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THE EFFECT OF TRANSVERSE VELOCITY GRADIENTS ON THE PERFORMANCE OF THE PRICE CURRENT METER

by

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SUMMARY

Theoretical analysis and experimental data are used to develop a mathematical model of the response of the Price meter rotor to a flow with a transverse velocity gradient. Application of the model showed that the Price meter over-registers when velocity gradients are positive and under-registers when such gradients are negative. In some cases, the error in a velocity measurement can be of the order of several percent. Some recommendations to reduce the effect of velocity gradients are made.

RÉSUMÉ

On utilise l'analyse théorique et des données expérimentales pour élaborer un modèle mathématique de la réponse du rotor du courantomètre Price à un écoulement présentant un gradient de vitesse transversal. L'application du modèle a montré que le courantomètre Price surestime les vitesses lorsque les gradients de vitesse sont positifs et qu'il les sous-estime lorsque les gradients sont négatifs. Dans certains cas, l'erreur dans une mesure de vitesse peut être de l'ordre de quelques pourcents. Certaines recommandations pour réduire l'effet des gradients de vitesse sont offertes.

MANAGEMENT PERSPECTIVE

Price current meters which are used extensively to obtain velocities in rivers and channels provide good results for uniform flows.

Measurements depart from average time velocity when there is a velocity gradient across the meter in a horizontal direction. This report provides a means to correct for the gradient effect if circumstances demand that measurements be made where there is a significant horizontal shear.

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PERSPECTIVE DE GESTION

Les courantomètres Price, qui sont largement utilisés pour obtenir les vitesses dans les rivières et les canaux, donnent de bons résultats lorsque les écoulements sont uniformes.

Les mesures présentent un écart avec la vitesse moyenne par rapport au temps lorsqu'il existe un gradient de vitesse horizontal à travers le courantomètre. Le présent rapport fournit une méthode pour corriger en fonction du gradient si les circonstances sont telles que les mesures doivent être effectuées là où il y a un cisaillement horizontal non négligeable.

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A	=	average "bluff body" area of the rotor cups.
C_{D1}	=	average drage coefficient for the part of the rotor exposing the inside of the rotor cups.
C_{D2}	=	average drag coefficient for the part of the rotor exposing the outside of the rotor cups.
$\bar{c}_{D2}$	=	average drag coefficient including resistance of the bearings, etc.
D	=	effective diameter of the rotor
E	=	percent error in meter response as a result of transverse velocity gradient.
K	=	$\sqrt{c_{D1}}/\sqrt{\bar{c}_{D2}}$.
N_o	=	rate of revolution of rotor in two dimensional flow.
N_Ω	=	rate of revolution of rotor in flow with transverse velocity gradient.
r	=	effective radius of the rotor.
T	=	torque due to resistance or bearings and gears in rotor assembly.
V_1	=	flow velocity at the open side of the rotor cups.
V_2	=	flow velocity of the closed side of rotor cups.
V_c	=	velocity at the centre of the rotor.
x	=	horizontal distance across the flume with origin at the centre of the flume.
π	=	3.14.....
ω	=	angular speed of the rotor.
ω_o	=	angular speed of the rotor in two dimensional flow.
ω_Ω	=	angular speed of the rotor in flow with transverse velocity gradient.
ρ	=	density of the fluid.

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1.0 INTRODUCTION

Current velocities in a river are measured by placing the current meter into the flow at a known depth and recording the rate of rotation of the rotor. The relationship between the linear current velocity and the rate of rotation of the meter rotor is normally determined from calibrations in a towing tank. Such calibrations have proved to be satisfactory for most applications when the flow is locally two-dimensional. However, when the meter is placed close to stream banks, bridge piers, canal walls, large boulders, at points of sudden changes in depth, etc., it is no longer exposed to two-dimensional flows. At such locations, the flow rate changes in the transverse direction resulting in a velocity gradient across the flow. The effect of such velocity gradients across the meter rotor at right angles to the flow is not accounted for in a conventional calibration. A review of the literature revealed only a small contribution by Kulin (1977) who reported that errors of several percent are possible when measuring flows with badly skewed profiles if the sum of the horizontal gradients across the measuring cross-section is not zero. Considering that the Price meter is the most commonly used instrument for stream flow measurement in North America, it is surprising that so little information is available on the resposne of this meter to flow with velocity gradients. Clearly, more work is required.

In this report the effect of velocity gradients across the rotor of the Price meter is examined using theoretical analysis together with some existing experimental data. The work is conducted for the purpose of providing information to the Water Survey of Canada and other users of the Price meter.

2.0 THEORETICAL CONSIDERATION

The rotor of the Price meter is an assembly of six conical cups mounted symetrically about the verical axis of rotation as shown in Figure 1. The forces which govern the rotation of the rotor are the drag forces on the inside and outside of the cups as well as the resistance due to bearings, gears and contacts in the rotor assembly. These forces create torques about the centre of rotation as shown in Figure 2.

For a given steady flow, the meter rotor turns at a constant rate and therefore the balance of the opposing torques may be written as

$$\frac{1}{2}\rho\ C_{D_1} A(V_1 - \omega r)^2\ r - \frac{1}{2}\rho\ C_{D_2} A(V_2 + \omega r)^2\ r - T = 0 \qquad (1)$$

in which ρ = density of the fluid, A = average "bluff body" area of the cups, V_1 and V_2 are the flow velocity at the open and closed side of the rotor cups respectively, r = effective radius of the rotor as shown in Figure 2, C_{D_1} and C_{D_2} = average drag coefficients for the parts of the rotor exposing the inside and outside of the cups respectively, ω = angular velocity of the rotor and T = the torque due to resistance of bearings, gears and contacts of the rotor assembly. The effect of T is known to be most significant at low velocities and its relative importance decreases as velocity increases (Engel, 1976). Therefore, for the sake of simplicity, the resisting torque due to the drag on the outside of the cups (designated by subscript 2) and the effect of T may be lumped together to produce a total resisting torque. Equation (1) can therefore be simplified to give

$$C_{D_1}(V_1 - \omega r)^2 - \overline{C_{D_2}}(V_2 + \omega r)^2 = 0 \qquad (2)$$

in which $\overline{C_{D_2}}$ replaces C_{D_2} to reflect the total "lumped" effect of the resisting torque. Equation (2) is now used to determine the response characteristics of the Price meter to two-dimensional flow and flow with a transverse velocity gradient.

