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QUADRANT-EDGE ORIFICE-MODIFICATION FOR BETTER PERFORMANCE

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This paper presents the results of an experimental investigation to extend the upper limit of Reynolds number for the constant discharge coefficient of a quadrant-edge orifice meter. The performance characteristics of this type of meter in the high turbulent zone is explained for the first time. The results show that the upper constancy limit of this meter with $\beta = 0.500$ can be increased from $R_D = 200{,}000$ to $450{,}000$ by cutting off the downstream tip of the quadrant edge by about 10 degrees. Some more methods are also suggested for possible similar extension of the constancy limit.

Nomenclature

β : ratio of diameter of orifice to the diameter of the pipe;
c : coefficient of discharge;
C_D : drag coefficient of a cylinder in a infinite fluid;
$C_{D(\text{plate})}$: drag coefficient of a quadrant-edge orifice plate;
r : radius of the quadrant edge;
d : diameter of throat;
R_D : pipe Reynolds number;
C_c : coefficient of contraction;
C_v : coefficient of velocity.

Introduction

The quadrant-edge orifice meter has been retained for an International Standardisation by the International Standards Association since 1939. Investigations are being carried out in many countries based on the results of Koennecke (1) [1], and his recommended values are shown in Table 1.

Table 1

β	$\frac{r}{d}$	c	Upper constancy limit of Reynolds number
0.225	0.10	0.769	56,000
0.400	0.11	0.782	140,000
0.500	0.135	0.804	240,000
0.600	0.208	0.842	250,000
0.625	0.285	0.859	250,000

Table 2 furnishes the results of other investigators regarding the upper constancy limits for $\beta = 0.5$.

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(1) Numbers in parenthesis refer to similarly numbered references in bibliography at end of paper.

Table 2 (2)

INVESTIGATOR	β	$\frac{r}{d}$	c	R_D MAX. (upper constancy limit)	REFERENCE
Koennecke:					
— (actual). . .	0.50	0.135	0.804	240,000	[1]
— (adjusted).	0.50	0.135	0.803	230,000	[1]
Ferroglio.	0.510	0,14	0.813	150,000	[2]
Jaumotte and Van Dijck. . .	0.50	0.136	0.792	152,000	[3]
Brand.	0.50	0.135	0.802	230,000	[4]
Ramamoorthy and Seetharamaiah	0.480 0.483	0.135 0.138	0.824 0.808	200,000 200,000	[5] Unpublished data of authors

The upper constancy limit is mainly guided by the steep upward trend in the discharge coefficient curve. This paper offers an explanation for this steep upward trend and based on this rational explanation, some methods are suggested to delay this upward trend to occur at a higher Reynolds number and thus extend the upper constancy limit. One of such methods is undertaken for an experimental verification and the results show that the theoretical explanation has been proved to be appropriate and rational.

SPECIFICATIONS OF THE QUADRANT-EDGE ORIFICE.

Plates used:

PLATE No.	β	$\frac{r}{d}$	MANOMETER TAPPING
3-1	0.4834	0.1376	D-D/2
3-2	0.4873	0.1360	D-D/2

A sketch of a quadrant-edge orifice meter is shown in figure 1.

Experimental set up:

A detailed description of the set-up has already been reported by the authors in reference [6].

Discharge coefficient curve:

Figure 2 shows a typical discharge coefficient curve of a quadrant-edge orifice meter of $\beta = 0.5$. The characteristic shape of the discharge coefficient curve is due to the fact that the quadrant edge behaves just the same way as that of a cylinder kept in an infinite fluid medium. It has been demonstrated by the authors [7] that the drag coefficient of a quadrant-edge orifice, $C_{D(\text{plate})}$, can be related to the drag coefficient of a cylinder, C_D, in an infinite fluid medium by the following relationship :

$$C_{D(\text{plate})} = \frac{(1+\beta^2)}{C^2} - 2\beta^2 \qquad (1)$$

ANALYSIS OF THE HIGHLY TURBULENT ZONE ($R_D > 100{,}000$).

This zone is characterised by the steep upward curve after the constancy region and a break off at the end of the rising curve. This phenomenon of the rapid increase in the discharge coefficient is explained in the following paragraphs.

There are two evidences to show that there is a contraction of the jet issuing out of the throat of the quadrant edge or in other words that C_c is less than unity.

