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ON THE EFFECT OF CHANGES IN GEOMETRY AND SUBMERGED WEIGHT OF THE PRICE METER ROTOR

by

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SUMMARY

Using dimensional anlaysis it was shown that the rotor response of a meter with vertical axis can be expressed independently in terms of a ratio of the drag coefficients of the driving elements and the submerged weight of the rotor. Experimental results from tests on a conventional Price meter rotor and a modified plastic price meter rotor were used to examine the effects of changing drag coefficients and submerged weight on general rotor performance and threshold velocity. The results indicate that considerable improvement in measuring low velocities may be obtained by using a rotor having the geometry of the conventional Price meter, and a substantially reduced submerged weight. Further tests are presently under way.

SOMMAIRE

Il est montré à l'aide de l'analyse dimensionnelle que la réponse du rotor d'un appareil de mesure à axe vertical peut être exprimée indépendamment entermes d'un ratio des coefficients de traînée des éléments d'entraînement et du poids submergé du rotor. Des résultats d'essais expérimentaux du rotor d'un appareil Price classique et d'un rotor modifié en plastique pour appareil Price ont servi à étudier les effets de la variation des coefficients de traînée et du poids submergé sur la performance générale du rotor et sur la vitesse limite. Les résultats indiquent qu'il est possible d'améliorer considérablement les mesures en basses vitesses en se servant d'un rotor de même forme que celui de l'appareil Price classique mais d'un poids submergé substantiellement réduit. D'autres essais sont actuellement en cours.

MANAGEMENT PERSPECTIVE

The rate of rotation for a conventional rotor and a new plastic rotor with a different shape for the Price meter are compared. The turning speed for the plastic rotor is less because although the bearing drag is reduced, the applied torque by the water is less.

Other things being equal, disposable plastic rotors should be acceptable in service. There are implications that if a plastic rotor were made similar to the standard metal conical cupped rotor, that the threshold velocity would be less but rotational speeds would be high.

There are longer term possibilities of financial savings with improved precision in measurements where the velocities are low.

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PERSPECTIVE DE GESTION

Les vitesses de rotation d'un rotor classique et d'un rotor modifié en plastique équipant un appareil de mesure Price sont comparées. La vitesse de rotation du rotor en plastique est moindre car, même si la traînée est réduite, le couple appliqué par l'eau est moindre.

Tous autres facteurs étant par ailleurs égaux, on pourrait se servir de rotors en plastique jetables. Pour un rotor de plastique semblable au rotor évasé conique métallique ordinaire, on obtient une vitesse limite moindre mais des vitesses de rotation élevées.

Les avantages sont qu'il est possible d'économiser de l'argent à long terme et d'améliorer la précision des mesures en basses vitesses.

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1.0 INTRODUCTION

The Price meter is the most commonly used instrument to measure streamflow discharge in North America. The rotor of the Price meter consists of an assembly of six conical cups oriented about a vertical axis of rotation and is attached to the frame of the meter as shown schematically in Figure 1. Traditionally, the rotor components have been fabricated out of sheet brass with the whole assembly being protected with chrome or nickel plating, Figure 2a. Recently, however, because of production costs of this type of rotor, the United States Geological Survey has introduced a plastic rotor which can be mass produced more cheaply and quickly using injection moulds. Apart from the material differences, the plastic rotor has also some structural differences, Figure (2a), most significant of which is that the conical elements of the rotor are now solids of revolution whereas in the original metallic rotor, these elements are conical cups.

The differences in the conical elements and the change in material density from plated brass to plastic are expected to have a significant effect on the response characteristics of the rotor. Engel and DeZeeuw (1981) found that the rate of revolution of the metallic rotor was reduced by about 8 percent when the conical cups were sealed with a flat circular plate of the same base diameter as the cups. The fact that the plastic rotor has a lower submerged weight can be expected to reduce its frictional resistance.

Recently, the writers conducted some standard calibrations of the new plastic rotor for the Water Survey of Canada. In this report the data obtained are used together with dimensional analysis to attempt to reveal the separate effects of changing the geometry and submerged weight of the Price meter rotor. The report is part of an ongoing study to assess the performance characteristics of the price meter. The results are intended for users of these meters in the government and private sectors.

2.0 EQUIPMENT AND APPARATUS

2.1 Meter Suspension

One Price winter type current meter yoke and assembly number 6-474 was used in these tests. The meter was used with a 20 mm diameter solid steel rod assembly fastened to the rear of the towing carriage as shown in Figure 3.

2.2 Towing Tank

The tank, constructed of reinforced concrete, founded on piles, is 122 metres long and 5 metres wide. The full depth of the tanks is 3 metres, of which 1.5 metres is below ground level. Normally, the water depth is maintained at 2.7 metres. Concrete was chosen for its stability, vibration reduction and to reduce possibly convection currents.

At one end of the tank is an overflow weir. Waves arising from towed current metres and their suspensions are washed over the crest, reducing wave reflections. Parallel to the sides of the tank, perforated beaches serve to dampen lateral surface wave disturbances. The large cross section of the tank also inhibits the generation of waves by the towed object.

2.3 Towing Carriage

The carriage is 3 metres long, 5 metres wide, weighs 6 tonnes and travels on four precision machined steel wheels.

The carriage is operated in three overlapping speed ranges:

0.5 cm/sec	-	6.0 cm/sec
5.0 cm/sec	-	60 cm/sec
50 cm/sec	-	600 cm/sec

The maximum speed of 600 cm/sec can be maintained for 12 seconds. Tachometer generators connected to the drive shafts emit a voltage signal proportional to the speed of the carriage. A feedback control system uses these signals as input to maintain the constant speed within specified tolerances.

2.4 Data Acquisition

2.4.1 Towing speed

The average speed data for the towing carriage is obtained from electric pulses emitted from a measuring wheel. This wheel is attached to the frame of the towing carriage and travels on one of the towing tank rails, emitting a pulse for each millimeter of travel. The frequency of these pulses is measured using the 5323A Hewlett Packard automatic counter. The frequency is converted to speed in cm/s by dividing the frequency by 10 since the frequency of the pulses is the same as speed in mm/s. The automatic counter determines the frequency over very short time increments and therefore a large number of average velocity determinations are made as the towing carriage travels down the tank. These "speed samples" are processed directly by a Hewlett Packard 85 computer as they are produced. The computer determines the overall average towing speed and the standard deviation about this average to make sure that the specified tolerances are met.

2.4.2 Rate of revolution of the rotor

The Price meter is equipped with a contact closure mechanism which gives an electric pulse for each complete revolution of the rotor. The pulses generated by the rotor are transmitted to a data acquisition module which begins counting the revolutions after the first pulse has been received. This ensures that all the pulses counted represent complete revolutions. In order to obtain the rate of rotation of the rotor in revolutions per second, time is measured simultaneously with the counting of the revolution using a crystal clock.

3.0 EXPERIMENTAL PROCEDURE

3.1 Meter Preparation

Before testing, the meter was assembled with the appropriate rotor and underwent the following inspections:

a) The gearing mechanism was checked to ensure that it was operating freely.
b) The contact wire was cleaned and adjusted for tension to provide good electrical contact.
c) All moving parts were lubricated.

Following the inspection, the meter was suspended in a small wind tunnel where it was made to spin for two hours to ensure that all moving parts were "run in".

3.2 Towing Tests

In each test, the meter was attached to the suspension rod and lowered into position 30 cm below the water surface. This depth was chosen to avoid surface effects and to create a minimum of drag on the steel rod, thus eliminating undesirable vibrations. Care was always taken that the meter was properly aligned in the horizontal and vertical direction to avoid any errors due to misalignment (Engel, DeZeeuw, 1978, 1979). The meter was towed at different speeds beginning at the threshold for each rotor to a maximum of 250 cm/s to obtain a total of 27 tests for the metallic rotor and 28 tests for the plastic rotor. Each time that the meter was towed, care was taken that steady state conditions prevailed when measurements were recorded. The waiting times between successive tests were equal or longer than those established by Engel and DeZeeuw (1977). For each test, the towing speed, revolutions of the meter rotor and the time to obtain the total number of revolutions were recorded. Water temperatures were not noted since temperature changes during the tests were small and do not affect the meter significantly (Engel, 1976).

The data for all the tests are given in Table 1.

3.2 Weight of the Rotors

The weight of each rotor was determined in air and in water, using standard procedures. The data are given in Table 2.

4.0 PRELIMINARY EXAMINATION OF DATA

The data in Table 1 were used to compute values of N/V (N = revolutions per second, V = velocity) for each rotor and these are given in Table 3 together with the corresponding velocity. Values of N/V represent the number of revolutions of the rotor per unit distance of travel along the towing tank during the tests and are therfore ideal for a general comparison of the response of different types of rotors. The data in Table 3 were then plotted as N/V vs V in Figure 4 for the conventional and the plastic rotor. In order to facilitate the analysis, average curves were drawn through the plotted points with emphasis on outlining the most significant characteristrics of each rotor. This effectively reduced the analysis to considerations of the dominant deterministic response of the rotors by removing the random components and these average curves were then used to compare the conventional and the plastic rotors' response characteristics over the range of velocities tested.