2.1 Two-Dimensional Flow

When the flow is two-dimensional, the velocity distribution is uniform as shown in Figure 2. This is the case encountered when meters are calibrated in a towing tank. For this type of velocity distribution $V_1 = V_2 = V_c$ in which V_c denotes the velocity at the centre of the rotor. Equation (2) can thus be rearranged to give

$$\omega_0 r = V_c \left[\frac{\sqrt{C_{D_1}} - \sqrt{C_{D_2}}}{\sqrt{C_{D_1}} + \sqrt{C_{D_2}}} \right] \tag{3}$$

One may also write

$$\omega_0 r = \pi N_0 D \tag{4}$$

in which $\pi = 3.14.....$, N_0 = rate of rotation of the rotor in rev/s when the flow is two-dimensional and D = effective diameter of the rotor (i.e., D = 2r). Substituting equation (4) into equation (3) results in

$$\frac{N_0 D}{V_c} = \frac{1}{\pi} \left[\frac{\sqrt{C_{D_1}} - \sqrt{\overline{C_{D_2}}}}{\sqrt{C_{D_1}} + \sqrt{\overline{C_{D_2}}}} \right] \tag{5}$$

Equation (5) can be further simplified by dividing through by $\sqrt{C_{D_2}}$ give

$$\frac{N_o D}{V_c} = \frac{1}{\pi}\left[\frac{K-1}{K+1}\right] \tag{6}$$

in which $K = \sqrt{C_{D_1}}/\sqrt{C_{D_2}}$.

Values of K must be obtained from calibrations in a towing tank.

Equation (6) reflects the typical response characteristics of the Price current meter in two-dimensional flow. N_oD/V_c is dependent only on the value of K which reflects primarily the shape and orientation of the cups. Over most of the operating range of the meter, that is for velocities greater than about 30 cm/s, towing tank tests show that N_oD/V_c is virtually constant and therefore over this range K must also be constant. For three randomly selected Price meters the average value of N_oD/V_c for $V_c > 30$ cm/s was found to be about 0.113 (Figure 3). When $V_c < 30$ cm/s N_oD/V_c decreases as V_o decreases because bearing and gear resistance are increasing. As a result there must be a corresponding decrease in K. Values of K for several values of $V_c < 30$ cm/s and the constant value of K for $V_c \geq 30$ cm/s are given in Table 1. When $V_c = 10$ cm/s, K = 2.027 whereas when $V \geq 30$ cm/s K = 2.101 showing that the variation of K for $10 \leq V_c \leq 30$ is about 4%.

2.2 Flow With Velocity Gradient

In most measuring situations the diameter of the rotor is very small relative to the width of the flow. Therefore, the velocity gradient across the rotor may be taken to be linear, resulting in a velocity distribution as given in Figure 4. In this case $V_1 \neq V_2$ and thus equation (2) results in

$$\omega_{\Omega} r = \left[\frac{KV_1 - V_2}{K + 1} \right] \tag{7}$$

in which K is the same as for two dimensional flow since the geometry of the rotor and assembly has not changed and velocity vectors are considered to act in parallel, and ω_{Ω} = the angular velocity for flow with gradient Ω. The velocity gradient across the rotor can be given as

$$\Omega = \frac{(V_1 - V_2)}{D} \tag{8}$$

in which Ω = the velocity gradient in s^{-1}. The gradient is positive when $V_1 > V_2$ and negative when $V_1 < V_2$. For the linear distribution in Figure 4, the average velocity across the width of the rotor occurs along a line coincident with the centre of rotation. Therefore, one may write

$$V_c = \frac{(V_1 + V_2)}{2} \tag{9}$$

in which V_c = the average velocity. From equations (8) and (9) one obtains

$$V_1 = \frac{1}{2} \left[2V_c + \Omega D \right] \tag{10}$$

and

$$V_2 = \frac{1}{2}\left[2V_c - \Omega D\right] \tag{11}$$

Substituting equations (10) and (11) into (7) one obtains

$$\omega_\Omega r = \left[\frac{(K - 1) + \frac{\Omega D}{2V_c}(K + 1)}{(K + 1)}\right] V_c \tag{12}$$

Finally using the relationship

$$\omega_\Omega r = \pi N_\Omega D \tag{13}$$

and substituting in equation (12) one obtains

$$\frac{N_\Omega D}{V_c} = \frac{1}{\pi}\left[\frac{K - 1}{K + 1} + \frac{\Omega D}{2V_c}\right] \tag{14}$$

Equation (14) represents the response characteristics of the Price current meter in a flow with a velocity gradient across the rotor. When $\Omega = 0$ the flow is two-dimensional and equation (14) simply reduces to the form of equation (6). Further examination of equation (14) shows that $N_\Omega D/V_c$ is a function of two dimensionless components. One component is nothing but the rotor response to two-dimensional flow given by equation (6) whereas the second component represents the velocity gradient effect. It also is clear from equation (14) that the Price meter over-registers when the gradient is positive ($\Omega > 0$) and under-registers when the gradient is negative ($\Omega < 0$). These effects of Ω can be seen clearly in Figure 5 which shows a plot of $\frac{N_\Omega D}{V_c}$ vs V_c with Ω as a parameter. For a given Ω the rate of change of $N_\Omega D/V_c$ with V_c decreases as V_c increases until a value of say V'_c is reached for which $N_\Omega D/_V$ is virtually constant. The magnitude of V'_c varies with Ω decreasing from $V'_c \approx 1000$ cm/s when $\Omega = 1.0\ s^{-1}$ to about 300 cm/s when $\Omega \approx 0.06255^{-1}$. Approximately the same is true for negative values of Ω . It is quite clear from Figure 5 that the effect of velocity gradient extends over most of the operating range of the meter ($5 < V_c \leq 300$ cm/s).