1. In the constancy region, though the overall losses of the quadrant-edge orifice for various β ratios are just the same as that of an *A.S.M.E.* Flow Nozzle [6] the discharge coefficient of the former varies from 0.77 to 0.885 for β ratios of 0.225 to 0.630 respectively, while the discharge coefficient of the latter is of the order of 0.97 and above. This indicates that, though the values of C_v are the same for both the meters, the value of c for the quadrant-edge orifice is far less than that of an *A.S.M.E.* Flow Nozzle. Since $C = C_c \times C_v$, it can be concluded that the value of C_c for a quadrant-edge orifice is less than that for a nozzle C_c of which is very nearly unity.

2. Figure 3 shows the typical flow around a circular cylinder kept in an infinite fluid medium. This figure has been reproduced from reference [8]. This figure indicates that when the laminar boundary layer becomes turbulent, the separation point moves from upstream of the diametral axis perpendicular to the direction of the flow to the downstream of the axis, with the increase in Reynolds number. By this the portion of the wake reduces in size and consequently there is a reduction in the drag coefficient. This is why the value of the drag coefficient suddenly falls down when the Reynolds number is of the order of 200,000 and the lowest value of C_D is attained at about $R_D = 500{,}000$, when the boundary layer becomes completely turbulent. It has been already established by the authors [7] that a quadrant-edge orifice especially with $\beta = 0.500$ exactly behaves as a cylinder in an infinite fluid medium. This indicates that the contraction of the jet which existed when the pipe Reynolds number is of the order of 200,000 is eliminated as the Reynolds number is increased further.

It is clear now that the steep rise in discharge curve is only due to the elimination of the contraction or in other words, due to the increase in the value of C_c with the increase in Reynolds number after the constancy region. The value of C_v has already been shown to be constant at these values of Reynolds numbers and also independent of the latter [6].

Elimination of the rise in discharge curve:

From the discharge curve of a quadrant-edge orifice with $\beta = 0.500$ it is seen the constancy