The two curves in Figure 4 show that there is a constant difference in N/V for velocities greater than about 35 cm/s with the plastic rotor turning at a rate which is about 6 percent slower. For $V < 35$ cm/s the curves in Figure 4 show that values of N/V for each rotor increases as V increases from the lowest value of V tested until, when $V \approx 35$ cm/s, N/V becomes constant. However, the rate of increase in N/V is different for each rotor. For the conventional rotor N/V changes at first very rapidly until when $V \approx 7$ cm/s the rate of increase of N/V with V gradually declines. When V ≈ 35 cm/s N/V becomes constant at a value of 1.47. In the case of the plastic rotor the rate of increase of N/V is more gradual until when V ≈ 35 cm/s N/V assumes a constant value of about 1.38. Values of the percent differences in N/V for $V \leq 35$ cm/s are given in Table 4. The results show that when V ≈ 5 cm/s the plastic rotor is about 9% slower and this difference decreases to the constant difference of 6% when V ≈ 35 cm/s.

The conventional and plastic rotor differ in two important respects, namely, the conical elements and the submerged weight. The conical elements of the conventional rotor are cups whereas those of the plastic rotor, although being identical in shape, are solids of revolution and have a flat surface at their base. This difference changes the drag coefficient (Engel, 1976, 1983) and results in a lower driving torque for the plastic rotor and thus it has to turn at a slower rate. The submerged weight of the plastic rotor is 2.4 times less than that of the conventional rotor and this would tend to enhance its rate of rotation, especially at the lower velocities. The curves in Figure 4 thus reflect the net effect of changing the conical elements and the submerged weight, but reveal nothing about the separate effects of these changes. A better insight into these separate effects can be obtained by using the principles of dimensional analysis.

5.0 INDEPENDENT EFFECTS OF CHANGES IN ROTOR PROPERTIES

5.1 Dimensional Analysis

When a current meter with a vertical axis is properly aligned in a flow with a uniform two dimensional flow distribution, the angular velocity of the rotor ω can be expressed in terms of eleven independent variables by writing

$$\omega = f[V, D, \rho, \mu, a, b, \Lambda, T_{\ell}, T_{V}] \qquad (1)$$

where ω = angular velocity of the rotor, f denotes a function, V =

velocity of the flow across the rotor, D = effective diameter of the rotor as defined in Figure 5, ρ = density of the fluid, μ = dynamic viscosity of the fluid, a = base diameter of conical elements as shown in Figure 5, b = perpendicular distance between the base and tip of the conical elements as shown in Figure 5, Λ accounts for the characteristic of the base of the conical elements (i.e, hollow cups for conventional rotor, flat bases for plastic rotor), T_ℓ = resisting torque due to horizontal bearing forces, T_v = resisting torque due to vertical bearing forces.

The resisting torque T_ℓ due to horizontal bearing forces varies primarily with the drag forces exerted on the rotor by the flow, bearing geometry and lubricants and may thus be expressed as

$$T_\ell = f_i\,[V,\rho,\mu,T_1,T_2,\text{ bearing geometry, lubricant}] \qquad (2)$$

where T_1 = the torque as a result of the drag forces acting on the bases of the conical elements, T_2 = the torque as a result of the drag forces acting on the tapered sides of the conical elements,

Since the bearings for both the conventional and the plastic rotor are identical and the same lubricant is always used, then for this analysis equation (2) may be reduced to

$$T_\ell = f_2[V,\rho,\mu,T_1,T_2] \qquad (3)$$

The vertical bearing forces contributing to the resisting torque T_v are directly the result of the submerged weight W_s of the rotor as well as the bearing geometry and lubricant. However, because the last two factors are constant, then the resisting torque T_v may be expressed as

$$T_v = f_3\,[W_s] \qquad (4)$$

where W_s = submerged weight of the rotor.

Substituting Equations (3) and (4) into Equation (1) and using the relationship $\omega = 2\pi N$ ($\pi = 3.14...$, N = rate of rotation of the rotor in rev/s), one obtains

$$N = f_4 [V, D, \rho, \mu, a, b, \Lambda, T_1, T_2, W_s] \qquad (5)$$

Using dimensional analysis, Equation (5) can be transformed into the dimensionless form

$$\frac{ND}{V} = f_5 \left[\frac{VD\rho}{\mu}, \frac{a}{D}, \frac{a}{b}, \Lambda, \frac{T_1}{\rho a^2 DV^2}, \frac{T_2}{\rho a^2 DV^2}, \frac{\rho D^2 V^2}{Ws}\right] \qquad (6)$$

The variables $T_1/\rho a^2 DV^2$ and $T_2/\rho a^2 DV^2$ represent drag coefficients which may be denoted as C_{D1} and C_{D2} respectively. In relation to the variables being considered the drag coefficients may be expressed as

$$C_{D1} = f_6 \left[\frac{VD\rho}{\mu}, \frac{a}{D}, \Lambda\right] \qquad (7)$$

and

$$C_{D2} = f_7 \left[\frac{VD\rho}{\mu}, \frac{a}{D}, \frac{a}{b}\right] \qquad (8)$$

Both C_{D1} and C_{D2} are completely specified by the variables in Equation (6) and thus for the sake of convenience one may replace Λ with C_{D1} and a/b with C_{D2}, after which one obtains

$$\frac{ND}{V} = f_8 \left[\frac{VD\rho}{\mu}, \frac{a}{D}, C_{D1}, C_{D2}, \frac{\rho D^2 V^2}{Ws}\right] \qquad (9)$$

It was shown by Engel (1976) that viscosity effects are not important and therefore $VD\rho/\mu$ may be removed from further consideration. The diameters "a" of the conical elements for the plastic and conventional rotors as well as their effective diameters D are the same and therefore a/D is constant and can be absorbed in the function. Equation (9) may now be written in the reduced form

$$\frac{ND}{V} = f_9 \left[\frac{\rho D^2 V^2}{Ws}, C_{D1}, C_{D2} \right] \tag{10}$$

Equation (10) in its present form is awkward to handle because C_{D1} and C_{D2} cannot be determined independently because the conical elements change their orientation with the flow as the rotor turns. However, values of the ratio C_{D1}/C_{D2} can be obtained with reasonable accuracy (Engel, 1983). Values of C_{D1} are different for the two rotors considered, but because a and b are constant, (i.e., size and shape of the conical elements are the same) C_{D2} will be same for both rotors and thus C_{D2} may be omitted from further consideration after forming the variable $K = C_{D1}/C_{D2}$. The final dimensionless equation is then

$$\frac{ND}{V} = f_{10} \left[\frac{\rho D^2 V^2}{Ws}, K \right] \tag{11}$$

Equation (11) shows that for a rotor of particular drag characteristics (i.e. for a given K) there should be a single curve of ND/V vs $\rho D^2 V^2/Ws$ over a common range of velocities V.

The data in Table 1 were used to compute values of ND/V and $\rho D^2 V^2/Ws$ and these are given in Table 5. The value of K for each rotor was determined using the theoretical model from Engel (1983) resulting in $K_c = 4.4$ and $K_p = 3.9$ for the conventional and plastic rotor respectively. Values of ND/V were then plotted versus $\rho D^2 V^2/Ws$ with K as a parameter in Figure 6. Once again average curves were fitted to the plotted points to facilitate the comparison. The curves show that ND/V for any value of $\rho D^2 V^2/Ws$ is always greater for the rotor with the larger value of K. In other words, the conventional rotor always turns faster than the plastic rotor for the same value of $\rho D^2 V^2/Ws$. For $K_c = 4.4$, ND/V increases as $\rho D^2 V^2/W_s$ increases, with the rate of increase decreasing until when $\rho D^2V^2/W_s \approx 0.6$, ND/V becomes constant at a value of 0.112. For $K_p = 3.9$ the rate of increase in ND/V with $\rho D^2V^2/W_s$ is more gradual extending over a wider range and ND/V becomes constant at a value of 0.105 when $\rho D^2V^2/W_s \approx 2.0$.

The curves in Figure 6 can now be used to reveal the separate effects of the conical elements (i.e., K) and the submerged weight on the response of the meter rotor. There are three cases of interest: a) the velocity at which N/V becomes constant; b) shape of the N/V vs V curves; c) threshold velocity.

5.2 Velocity at Which N/V Becomes Constant

When ND/V becomes independent of $\rho D^2V^2/W_s$ for a given value of K, the rate of rotation of the rotor is no longr dependent on the submerged weight W_s. If one denotes this value of $\rho D^2V^2/W_s$ as being equal to, say a_k, then the maximum velocity V_m for which W_s influences the response of the rotor can be written as

$$V_m = \sqrt{\frac{a_k W_s}{\rho D^2}} \tag{12}$$

In the case of the conventional rotor $a_{kc} = 0.6$ and for the plastic rotor $a_{kp} = 2.0$ as indicated in Figure 6. Given that $\rho = 1000$ kg/m^2 and D = 7.62 cm values of V_m for each rotor were computed for values of W_s up to 2.0 newtons and these values were plotted as V_m vs W_s in Figue 7. The curves in Figure 7 show that V_m always increases as W_s increases and the rate of increase is always greater for the rotor with the lower value of K. It is also clear from Figure 7 that for a given W_s, V_m is always greater for the rotor with the lower value of K. The reason for these differences in rotor response is that the rotor with the lower K has less available driving torque and because the torque depends on the square of the flow velocity, a larger velocity is required to overcome the bearing resistance due to the submerged weight. It is also interesting to note that, as W_s decreases, the differences in V_m for two rotors of different K at a given value or W_s decreases.

5.3 Shape of the N/V vs V Curves

The shape of the rotor response curves depends on K and W_s for values of $V_o \leq V < V_m$ where V_o = threshold velocity. For values of $V > V_m$, N/V is constant and is affected by K only. To examine the effect of W_s values of N/V for given values of V were computed from the curves of ND/V vs $\rho D^2V^2/W_s$ in Figure 6 for values of W_s = 0.2 newtons, 2.0 newtons as well as the actual submerged weights of each rotor. The results were plotted for K = 4.4 in Figure 8a and for K = 3.9 in Figure 8b. The curves in Figure 8a and 8b show that reducing the submerged weight in each case improves the response of the rotor by reducing the range of velocities over which there is a significant variation of N/V with V. The effectiveness of a given reduction in W_s depends also on the value of K. As K decreases, the effectiveness of reducing W_s becomes greater. Clearly, for a given value of K, considerable advantage can be gained by reducing the submerged weight of the rotor.