The behaviour of the rotor can be explained with reference to Figure 4. When $\Omega > 0$ the velocity on the side of the rotor with the open cups exposed to the flow is greater than the velocity of the flow passing the closed side of the cups. This results in a larger difference between the driving and opposing drag forces than obtained in two-dimensional flow (i.e., $\Omega = 0$) resulting in a faster constant rate of rotation of the rotor. Such a situation would normally occur when a meter is placed near a boundary on the right hand side of the flow (observer looking upstream). When $\Omega < 0$ the net driving force is reduced because now $V_1 < V_2$ causing the rotor to turn slower than would be observed for two-dimensional flow. Such a situation would occur when a meter is placed near a boundary on the left hand side of the flow. Theoretically, as the magnitude of the negative gradient increases, the rate of rotation N_Ω will decrease until the magnitude of the gradient has reached a value, for which the rotor will not turn at all, that is $N_\Omega = 0$. This condition is reached when the numerator of the right hand side of equation (14) is equal to zero, which results in

$$\frac{\Omega_o D}{V_c} = -2 \left[\frac{K - 1}{K + 1}\right] \tag{15}$$

where Ω_o = gradient at zero rotation.

Comparing equation (15) with equation (6), reveals that the condition for zero rotation of the rotor can also be written as

$$\frac{\Omega_o D}{V_c} = -2\pi \left[\frac{N_o D}{V_c}\right] \tag{16}$$

Equation (16) shows that the variation of $\Omega_o D/V_c$ is similar to the response of the meter to two-dimensional flow but of opposite sign and amplified by a factor 2π. Using the curve in Figure 3, values of Ω_o were computed for different values of V_c and these values were plotted in Figure 6. The curve in Figure 6 shows that the condition of $N_\Omega = 0$ is most plausible for lower velocities since in this range the values of Ω_o are small enough to be realistic for ordinary flows. Such a situation could conceivably arise when a meter is placed close to a boulder near the bank of a stream. When the gradient is decreased, below Ω_o the meter rotor will rotate in the opposite direction to that normally observed in two-dimensional flow. This condition occurs when

$$\frac{\Omega_o D}{V_c} < -2\pi \left[\frac{N_o D}{V_c}\right] \tag{17}$$

Once again equation (17) is most likely valid for very low velocities in order for values of Ω to be of reasonable magnitude.

3.0 EXAMINATION OF AVAILABLE EXPERIMENTAL DATA

A review of the literature revealed only one set of experiments from Loquist (1978) in which a Price meter was tested both in two-dimensional flow and flow with a transverse linear gradient.

3.1 Experimental Conditions

Loquist (1978) used an existing experimental facility in which "honeycombs" could be used as flow retardants to set up the required velocity gradient. A single Price meter was tested under the two following conditions:

a) straight flow $\Omega = 0$
b) flow with gradient $\Omega < 0$

The cross-section of the flow was rectangular, about 40 cm wide and 26 cm deep for both types of flow. For each flow condition the meter was positioned at the centre of the flume cross-section so that the geometric centre of the rotor was 15 cm above the bed. The reference velocities and transverse velocity profiles were measured with a small vane type "Neyrpic" current meter and these were treated as being accurate. To ensure two-dimensional flow in the one case and to determine the velocity gradient in the other case, velocity measurements with the "Neyrpic" meter were made at 3.8 cm (1.5 in) intervals at a height of 15 cm above the bed across the full width of the flume. In the case of the gradient flow the transverse velocity distribution was determined from the measurements to be

$$V = 44.195 - 0.630\, x \tag{18}$$

where χ = distance across the flume. When $\chi = 0$, $V = V_c$ and thus $V_c = 44.195$ cm/s. The measurements for the two-dimensional flow and "skewed" flow are given in Table 2.

3.2 Data Analysis

The measurement for the two-dimensional flow was used to compute the value of K for the meter used by Loquist, using equation (6). The value of K = 2.163 is slightly higher than the average value of K = 2.101 for the three meters at the same velocity in Figure 3. Using K = 2.163, values of the meter response were computed using equation (14). The results together with the measured values are given in Table 3. It can be seen that the computed meter response of $N_{\Omega c} = 0.587$ rev/s is slightly lower than the measured value of $N_{\Omega}m = 0.591$ rev/s with the difference being about 0.7%. Such a small difference can easily be due to experimental error. The computed response curve for which $\Omega = -0.630$ s^{-1} was plotted in Figure 7 together with the single experimental measurement. Figure 7 shows that the close agreement between computed and measured meter response is in a region of the $N_{\Omega}D/V_c$ versus V_c curve in which there is significant curvature, thus lending further credibility to equation (14). Therefore equation (14) is considered to be sufficiently reliable to predict the behaviour of the Price meter in a flow with transverse velocity gradient.

4.0 EFFECT OF VELOCITY GRADIENTS ON ACCURACY OF MEASUREMENTS

4.1 The Error in Measurements

The percent error in a velocity measurement obtained when a meter calibrated in a towing tank is used to measure flow which is not two-dimensional, can be expressed as

$$E = \left[\frac{N_\Omega - N_o}{N_o}\right] \times 100\% \tag{19}$$

in which E is the percentage error. Equations (19) can be written with reference to equation (6) and (1) as

$$E = \frac{\left[\dfrac{\Omega D}{2\pi V_c}\right]}{\left[\dfrac{N_o D}{V_c}\right]} \times 100\% \tag{20}$$

Equation (20) shows that the percentage error in the meter response is simply the ratio of the gradient component of equation (14) divided by the meter response to two-dimensional flow obtained from equation (6). In order to reveal the error in a velocity measurement due to the gradient Ω for a given flow velocity V_c, E was plotted versus Ω with V_c as a parameter in Figure 8 and Ω was plotted versus V_c with E as a parameter in Figure 9. The curves are valid for positive or negative values of Ω. When $\Omega > o$, $E > o$ and when $\Omega < o$, $E < o$.