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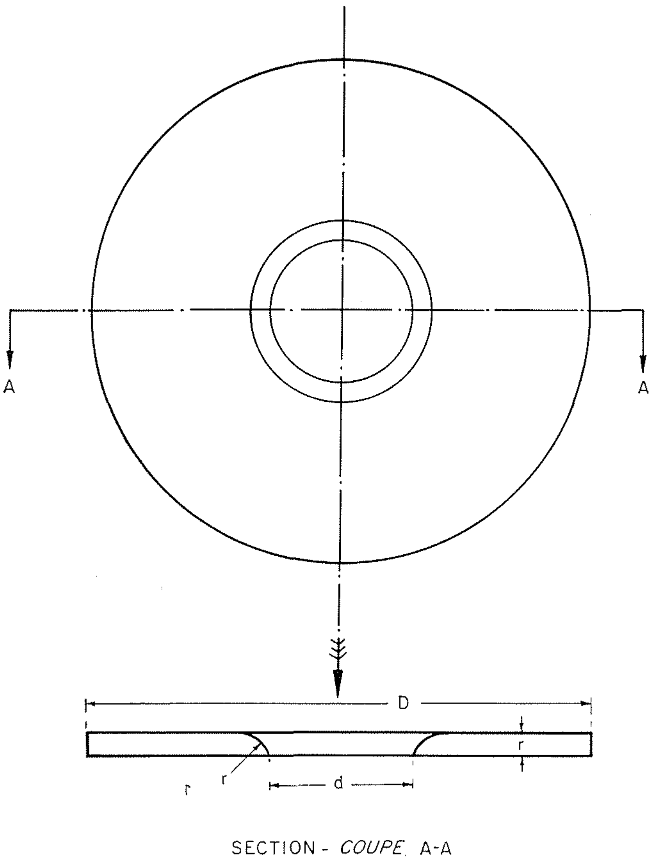
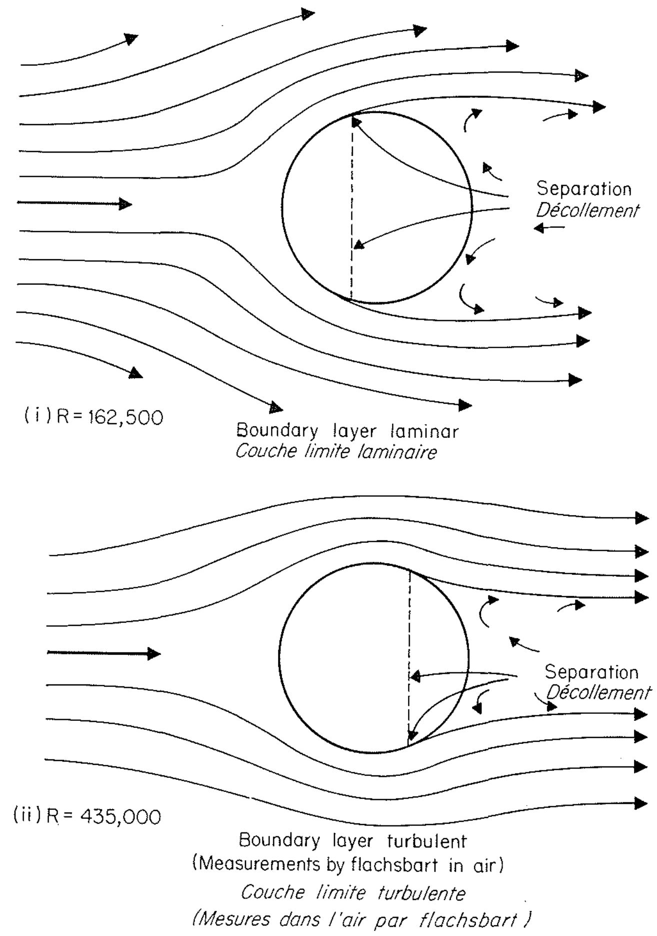
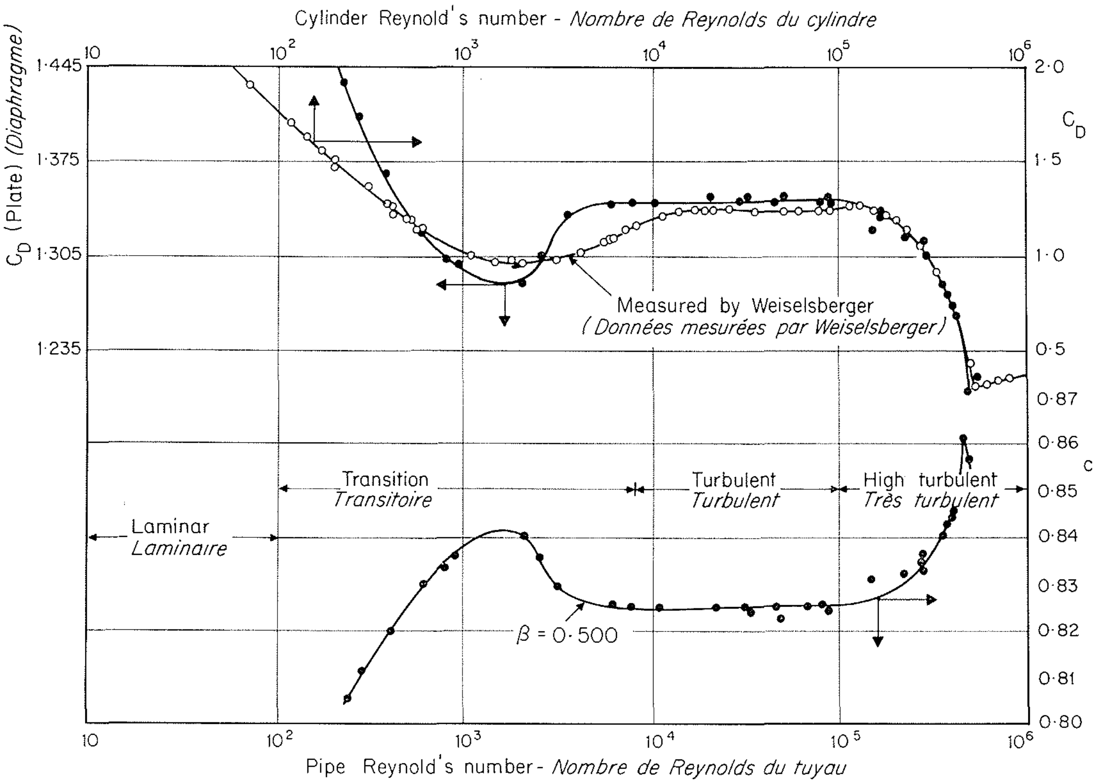
(2) Only the results of those investigators whose equipment did not pose any limitations to reach this limit are listed.