At this point it is interesting to examine the degree of improvement in rotor response that could be achieved if the submerged weight of the conventional rotor were reduced from its actual weight of 1.3 newtons to that of the plastic rotor of 0.54 newtons. Such a change would utilize the advantages of each rotor, that is the larger K of the conventional rotor and the lower W_s of the plastic rotor. Values of N/V were computed for given values of V and the results plotted in Figure 9. The curves show that the difference in N/V for a given V increases as V decreases and when V = 5 cm/s the lighter conventional rotor would turn about 6 percent faster. Clearly, such a reduction in submerged weight of the conventional rotor, while retaining the advantage of the conical cups, would be beneficial to measurements of low velocities.

To determine the separate effect of K, the curves of N/V vs V for the plastic rotor with K = 3.9 and W_s = 0.54 newtons in Figure 8b and the curve for the conventional rotor with K = 4.4 if its weight were reduced to that of the plastic rotor, as shown in Figure 9, can be used. For the sake of comparison these two curves are reproduced in Figure 10. The separate effect of K is revealed through the difference in the shape of the curves for values of $V < 45$ cm/s and their relative values of N/V for a given value of V, being always greater for the greater value of K. When V = 5 cm/s the conventional rotor, if it had the same submerged weight as the plastic rotor, will turn about 15% faster. Clearly, the effect of K on rotor response is considerably greater than the effect of W_s indicating the importance of the small difference in the geometry of the two rotors.

Having determined the separate effects of K and W_s, the results can now be used to explain the difference in the curves for the actual conventional and plastic rotors in Figure 4. When V = 5 cm/s the difference in N/V for the two actual rotors is about 9%. This difference is due to the combined effects of K and W_s. Now, if the conventional rotor's weight is reduced to that of the plastic rotor then when V = 5 cm/s it will turn about 6% faster as shown in Figure 9, and this effect is due to W_s only. Then comparing the conventional rotor and the plastic rotor for the case of W_s = 0.54 newtons, the conventional rotor would turn about 15% faster, when V = 5 cm/s (Figure 10). This latter difference is due only to the effect of K. The effects of K and W_s oppose each other. The 15% advantage that would be gained by using the conventional rotor having the same weight as the plastic rotor (i.e., 0.54 newtons) is offset by a loss of 6% in the rate of rotation because the submerged weight of the conventional rotor is 2.4 times greater. The difference in the opposing effects is then 15%-6% which is equal to the 9% difference observed for the actual rotors in Figure 4. when V = 5 cm/s.

5.4 Threshold Velocity

Theoretically, the threshold velocity is the maximum velocity for which the rotor remains stationary. In other words, it is the flow velocity at which the rotor is on the verge of beginning rotation. For this condition ND/V=0 and Equation (11) becomes

$$f_{10} \left[\frac{\rho D^2 V_o^2}{W_s}, K\right] = 0 \qquad (13)$$

in which V_o = the threshold velocity. Rearranging Equation (13) one obtains

$$\frac{\rho D^2 V_o^{\,2}}{W_s} = f_{11}(K) \qquad (14)$$

Equation (14) states that for a given K there is a value of, say, b_k which is the intercept of the $\rho D^2 V^2/W_s$ axis on a ND/V vs $\rho D^2 V^2/W_s$ curve. This is shown schematically in Figure 11. To obtain the threshold velocity for a rotor of a given K one may write

$$\frac{\rho D^2 V_o^{\,2}}{W_s} = b_k \qquad (15)$$

from which the threshold velocity can be expressed as

$$V_o = k_K \; W_s^{\,1/2} \qquad (16)$$

in which $k_K = \sqrt{\dfrac{b_k}{\rho D^2}}$

Values of b_K vary only with K and decrease as K increases. Therefore, for a given W_s, the rotor with the greater K value will have a lower threshold velocity. It is also clear from Equation (16) that for a given K the threshold velocity of a rotor can be decreased by decreasing its submerged weight. For example, if the submerged weight of the conventional rotor were reduced from its present value of 1.3 newtons to that of the plastic rotor which is 0.54 newtons, then the threshold velocity would be reduced by about 36%. Indeed, for a given K, the lower limit of V_0 according to Equation (16) is governed only by the ability to reduce the submerged weight of the rotor. If one could develop a neutrally buoyant rotor, one should obtain zero threshold velocity.

The implications of these results are that the problem of measuring low velocities can be considerably improved by designing a rotor of suitable K and making W_s as small as possible. Tests are presently underway to further investigate this speculation.

6.0 CONCLUSIONS

6.1 Examination of experimental results showed that the rate of rotation of the conventional rotor is about 6% faster than the U.S.G.S. plastic rotor for velocities greater than about 45 cm/s. For velocities less than 45 cm/s the difference in the two rotors increases as the velocity decreases until when the velocity is 5 cm/s, the rate of rotation of the conventional rotor is about 9% faster.

6.2 Using dimensional analysis a functional relationship was developed which shows that the rate of rotation of the Price meter rotor is governed primarily by the magnitude the ratio of drag coefficient of the conical elements of the rotor and the submerged weight of the rotor.

6.3. It was found that the velocity V_m above which N/v is constant depends on both the geometry of the conical elements reflected by $K = C_{D1}/C_{D2}$ and the submerged weight W_s of a given rotor. For a given W_s, the rotor with the lower value of K has a higher value of V_m. For a rotor of a given value of K, the rotor with the lower W_s has a lower velocity V_m. In the case of the tested conventional and plastic rotors values of V_m are about 35 cm/s and 45 cm/s respectively.

6.4 It was found that the shape of the rotor response curve depends on K and W_s for values of $V < V_m$ but only on K for values of $V > V_m$.

6.5 If the submerged weight of the tested conventional rotor were reduced from 1.3 newtons to that of the plastic rotor at 0.54 newtons, its rate of rotation would be increased. When V = 5 cm/s, the increase would be about 6%.

6.6 The separate effect of K for $V < V_m$ was revealed by comparing the rotor response for the conventional rotor, if its weight were reduced to that of the plastic rotor. When V = 5 cm/s the difference in N/V for these two cases was about 15%, thus showing that the independent effect of K is more signficant at this velocity than the effect of submerged weight.

6.7 The overall effect of K and W_s on the rotor response characteristics is equal to the independent effect due to the influence of K minus the independent effect of the submerged weight W_s.

6.8 The value of the threshold velocity for a rotor of a given submerged weight W_s decreases slightly with an increase in K.

6.9 The value of the threshold velocity for a rotor of a given K decreases as the submerged weight is decreased.

6.10 The results indicate that low velocity measurements can be greatly improved by developing a rotor with a manageable combination of K and W_s, with emphasis on keeping W_s as small as possible.

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TABLE 1. Calibration Data

D = 7.62 cm	Plastic Rotor W_s = 0.54 newtons		Conventional Rotor W_s = 1.29 newtons	
Test Number	V cm/s	N rev/s	V rev/s	N rev/s
1 *	3.03	0.0039	4.040	0.0578
2	4.03	0.0452	5.04	0.0650
3	5.04	0.0600	6.06	0.0847
4	6.05	0.0734	7.04	0.0973
5	7.08	0.0873	8.05	0.1122
6	8.05	0.1004	10.07	0.1426
7	10.15	0.1309	12.07	0.1722
8	12.16	0.1563	15.08	0.2222
9	15.07	0.2048	18.09	0.2630
10	18.09	0.2423	20.13	0.2940
11	20.11	0.2723	25.03	0.3636
12	25.02	0.3397	30.11	0.4473
13	30.16	0.4175	35.12	0.5197
14	35.14	0.4846	40.12	0.5898
15	40.08	0.5485	45.07	0.6642
16	45.02	0.5249	50.15	0.7464
17	50.12	0.6999	55.10	0.8117
18	55.06	0.7691	60.03	0.8875
19	60.04	0.8313	70.05	1.0325
20	70.35	0.9786	80.44	1.1772
21	80.71	1.1175	91.00	1.3307
22	90.86	1.2529	100.19	1.4728
23	100.76	1.3876	120.32	1.7712
24	120.88	1.6644	150.32	2.109
25	150.86	2.0790	180.53	2.6617
26	181.08	2.4981	210.35	3.1124
27	210 98	2.9155	250.59	3.7092
28	250.98	3.4164		

* Threshold velocity

TABLE 2. Weight in Air and Water for Metallic and Plastic Rotors

Rotor	Weight in Air Newtons	Weight in Water Newtons
Metallic	1.47	1.29
Plastic	2.06	0.54