The curves in Figure 8 clearly show that the effect Ω is greatest when the velocities are small and this effect decreases as V_c increases. Also, for a given Ω the rate of decrease in E as V_c

increases is rapid at low velocities and becomes less as V_c becomes larger. Figure 9 shows the combinations of Ω and V_c required to obtain an error of a certain fixed magnitude. The most interesting information revealed by Figures 8 and 9 is that values of E are quite large for very low values of Ω. For example, when $\Omega \approx 0.1\ s^{-1}$ and $V_c = 10$ cm/s, E is about 11% and when $V_c = 40$ cm/s at $\Omega \approx 0.1\ s^{-1}$ $E \approx 2.8\%$. Even when $V_c \approx 100$ cm/s $E \approx 1.2\%$ for the same value of Ω. A value of $\Omega = 0.1\ s^{-1}$ means that for any flow the velocity difference across the rotor is about 0.8 cm/s (i.e., $\Delta V = \Omega D$) since $D \approx 7.65$ cm. Such velocity differences are quite reasonable for flows near boundaries and thus it must be clear that values of Ω larger than $0.1\ s^{-1}$ are possible with the consequence of larger measurement errors. The possibility of such errors is disturbing especially when Price meters are regularly calibrated to an accuracy of better than 1%. Values of gradients required to cause an error of ±1% as a function of flow velocity can be obtained from Figure 9. When $\Omega = 0.1\ s^{-1}$ errors of ±1% can be exceeded for velocities as high as 100 cm/s.

Knowledge of the Price meter's behaviour in uneven flow, unfortunately, does not help much in reducing measurement errors due to velocity gradients. In situations where such gradients can be anticipated, it is difficult, if not impractical, to determine their magnitude. Indeed, in some situations such as in streams with large boulders on the bed (mountain streams) or when there are sudden changes in depth, velocity gradients and the possible errors may not even be suspected. This uncertainty in the flow measurements is directly attributable to the geometry of the rotor. Since the rotor is turned by the action of drag forces which act at the circumference of the rotor, the Price meter is more susceptible to uneven flow velocities than a meter of some other geometry, such as, perhaps, a meter with a propeller type totor. If it can be demonstrated that propeller type meters are less affected by velocity gradients than the

Price meter, then considerations should be given to using such meters in situations where velocity gradients are known to be significant.

4.2 Selection of Discharge Measuring Sites

Knowledge of the possible effects of velocity gradients should be included in the criteria to select suitable measuring sites on rivers. In order to avoid uneven flow situations as much as possible, measuring cross-sections should be in a straight, uniform reach, have banks or flow edges devoid of large boulders or outcrops, and there should be no eddies near the edge of the flow. Sections, where measurements must be made alongside bridge piers, should be carefully evaluated to ensure that the likely errors do not significantly add to the perceived allowable error of the total discharge measurement. Considerations should also be given to the effects of large boulders on the stream bed, when the meter is placed at the conventional 0.8 depth during a standard measurement. Errors could be considerable if the meter is placed between adjacent boulders, a situation which can arise at many streams during medium to low stages.

Unfortunately, for reasons of cost, access, regional geology, etc., there is seldom an ideal measuring section. One must therefore keep in mind the possibility of errors as indicated in Figure 9 when the Price meter is used.

5.0 CONCLUSIONS

5.1 A reliable equation to predict the response of the Price meter rotor to an uneven flow has been developed using theoretical considerations and experimental data from towing tank calibrations.

5.2 It has been shown that the Price meter is prone to measurement error when placed in a flow with a transverse velocity gradient across the rotor. When the gradient is positive, the Price meter over-registers; when the gradient is negative, the meter under-registers.

5.3 The error in velocity measurement incurred with the Price meter in shear flow depends on the velocity gradient and the flow velocity. The effect of velocity gradients is greatest at low velocities and becomes less as velocities increase. For a given velocity gradient the rate of decrease in measurement error as the flow velocity increases is greatest at low velocities and decreases as velocities increase.

5.4 The gradient for which the measurement error is 1% (i.e., accuracy of Price meter calibration) is only 0.1 s^{-1} when the average velocity across the rotor is 120 cm/s, and only 0.05 s^{-1} when the average flow velocity is 60 cm/s. Gradients larger than this are possible indicating that measurement errors considerably larger than 1% can occur.

5.5 In an actual flow measurement the errors due to velocity gradients are unknown because such gradients are difficult or impractical to measure in the field. In addition, situations may occur in which velocity gradients are not suspected, resulting in unknown measurement errors.

5.6 Price meters should be compared with propeller type meters under conditions of flow with a transverse gradient. If propeller type meters prove to be less affected by such flows, then some consideration should be given to using such meters in situations where velocity gradients are significant.

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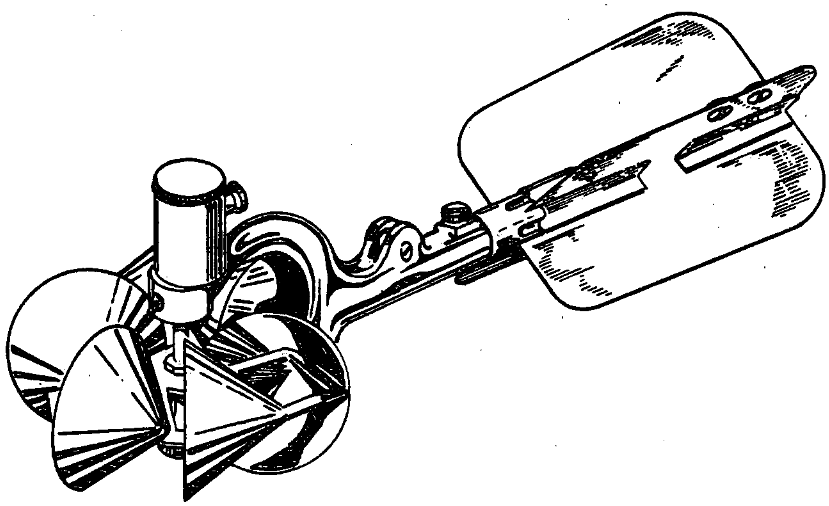