1/ A quadrant-edge orifice plate.
Diaphragme en quart de cercle.



3/ Flow around a circular cylinder.
Ecoulement autour d'un cylindre circulaire.



C, C_D, $C_{D(\text{plate})}$ curves **/2/** *Courbes de C, C_D, $C_{D(\text{diaphragme})}$.*

region extends upto $R_D = 200{,}000^{\pm}$ and the peak point occurs at $R_D = 500{,}000^{\pm}$. This means that the contraction of the jet which remains unaltered till R_D reaches a value of $200{,}000^{\pm}$, gets completely stabilised at $R_D = 500{,}000^{\pm}$. If we visualise the contraction of the jet gradually fading away with the separation point moving downstream as in Figure 4, it is possible to suggest some methods of eliminating such a change in the jet and thereby making the value of C_c unaltered, even after R_D reaches a value of 200,000.

The methods suggested are:

1. Cut off the downstream tip of the quadrant edge to the point where the separation point existed at $R_D < 200{,}000$ and thereby providing no surface for the separation point to move downstream any further, along the curved edge. Since this position is not known exactly, trial and error method has to be adopted to find this position exactly. The modification upto this position will not alter the discharge curve in the constancy region, as long as the flow is turbulent.

2. Make the surface of the edge as smooth as possible and hence delay the point of separation as far downstream and closer to the outlet tip as possible. This will enable to delay the rise in discharge coefficient curve to a higher Reynolds number and thus extend the constancy limit. This may pose a problem as to how to standardise the smoothness of the surface.

3. The existence of the laminar boundary layer itself could be destroyed by creating turbulence using a mesh just upstream of the plate and making the boundary layer remain turbulent even before $R_D = 200{,}000$. This may however increase the discharge coefficient even at constancy region, since the contraction of the jet is completely avoided except for a thin turbulent boundary layer. But the disadvantage of this method would be with regard to the standardisation since this method involves the difficult maintenance and control of the similarity of turbulence.

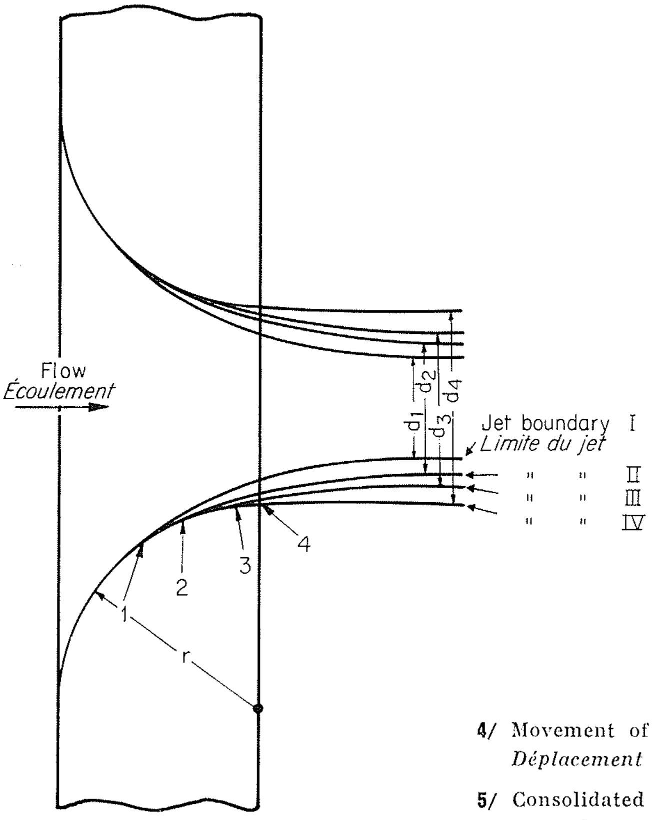
4. By the boundary layer suction with extraneous means to make the separated jet stick to the boundary. This method can only serve for a theoretical interest and by no means adoptable in practice.

The first of the four methods has been successfully tried and has been reported here.

EXPERIMENTAL DATA ANALYSIS.