TABLE 3. **Values of N/V**

D = 7.62 cm	Plastic Rotor W_s = 0.54 newtons			Conventional Rotor W_s = 1.29 newtons		
Test Number	V cm/s	N rev/s	N/V rev/m	V cm/s	N rev/s	N/V rev/m
1 *	3.03	0.0039	1.119	4.04	0.0518	1.282
2	4.03	0.0452	1.122	5.04	0.0650	1.290
3	5.04	0.0600	1.190	6.06	0.0847	1.398
4	6.05	0.0734	1.213	7.04	0.0973	1.382
5	7.08	0.0873	1.233	8.05	0.1122	1.394
6	8.05	0.1004	1.247	10.07	0.1426	1.416
7	10.15	0.1309	1.290	12.07	0.1722	1.427
8	12.16	0.1563	1.285	15.08	0.2222	1.473
9	15.07	0.2048	1.359	18.09	0.2630	1.454
10	18.09	0.2423	1.339	20.13	0.2940	1.461
11	20.11	0.2723	1.354	25.03	0.3636	1.453
12	25.02	0.3397	1.358	30.11	0.4473	1.486
13	30.16	0.4175	1.384	35.12	0.5197	1.480
14	35.14	0.4846	1.379	40.12	0.5898	1.470
15	40.08	0.5485	1.369	45.07	0.6642	1.474
16	45.02	0.6249	1.388	50.15	0.7464	1.488
17	50.12	0.6999	1.396	55.10	0.8117	1.473
18	55.06	0.7691	1.397	60.03	0.8875	1.478
19	60.04	0.8313	1.385	70.05	1.0325	1.474
20	70.35	0.9786	1.391	80.44	1.1772	1.463
21	80.71	1.1175	1.385	91.00	1.3307	1.462
22	90.86	1.2529	1.379	100.19	1.4728	1.470
23	100.76	1.3876	1.377	120.32	1.7712	1.472
24	120.88	1.6644	1.377	150.32	2.211	1.471
25	150.86	2.0790	1.378	180.53	2.6617	1.474
26	181.08	2.4981	1.380	210.35	3.1124	1.480
27	210 98	2.9155	1.382	250.59	3.7092	1.480
28	250.98	3.4164	1.379			

* Threshold velocity

TABLE 4. Difference Response of Conventional and Plastic Rotors

V cm/s	N_c/V rev/m	N_p/V rev/m	$\frac{N_p - N_c}{N_c}$ %
5	1.310	1.190	-9.1
10	1.412	1.275	-8.7
15	1.440	1.325	-8.0
20	1.455	1.350	-7.2
25	1.467	1.367	-6.8
30	1.470	1.375	-6.4
35	1.470	1.378	-6.1

TABLE 5. Dimensionless Variables from Data

D = 7.62 cm	Conventional Rotor W_s = 1.29 newtons		Plastic Rotor W_s = 0.54 newtons	
Test Number	$\frac{N_c D}{V}$	$\frac{\rho D^2 V^2}{WS}$	$\frac{N_p D}{V}$	$\frac{\rho D^2 V^2}{WS}$
1	0.1090	0.00735	0.0852	0.00967
2	0.0983	0.0114	0.0855	0.0175
3	0.1065	0.0165	0.0907	0.0273
4	0.1053	0.0223	0.0925	0.0394
5	0.1062	0.0292	0.0940	0.0539
6	0.1079	0.0456	0.0950	0.0697
7	0.1087	0.0656	0.0983	0.1108
8	0.1123	0.1024	0.0979	0.1590
9	0.1108	0.1473	0.1036	0.2442
10	0.1113	0.1824	0.1021	0.3519
11	0.1107	0.2820	0.1032	0.4349
12	0.1132	0.4081	0.1035	0.6731
13	0.1128	0.5552	0.1055	0.9781
14	0.1120	0.7245	0.1051	1.3278
15	0.1123	0.9143	0.1043	1.7274
16	0.1134	1.1320	0.0888	2.1794
17	0.1123	1.3665	0.1064	2.7012
18	0.1127	1.6220	0.1064	3.2599
19	0.1123	2.2086	0.1055	3.8762
20	0.1115	2.9124	0.1060	5.3218
21	0.1114	3.7272	0.1055	7.0046
22	0.1120	4.5181	0.1051	8.8772
23	0.1122	6.5161	0.1049	10.917
24	0.1069	10.171	0.1049	15.712
25	0.1123	14.669	0.1050	24.472
26	0.1127	19.916	0.1051	35.269
27	0.1128	28.264	0.1053	47.864
28	-	-	0.1051	67.734