FIGURE 1. PRICE METER WITH TAIL FIN

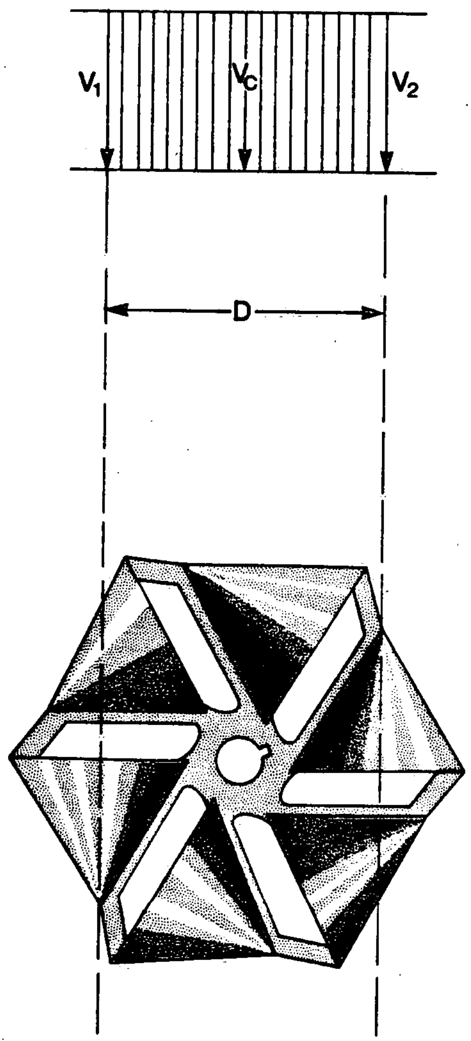

FIGURE 2. VELOCITY DISTRIBUTION FOR TWO DIMENSIONAL FLOW RELATIVE TO METER ROTOR

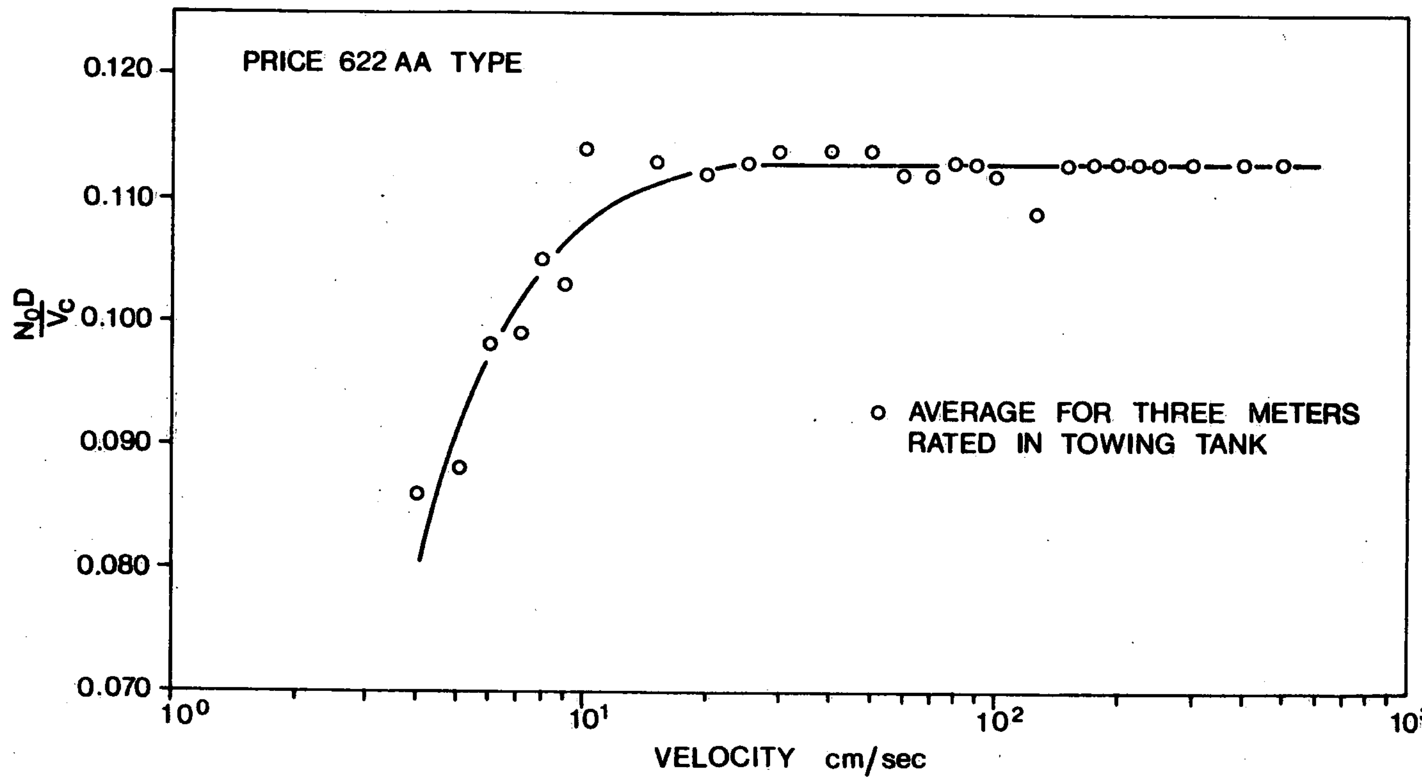

FIGURE 3. RESPONSE OF PRICE METER TO TWO DIMENSIONAL FLOW

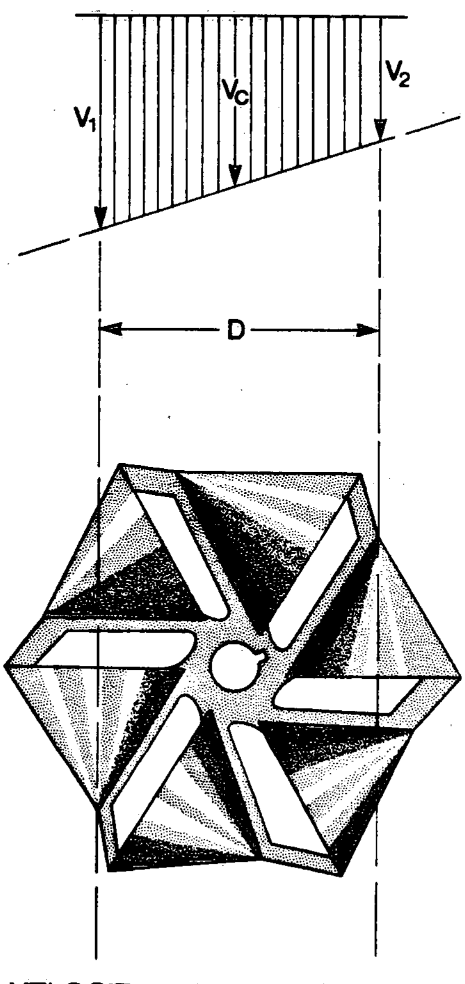

FIGURE 4. VELOCITY DISTRIBUTION FOR FLOW WITH TRANSVERSE GRADIENT ACROSS THE METER ROTOR