Since the position of the separation point cannot be exactly located by any theoretical analysis at present, a trial and error method has been adopted. Referring to Figure 4 if the portion of the orifice plate beyond the point 3 is cut off, the movement of the separation point will be stopped upto the point 3, since there is no surface provided for further movement. This means that diameter of the jet cannot increase any further beyond d_3 and the peak of the discharge coefficient curve will be lowered to that extent. Since the stabilisation of the jet boundary is complete only at $R_D = 500{,}000$, the peak point even when lowered has to be at this Reynolds number only. This will try to flatten out the discharge coefficient curve. By trial and error the optimum amount of cutting off the downstream tip required to obtain the flattest curve may be found.

In the experiments conducted two types of cuts were made as shown in the inset block diagrams



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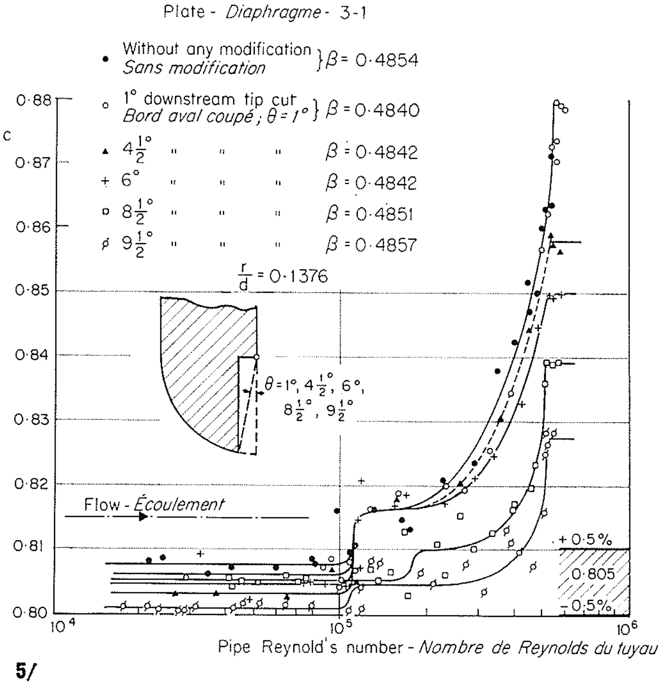

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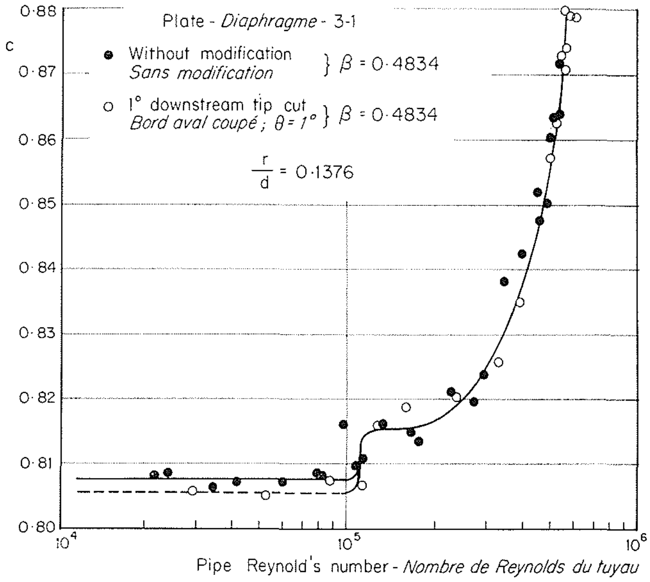
4/ Movement of separation point and the increase of jet diameter.
Déplacement du point de décollement et augmentation du diamètre du jet.

5/ Consolidated test results.
Ensemble des résultats d'essais.