* Threshold velocity

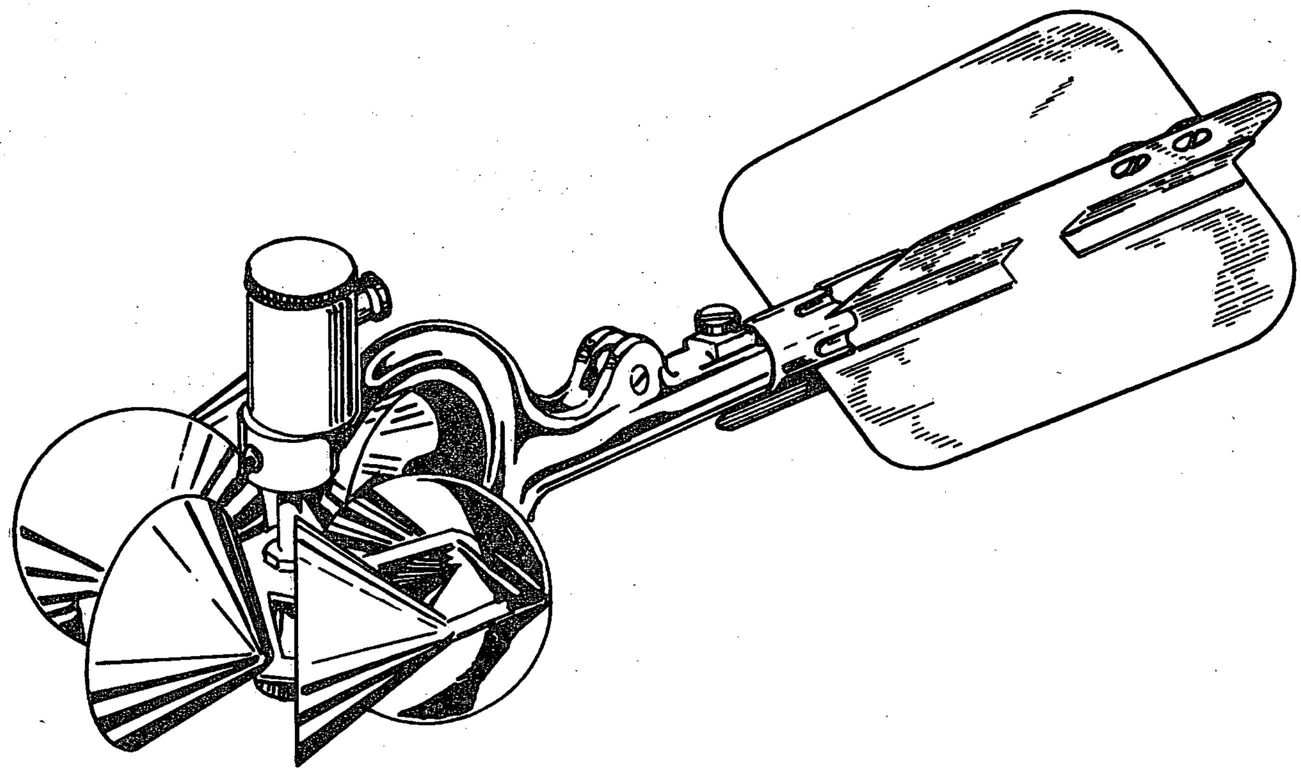

FIGURE 1. PRICE METER WITH CONVENTIONAL ROTOR

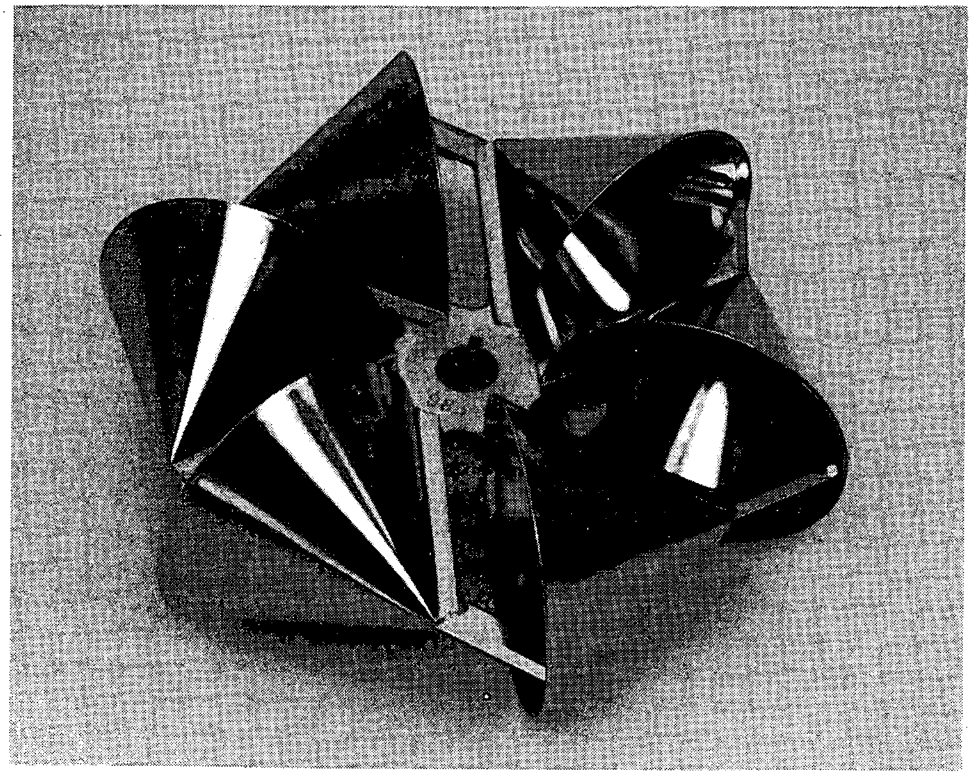

FIGURE 2a. CONVENTIONAL ROTOR

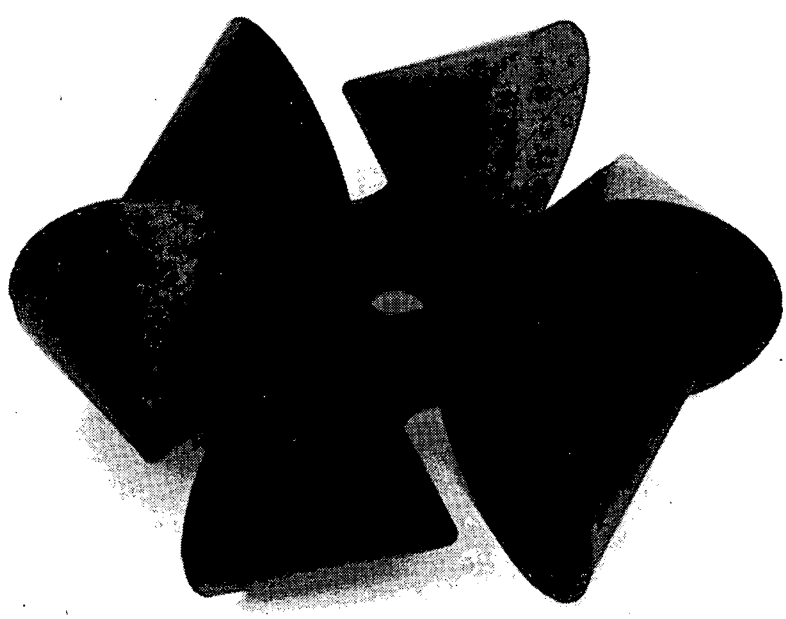

FIGURE 2b. PLASTIC ROTOR

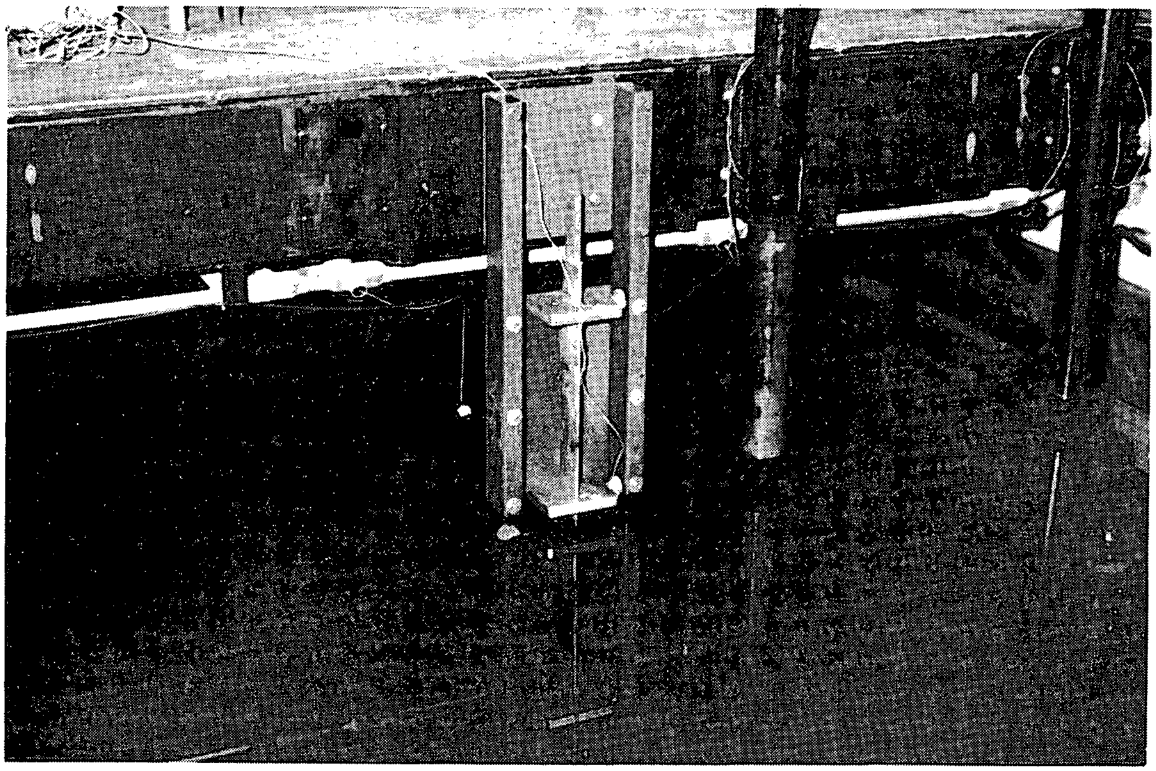

FIGURE 3. METER SUSPENSION POST AT REAR OF TOWING CARRIAGE

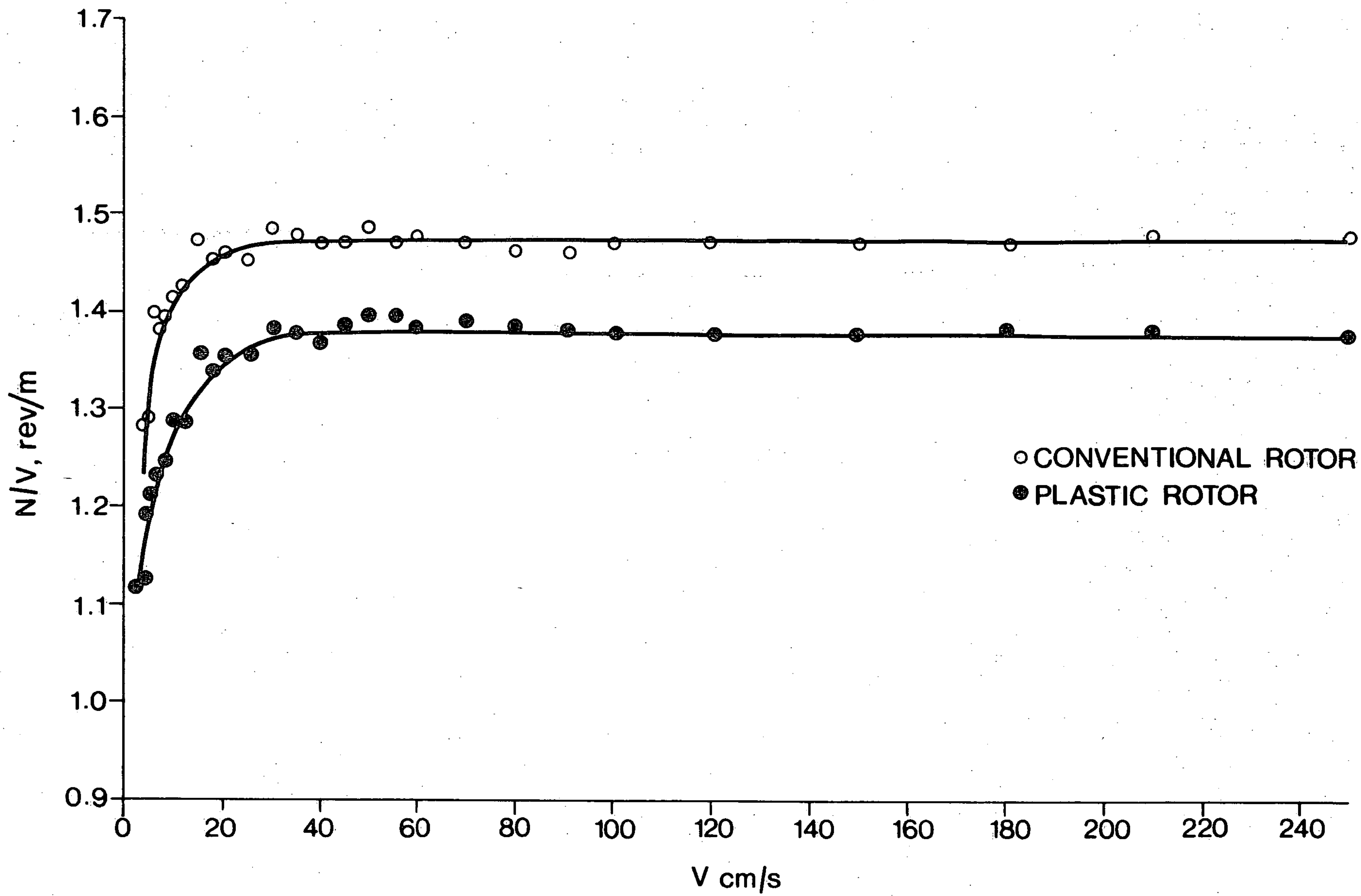

FIGURE 4. RESPONSE OF CONVENTIONAL AND PLASTIC ROTORS.