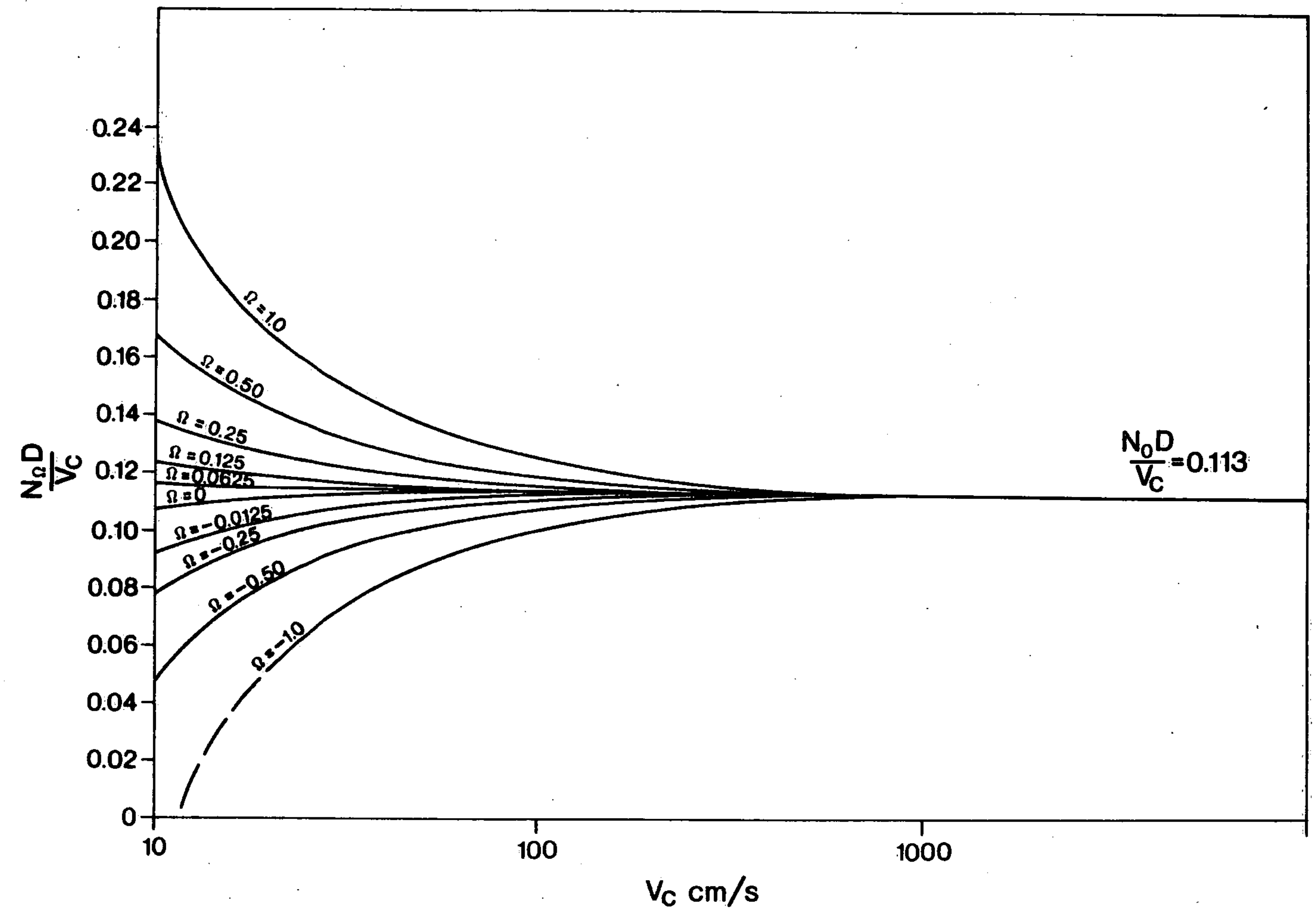

FIGURE 5. METER RESPONSE CURVES FOR DIFFERENT GRADIENTS

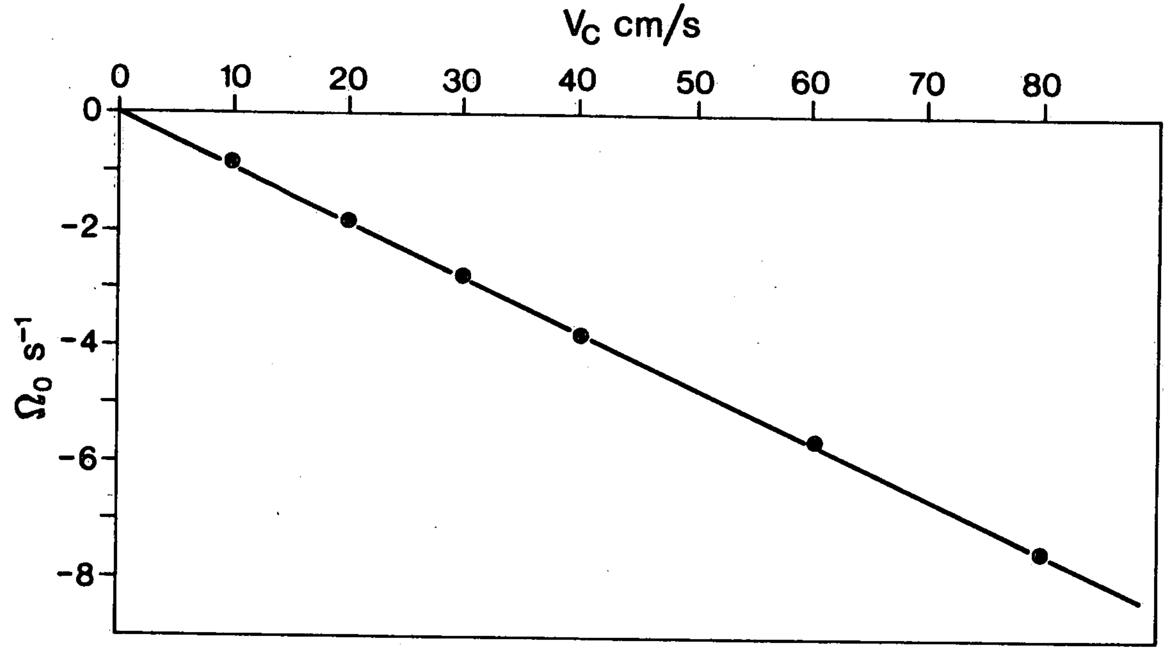

FIGURE 6. VELOCITY GRADIENT AT WHICH METER ROTOR WILL NOT TURN

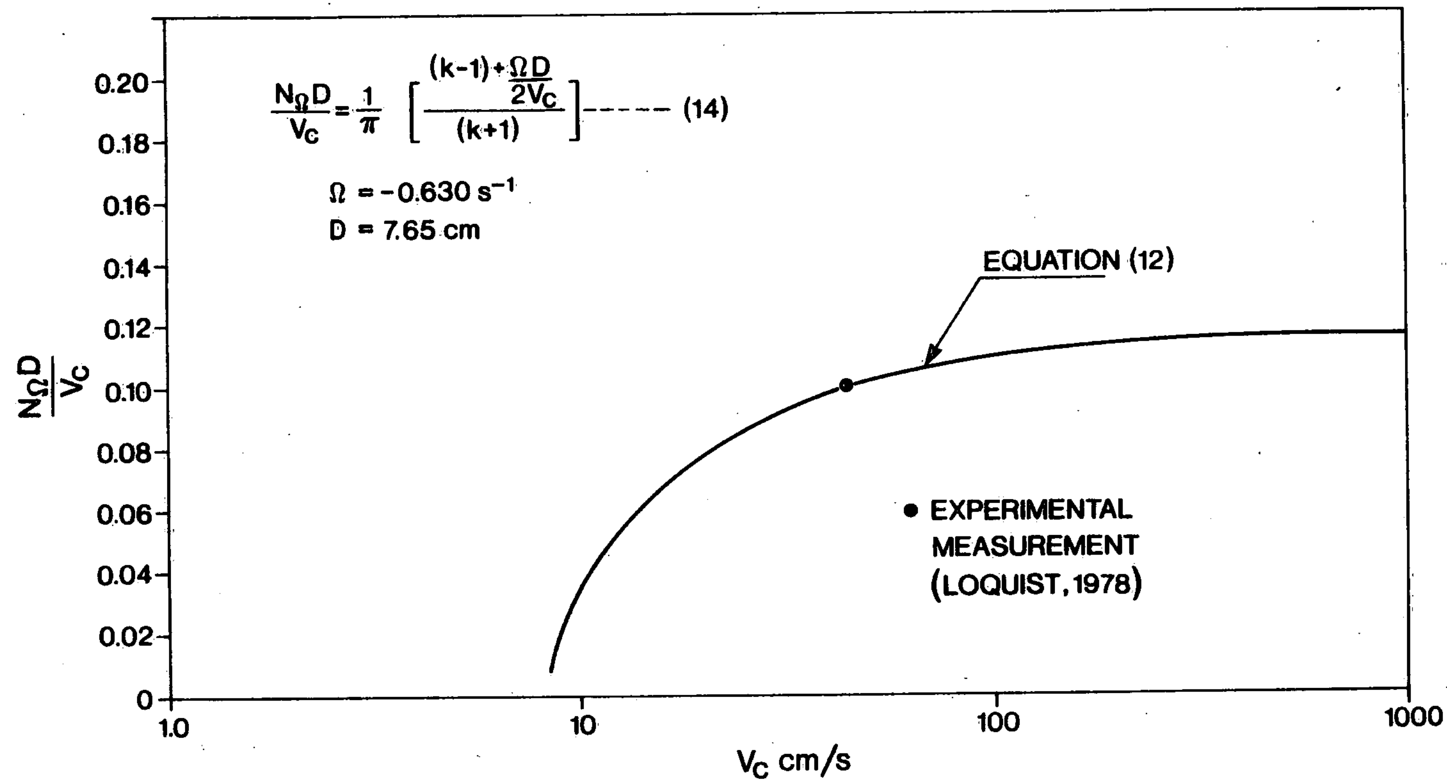

FIGURE 7. COMPARISON OF ANALYTICAL AND EXPERIMENTAL RESULTS

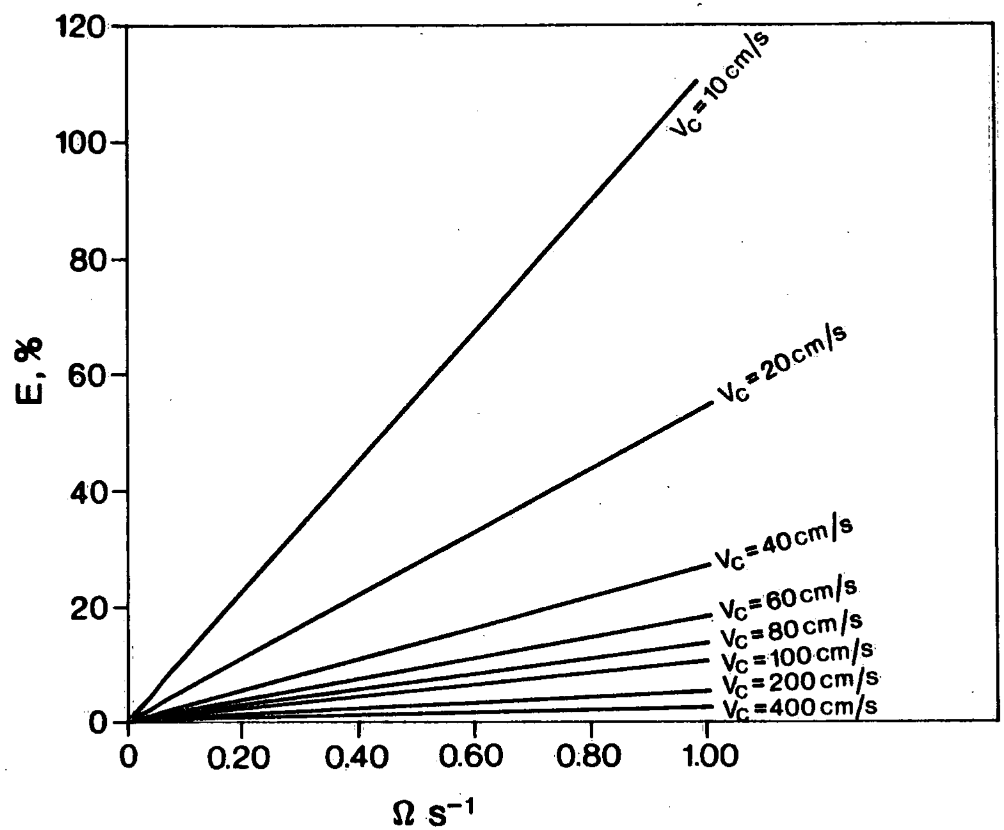

FIGURE 8. VARIATION OF MEASUREMENT ERROR WITH VELOCITY GRADIENT