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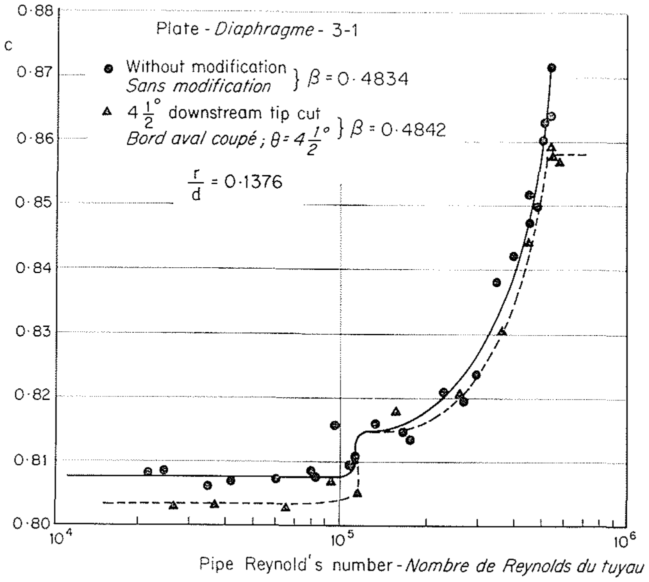

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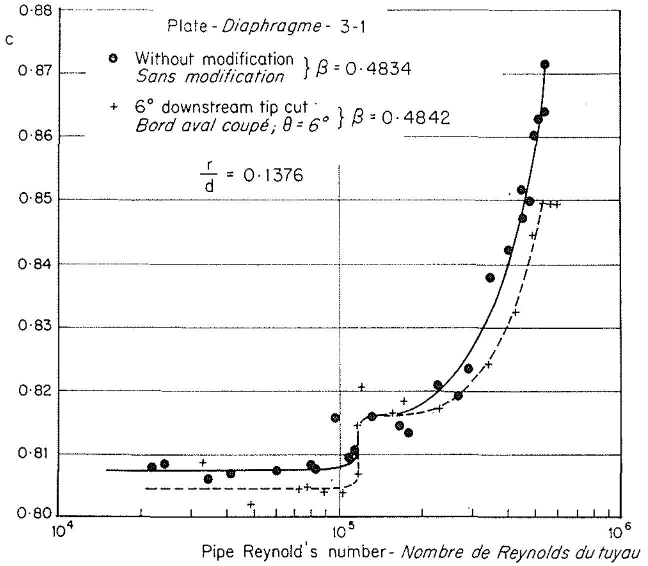
of Figure 11. In plate 3-1 straight cuts were made so that θ is made equal to 1°, 4½°, 6°, 8½° and 9½°. After each cut the calibration tests were made. Care was taken to note the change in the diameter of the throat after each cut and hence in the value of β ratio and the corresponding new value of β was used in the computations of the values of C. In Figure 5 the consolidated results are shown. It can be noticed that the peak point gets lowered consistently at $R_D = 500{,}000$ and with 9½° cut, the constancy limit is extended upto $R_D = 450{,}000$ allowing a ± 0.5 % tolerance.

In order to have a clearer picture of the change in performance with cutting off tips to various degrees, figures 6, 7, 8, 9 and 10 are furnished. In order to check for the reproducibility, another plate (plate 3-2) with a 10° inclined cut was made and tested. The results of tests on both the plates (3-1) and (3-2) are shown in Figure 11. It can be seen that the results are amazingly consistent.

As predicted by the theory, the cuts made at the downstream tip do not affect the discharge coefficient in the constancy region beyond the allowable



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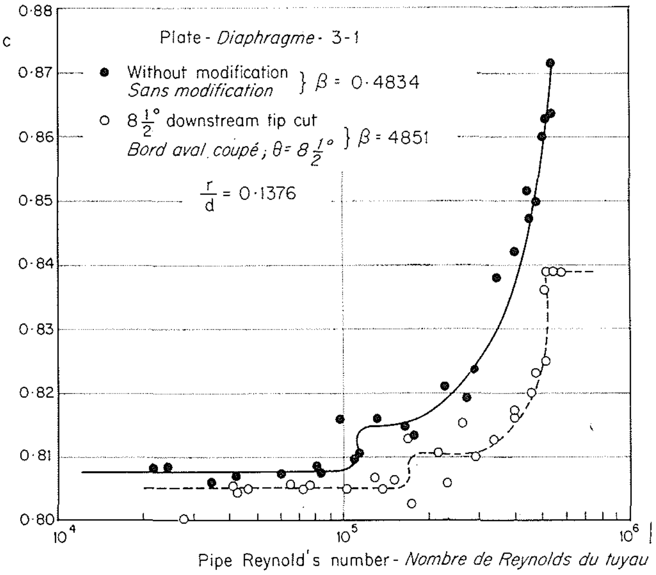