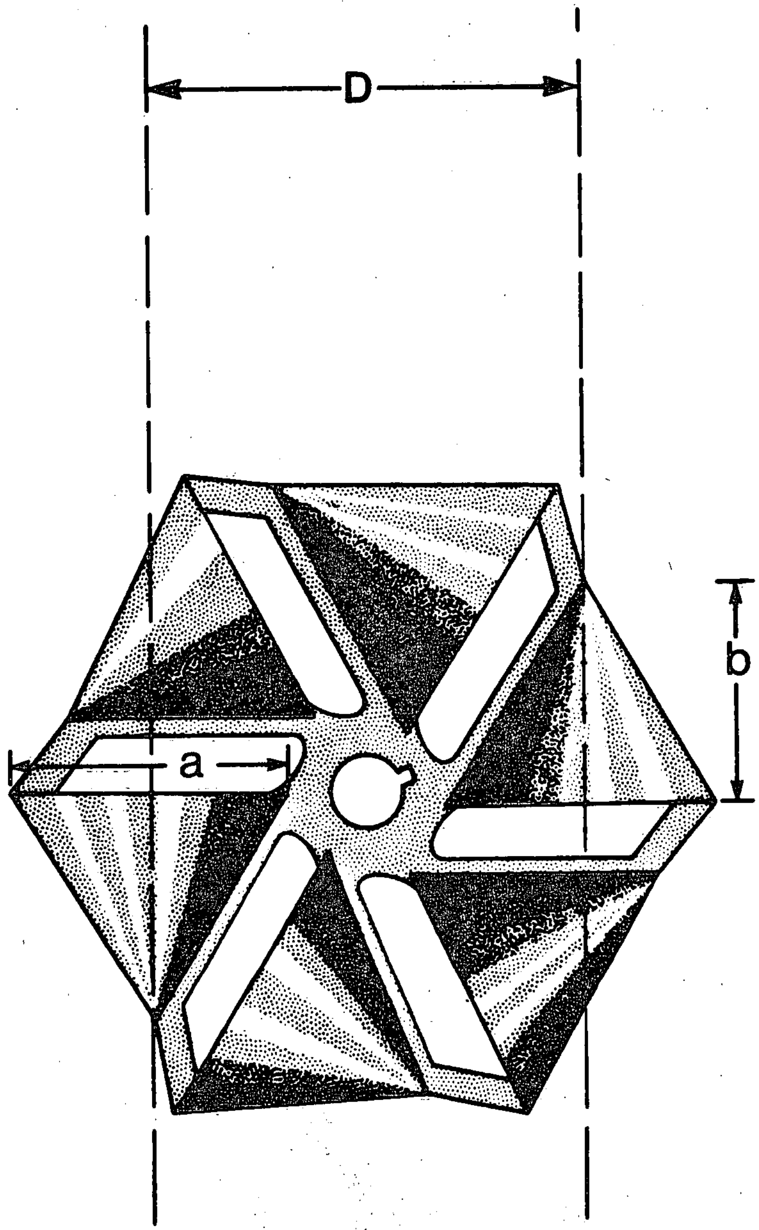

FIGURE 5. DEFINITION OF ROTOR DIAMETER D AND CRITIAL DIMENSIONS a AND b OF CONICAL ROTOR ELEMENTS

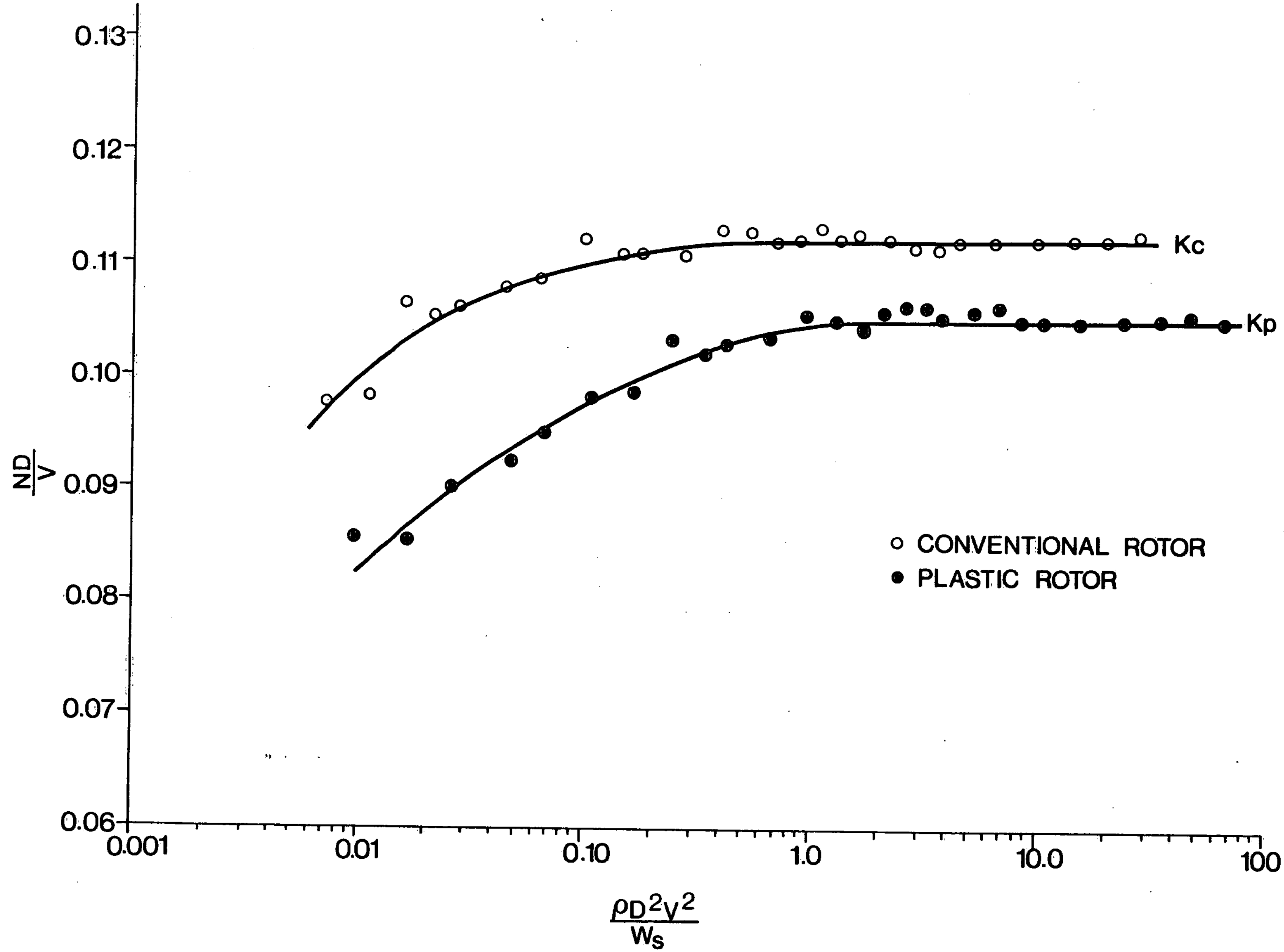

FIGURE 6. DIMENSIONLESS RESPONSE CURVES

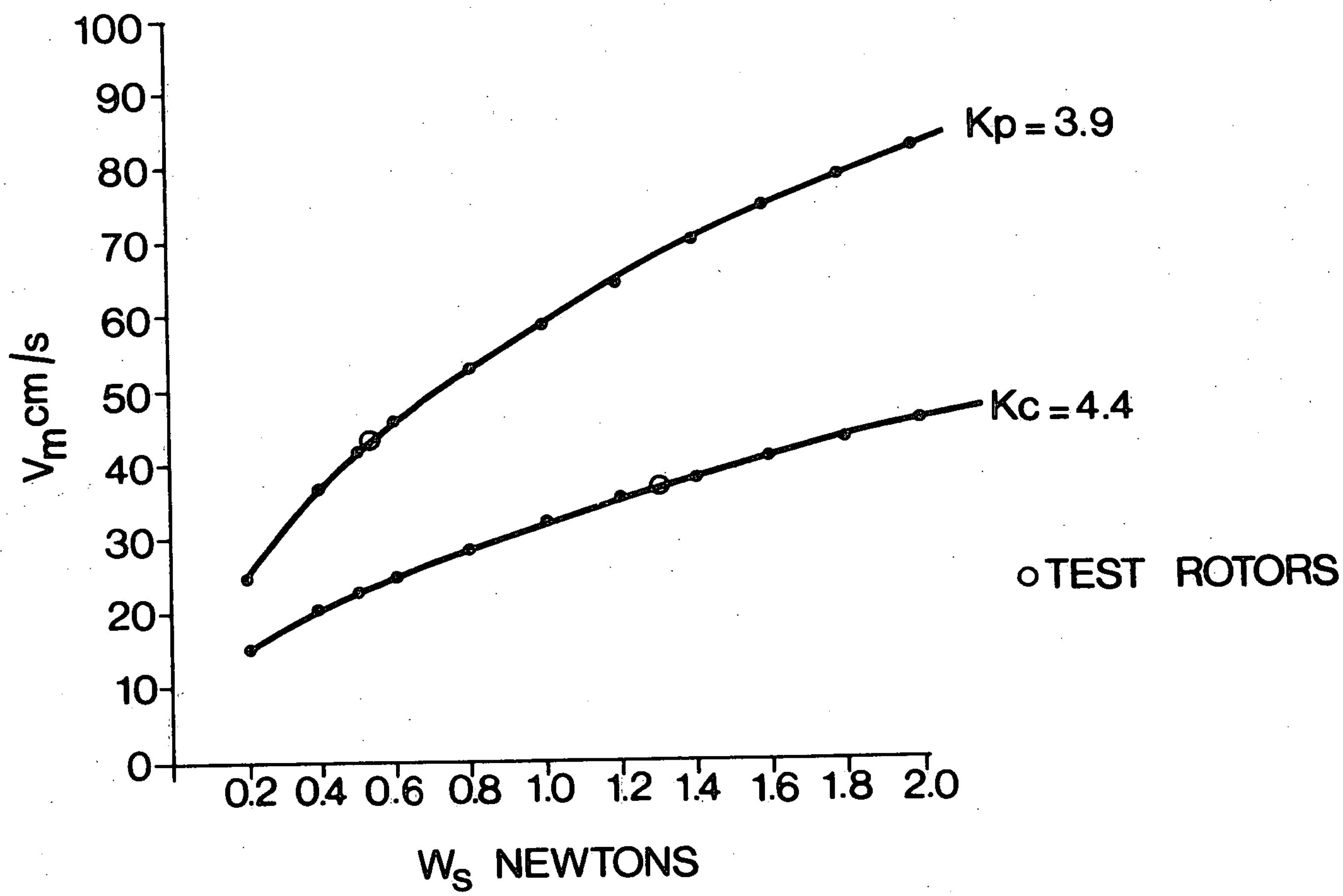

FIGURE 7. VELOCITY ABOVE WHICH EFFECT OF W_S IS INSIGNIFICANT