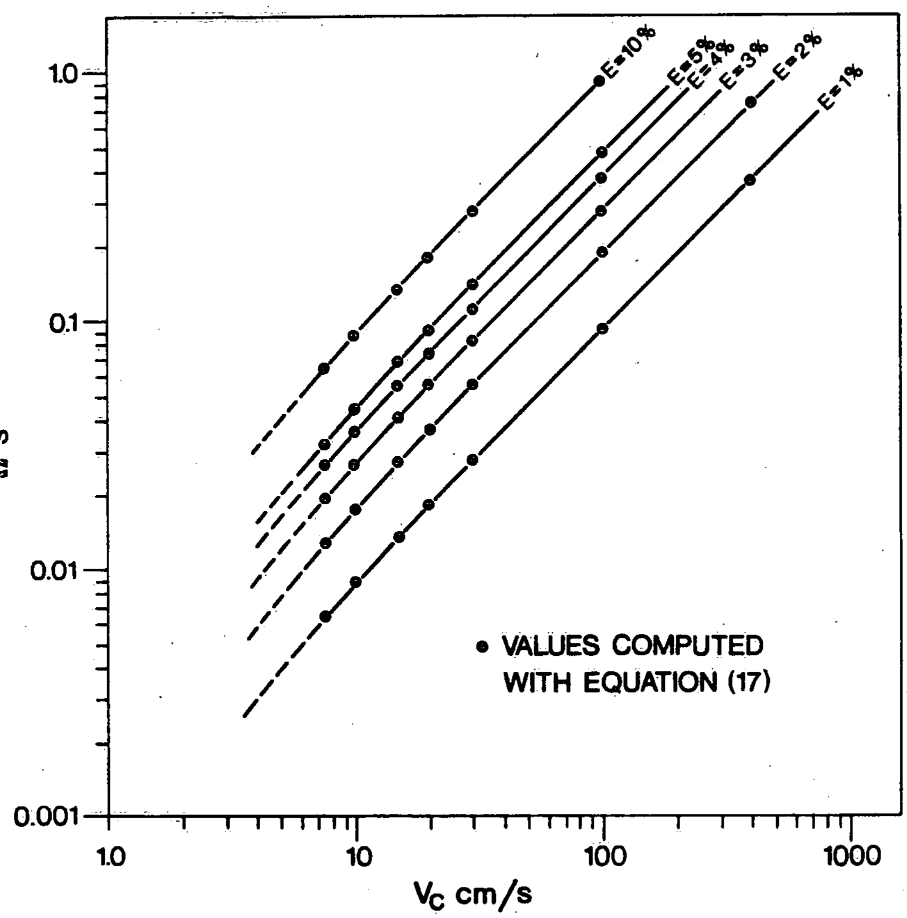

FIGURE 9. VALUES OF GRADIENT AND AVERAGE VELOCITY FOR CONSTANT ERROR

TABLE 1. ESTIMATES OF K

V cm/s	$\frac{N_o D}{V}$	K
10	0.108	2.027
15	0.111	2.071
20	0.112	2.086
230	0.113	2.101

TABLE 2. EXPERIMENTAL DATA (Loquist, 1978)

Two-Dimensional Flow				Skewed Flow $\Omega = -0.630\ s^{-1}$			
V_c cm/s	N_o rev/s	K	$\frac{N_o D}{V}$	V_c cm/s	N_Ω rev/s	K	$\frac{N_\Omega D}{V}$
44.2	0.673	2.163	0.114	44.2	0.591	2.163	0.101

TABLE 3. COMPARISON OF MEASURED AND COMPUTED ROTOR RESPONSE FOR SKEWED FLOW

Measured Data			Computed Data			
V_c cm/s	$N_{\Omega m}$ rev/s	$\frac{N_{\Omega m} D}{V_c}$	V_c cm/s	$N_{\Omega c}$ rev/s	$\frac{N_{\Omega c} D}{V_c}$	% Diff.
44.2	0.591	0.101	44.2	0.587	0.100	-0.68

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