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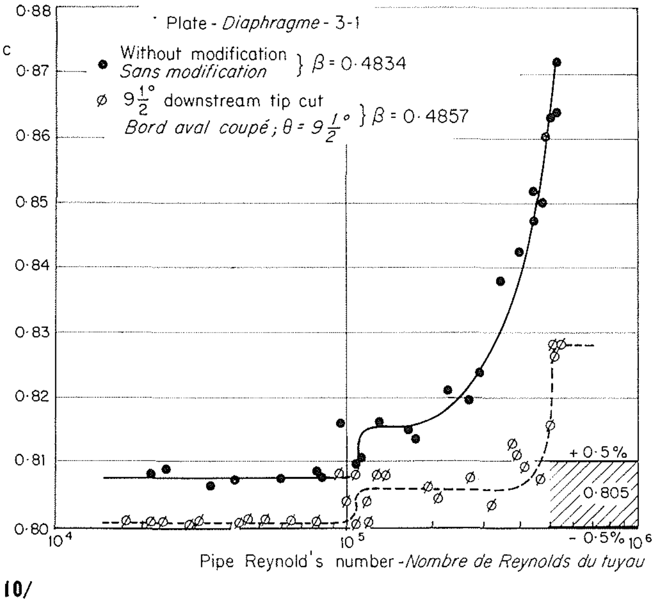

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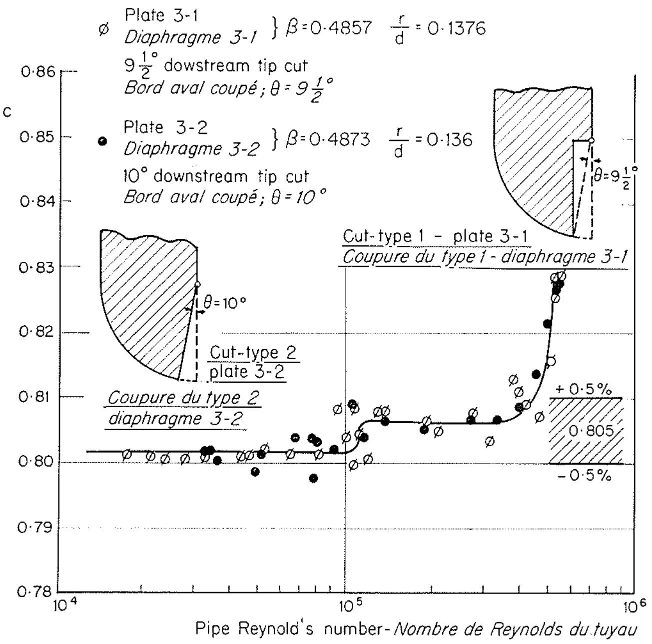
6/ to 10/ Effect of downstream tip cut.
Effet de la coupure du bord aval.



11/ Comparison of test results on plates 3-1 and 3-2.
Comparaison des résultats obtenus avec les diaphragmes 3-1 et 3-2.

tolerance of ± 0.5 %. It remains to be seen the effect of this modification when the whole flow is laminar.

Scope for further work:

Experiments are being conducted for checking the validity of the other three methods suggested herein and the results will be reported soon.

The optimum amount of 10° cut may be peculiar to the case of $\beta = 0.500$. The optimum values for other β ratios are still to be found out.

Experiments are necessary to study the effect of cutting off tips when the whole flow is laminar.

Conclusions

1. A rational theory has been suggested for the steep rise in the discharge curve of a quadrant-edge orifice at very high Reynolds numbers.

2. Four methods have been suggested for increasing the upper constancy limit.

3. Results of tests conducted on two plates $\beta \simeq 0.500$ show consistently that a downstream cut of $9\frac{1}{2}$° to 10° extends the constancy limit from $R_D = 200{,}000$ to 450,000.

