter correlation was still good.

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