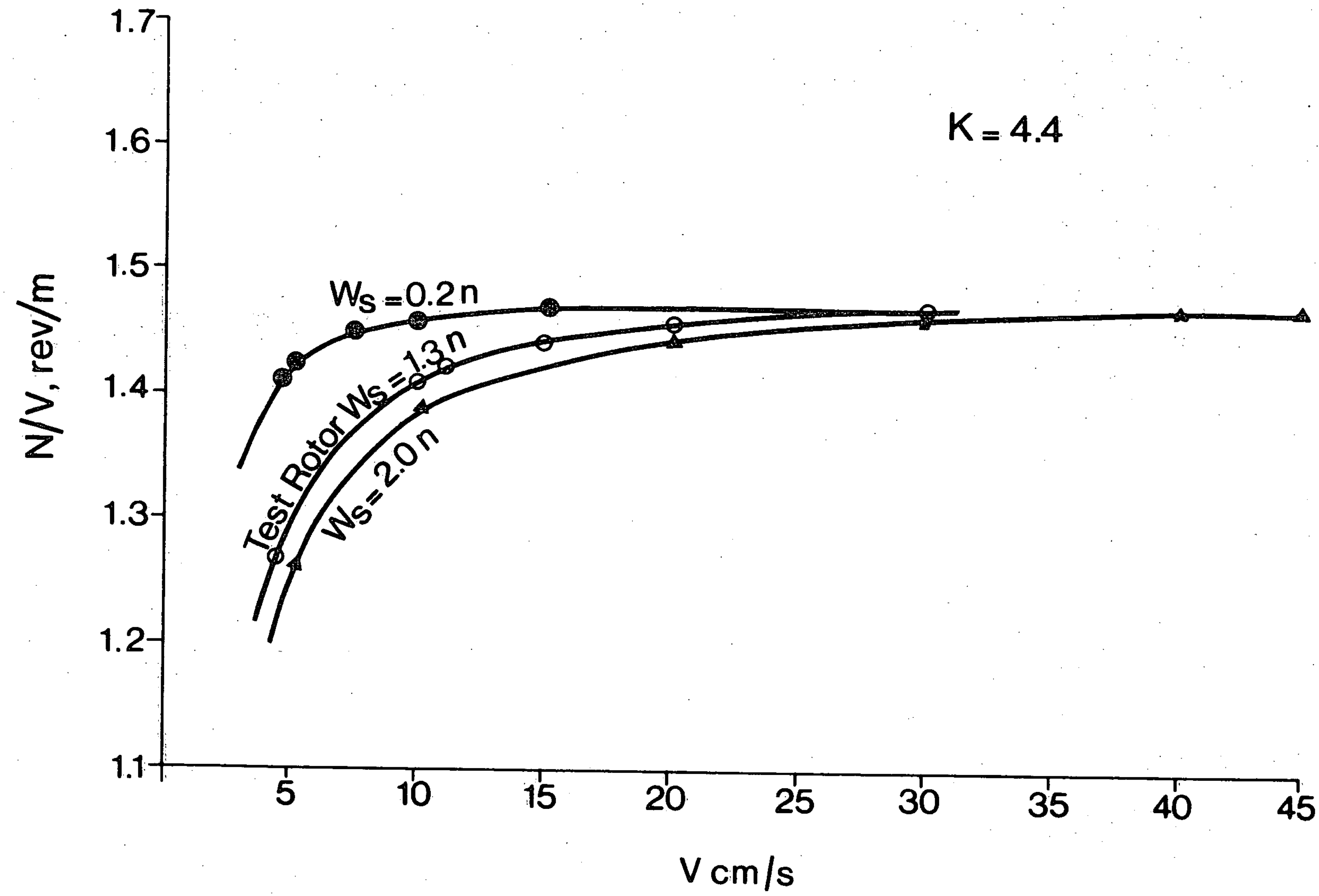

FIGURE 8a. EFFECT OF CHANGING W_s ON RESPONSE OF CONVENTIONAL PRICE METER ROTOR

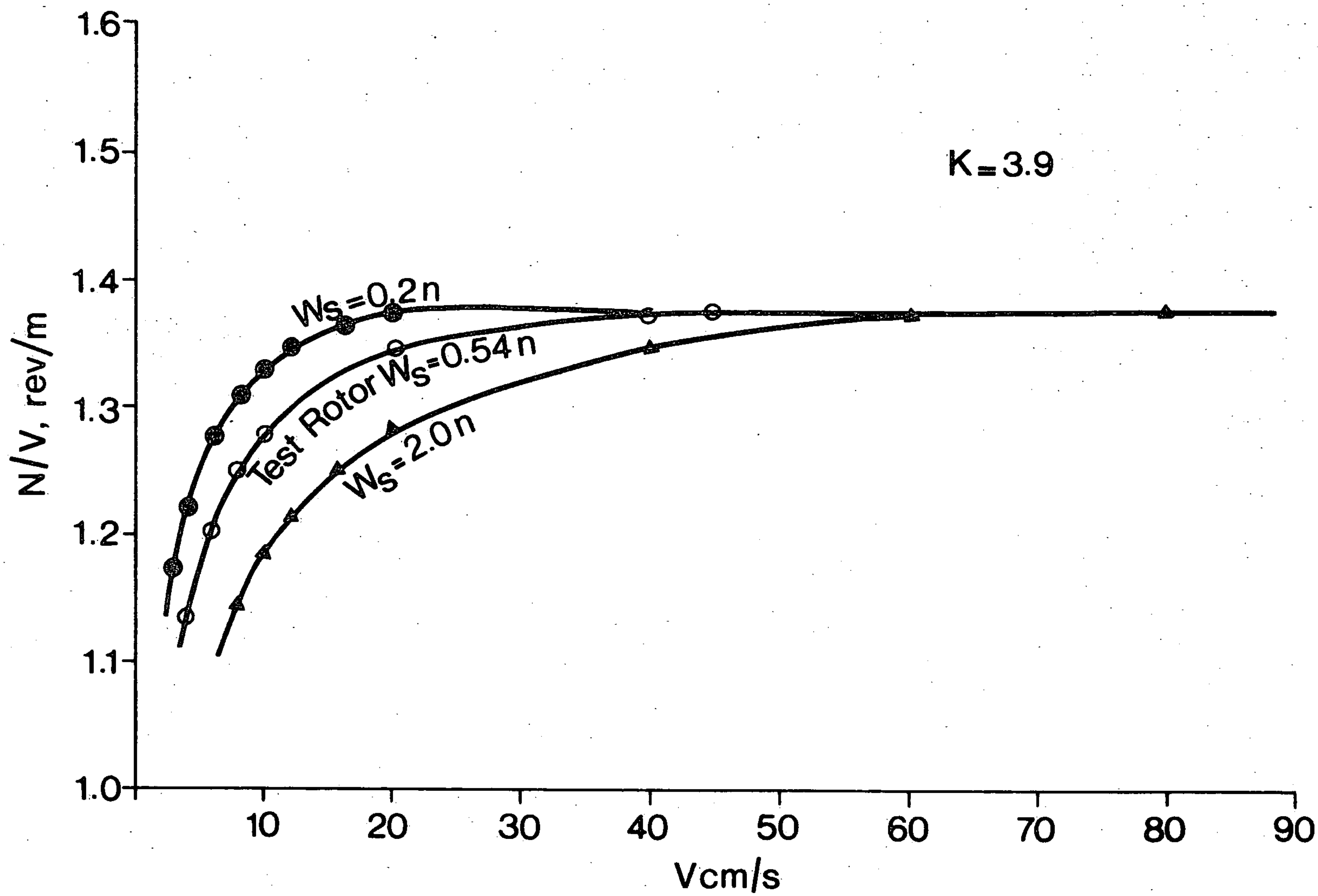

FIGURE 8b. EFFECT OF CHANGING Ws ON RESPONSE OF PLASTIC PRICE METER ROTOR

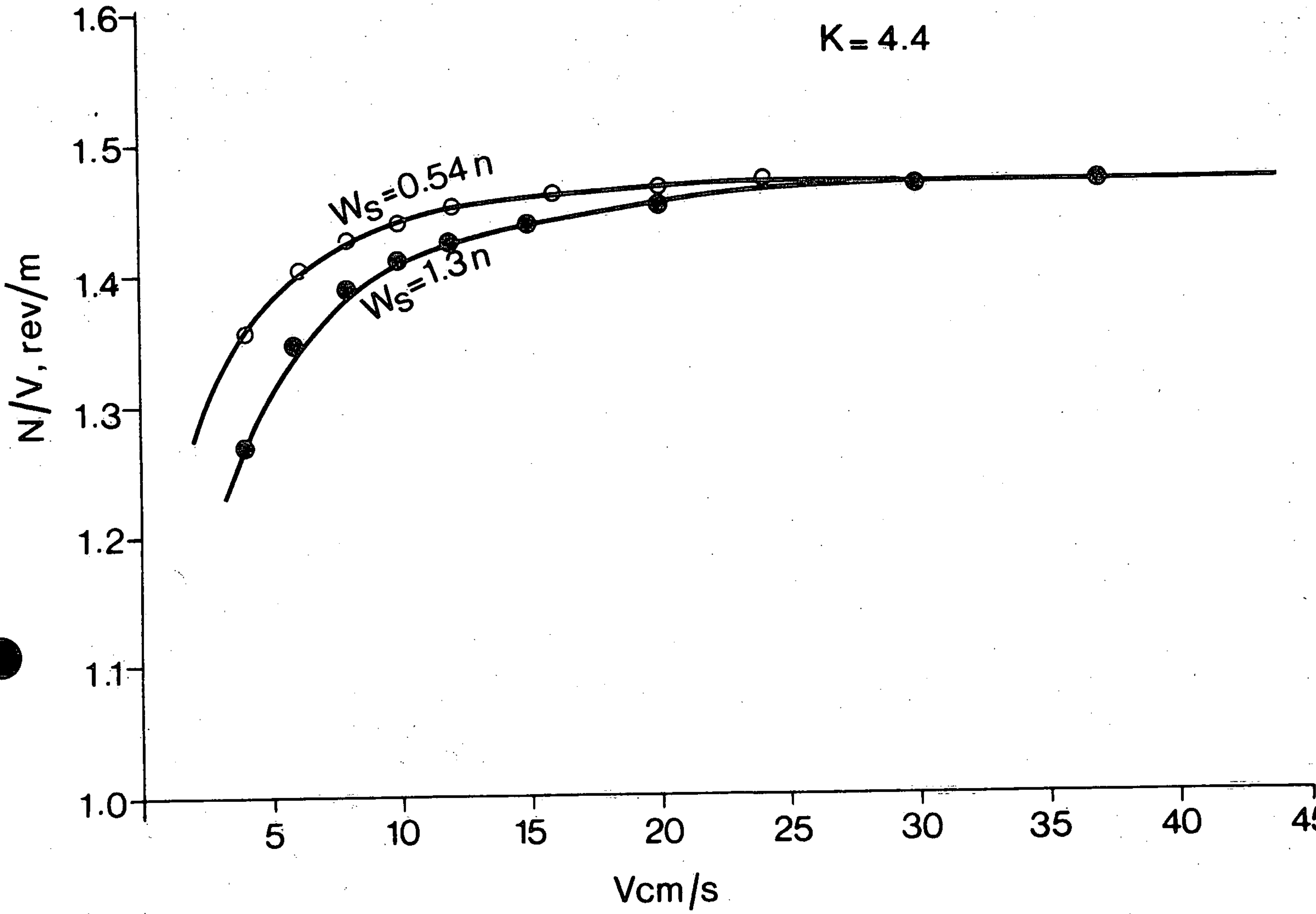