4. Scope for further work on the extension of the constancy limit has been suggested.

Acknowledgements

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Résumé

Diaphragme à bord amont profilé en quart de cercle Modification lui assurant un meilleur fonctionnement

par M. V. Ramamoorthy * et K. Seetharamaiah **

Le diaphragme débitmètre à bord amont profilé en quart de cercle a été retenu pour une Normalisation Internationale par la International Standards Organisation dès 1939. Les limites supérieures de la constance des coefficients de débit, préconisées par Koennecke [1], sont indiquées au tableau 1. Le tableau 2 présente les résultats obtenus par d'autres chercheurs, en ce qui concerne les limites supérieures de cette constance, pour $\beta = 0{,}5$. Le présent article propose une explication de la montée raide de la courbe des coefficients de débit à partir de la région constante, ainsi que certaines méthodes pouvant permettre d'étendre cette zone de constance jusqu'à un nombre de Reynolds plus élevé.

La figure 1 représente le schéma d'un diaphragme à bord amont profilé en quart de cercle. La figure 2 montre une courbe type des coefficients de débit correspondant à un tel diaphragme-débitmètre, pour lequel $\beta = 0{,}50$. Dans une étude antérieure [1], les auteurs avaient démontré la possibilité de relier le coefficient de traînée d'un tel diaphragme, $C_{D(pl)}$ à celui d'un cylindre C_D, maintenu dans un milieu fluide infini, par la relation :

$$C_{D(pl)} = \frac{(1 + \beta^2)}{C^2} - 2\,\beta^2 \qquad (1)$$

D'après cette équation (1), la montée raide de la courbe des coefficients de débit correspondrait à la brusque chute des valeurs du coefficient C_D, correspondant à un cylindre. On sait que cette chute soudaine est due à la fois à la transition de la couche limite au régime turbulent, et au déplacement ainsi provoqué du point de séparation de l'amont vers l'aval, et enfin à une réduction des dimensions du sillage. La figure 3 représente l'écoulement type autour d'un cylindre, dans un milieu fluide infini.

La figure 4 montre un phénomène semblable, à l'intérieur du diaphragme à bord amont profilé en quart de cercle. On voit, d'après cette figure, que lorsque la couche limite passe du régime laminaire au régime turbulent, le diamètre du jet augmente, ainsi que la valeur de C_C. Il a déjà été démontré que la valeur de C_V reste constante, pour ces valeurs du nombre de Reynolds, et qu'elle reste également indépendante de ce nombre [6]. Puisque $C = C_C \times C_V$. la valeur de C croît en fonction de la transition.

Il est possible d'éviter cette brusque augmentation de la valeur de C, et ainsi d'agrandir le domaine de constance, à l'aide des quatre méthodes suivantes :

1. Si nous coupons le bord aval du diaphragme jusqu'à l'endroit où existait le point de décollement correspondant à $R_D < 200\,000$, de sorte que nous enlevons la surface qui aurait permis à ce point de décollement de se déplacer plus vers l'aval, nous pouvons empêcher la croissance du diamètre du jet. Il s'agit ici d'un procédé à tâtonnements, puisque nous ne connaissons pas la position exacte de ce point de décollement. Nous avons recoupé les bords du diaphragme n° 3-1 à 1°, 4 1/2°, 6°, 8 1/2° et 9 1/2°; l'extension de la limite de constance ainsi obtenue est montrée sur la figure 5. Les figures 6, 7, 8, 9, et 10 montrent plus nettement l'élimination progressive de la courbe raide et montante.

Dans le but de vérifier la reproductibilité de ces résultats, nous avons recoupé le bord d'un diaphragme n° 3-2 (semblable au n° 3-1) en fonction d'angles différant de ceux du cas précédent, et allant jusqu'à 10°. La figure 11 montre la comparaison des résultats obtenus, et ceux correspondant au diaphragme n° 3-1.

Une caractéristique intéressante de cette méthode est qu'elle ne modifie guère le coefficient de débit à l'intérieur de la zone de constance.

2. En rendant la surface du bord du diaphragme aussi lisse que possible, dans le but de retarder la transition de la couche limite vers un nombre de Reynolds plus élevé.

3. On pourrait détruire la couche-limite laminaire par la création de turbulence, à l'aide d'une toile métallique placée juste à l'amont du diaphragme. Ceci augmenterait éventuellement le coefficient de débit, même à l'intérieur de la zone de constance, étant donné l'élimination complète de la contraction du jet.

4. Par aspiration de la couche limite, à l'aide de dispositifs extérieurs, afin de « plaquer » le jet décollé contre la limite.

Ces différentes méthodes devraient permettre l'extension de la zone de constance jusqu'à $\mathcal{R} = 500\,000$.

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