FIGURE 9. EFFECT OF REDUCING W_S OF CONVENTIONAL ROTOR TO W_S OF PLASTIC ROTOR.

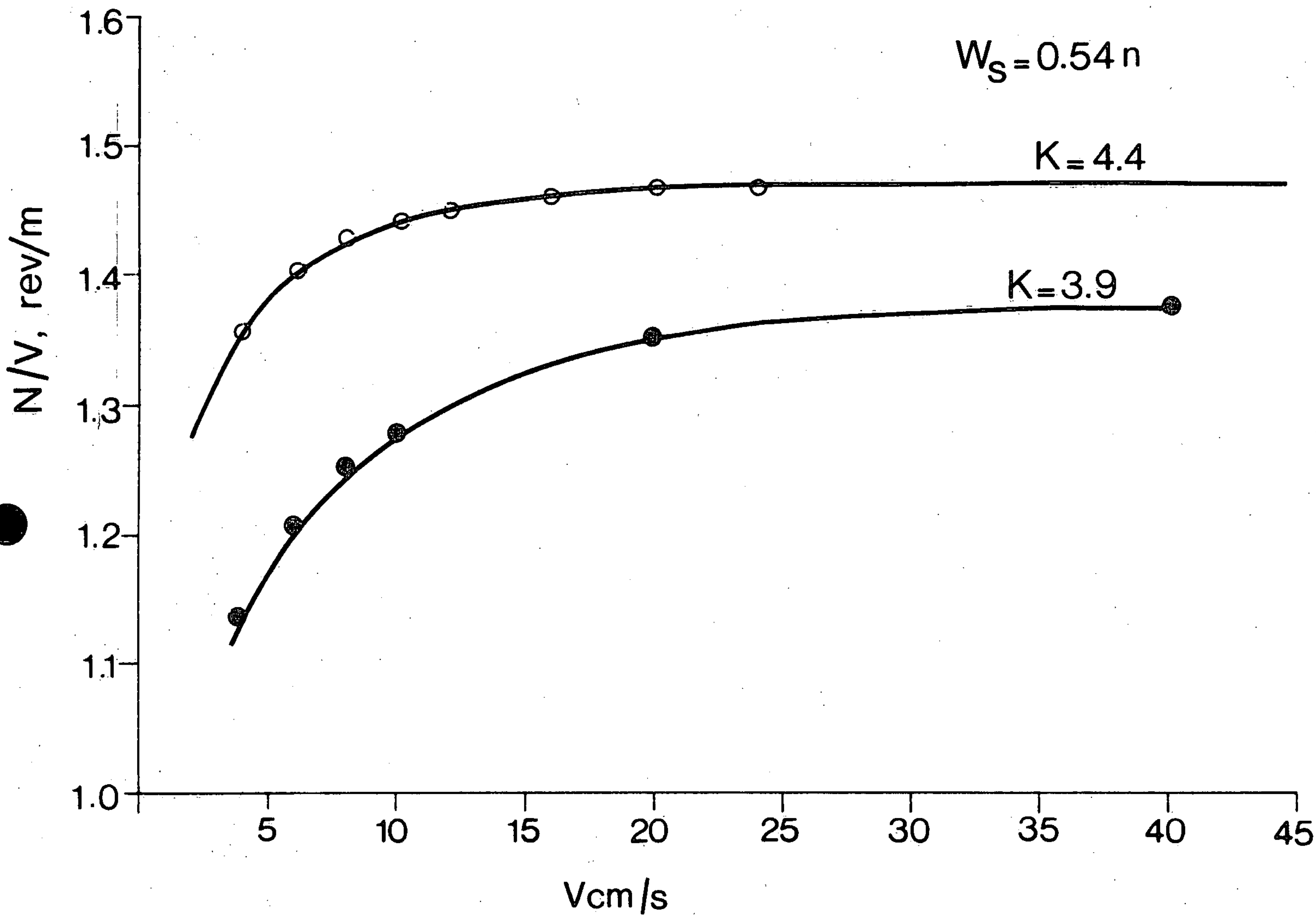

FIGURE 10. THE EFFECT OF K WHEN W_S OF CONVENTIONAL ROTOR HAS BEEN REDUCED TO W_S OF PLASTIC ROTOR.

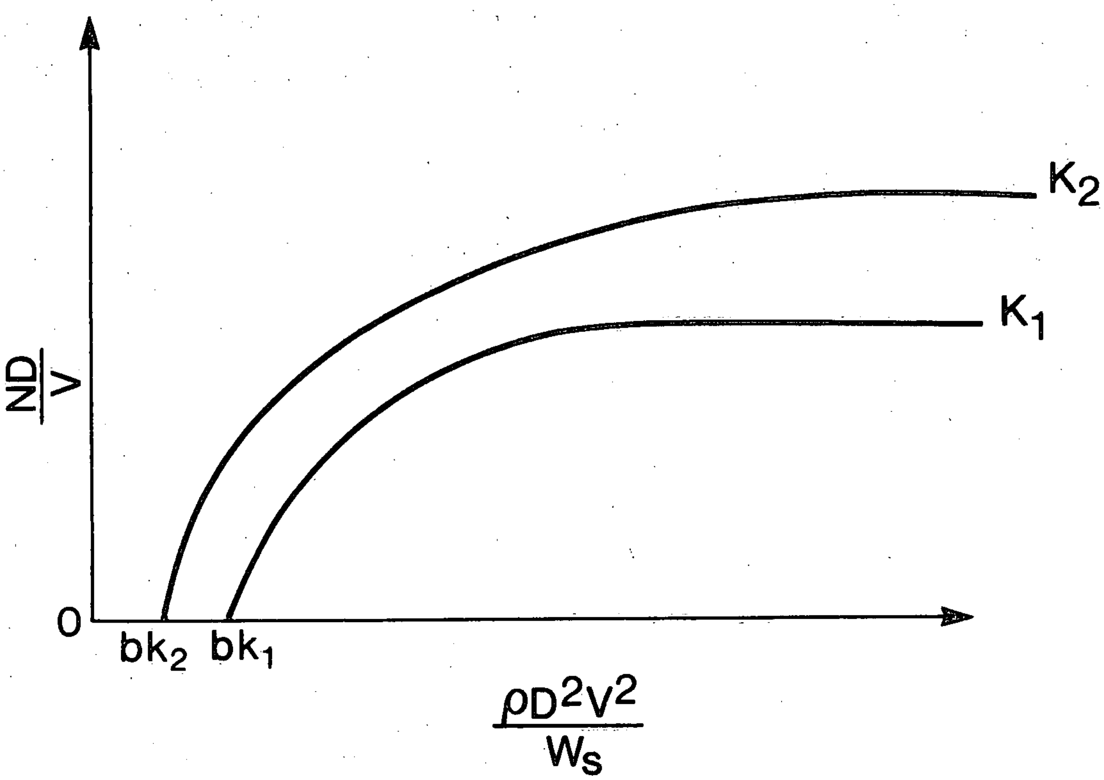

FIGURE 11. SCHEMATIC DEFINITION OF THRESHOLD VELOCITY.