Permanent Pressure Drop Measurements in Converging - Diverging Plain Annuli

By

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ABSTRACT :

This paper presents the results of a series of experiments on the measurements of pressure losses for turbulent water flow (Re > 10,000) in convergent divergent plain annuli.

Depending upon the convergence angle and the divergence angle four different annuli were studied .

From these experiments, generalized empirical correlations were deduced to describe pressure losses for turbulent water flow in the convergent portion, in the divergent portion and in the whole annuli. These correlations correlate the experimental data within ± 4%.

In general pressure losses for convergent-divergent plain annuli were found to be functions of both the convergence angle and the divergence angle. Two exceptions were noted from this general rule, when the divergence angle was greater than 10 degrees and the convergence angle was equal to or greater than 7.5 degrees, pressure loss over the whole annulus was function of the divergence angle only. The other expception was when the divergence angle was about 3.5 degrees, pressure loss over the divergent portion took a certain value irrespective the value of the convergence angle.

NOMENCLATURE:

K, K_1, K_2 Empirical loss coefficients

ΔP_T Permanent pressure loss over the whole annulus, gm_f / cm^2

ΔP_1 Permanent pressure loss over the converging portion of the annulus, gm_f/ cm^2

ΔP_2 Permanent pressure loss over the diverging portion of the annulus, gm_f / cm^2

U Velocity at the throat, cm/sec.

α_1 Half-apex angle of the forward inner wall cone (convergence angle), degrees.

α_2 Half-apex angle of the backward inner wall cone (divergence angle), degrees.

Introduction:

Because of its importance in heat exchangers, nuclear reactor design applications and efficient transport of materials, e.g. capsule transport in pipelines, the annulus geometry had been the subject of much attention both experimental and theoretical. [1,2,3,4,5,6,7]

Rothfus et. al. [8] defined inner and outer-wall friction factors for annuli and correlated friction-loss data over a Reynolds number range from 10,000 to 45,000.

Little investigation had been made on the mechanism of the flow of fluids in modified annuli, although considerable work had been done on the study of the pressure drop in such annuli. Knudsen and Katz [9] determined the friction factor .

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for water flowing in annuli containing a transverse-helical-fin tubes. Wankel [9] studied several kinds of modified annuli in which the inner tube had rings on its surface. His equations apply for Reynolds number up to 16,000. No general correlation can be obtained from this investigation.

In spite of the lot of data concerning annular spaces in the literature, there is no available data concerning flow through convergent-divergent annuli. Therefore, the object of the present study was to obtain experimantally the momentum transfer characteristics for turbulent water flow through convergent-divergent annuli.

The effect of streamlining both the convergent and divergent sections was studied through the use of four different annuli. The inner walls for these annuli are two base-to-base cones between them a cylinderical throat having a length equals to the clearance between the inner and outer walls at the throat.

Experimental equipment:

The experimental setup (Fig.1-a) consists of an 22 mm. internal diameter, 2000 mm. long, horizontal galvanized iron tube (test section). Along the test section there were 16 pressure taps situated at certain chosen positions to help in tracing the changes in pressure along each annulus. These holes were 1.5 mm. in diameter and were carefully deburred on the inside. The ends of the test section were provided with flexible end joints for easy interchange of the central rod carrying the bodies that forms the annuli with the tube wall.

The other equipment used comprised a constant head water feed tank, a centrifugal pump and a calibrated orifice-meter. There was a sufficient calming lengths to ensure accurate static pressure measurements. The output from the test section passed through a sufficient tube length to avoid back pressure effects, then recycled to the constant level supply tank used to prevent fluctuations in the pump output.

A manometric system made up of two inclined U-tube manometers and ten vertical U-tube manometers was used to accurately measure the pressure drop and flow rates of water using mercury (sp.gr. = 13.6) or carbon tetrachloride (sp.gr. = 1.593) as manometric liquids.

Bodies used to produce the annular spaces with the tube wall were machined from aluminum, in the shape of two base-to-base cones between them a cylinderical throat having a diameter of (0.78 d) as recommended by L.B.Evans and S.W. Churchill for minimum pressure loss [10] (Fig. 1-b). Each annulus is defined by the half-apex angles of the two cones of its inner wall, e.g., annulus (2.5/7.5) means that the half-apex angle of the forward inner wall cone (α_1) equals 2.5 degrees while the half-apex angle of the backward inner wall cone (α_2) equals 7.5 degrees. and so on. Four different annuli were studied, (2.5 / 2.5) annulus, (2.5 /7.5) annulus, (7.5/7.5) annulus, and (7.5/2.5) annulus.

Two different strings were made from each annulus with spacings of 30 and 50 cm between each two successive annuli. For each annuli string, the flow rate was varied and at every flow rate gauge pressures at certain specified positions were recorded.

Experimental results and discussion:

For each annulus of the four studied annuli, gauge pressures recorded were drawn as pressure profiles. A sample plot from such profiles is shown in Fig.2.

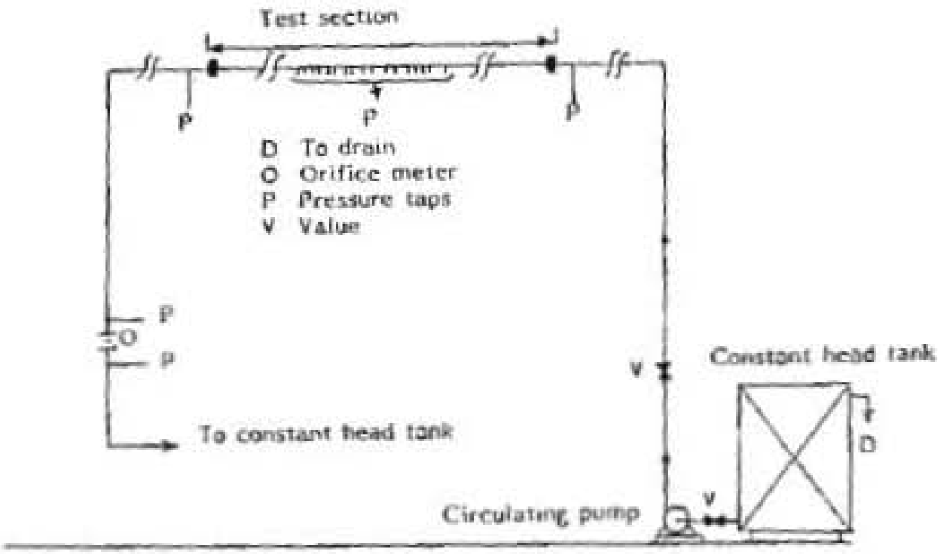

Fig. (1-a) Sketch of experimental apparatus.

Fig. (1-b) Photograph of bodies forming convergent-divergent annuli with the tube wall.

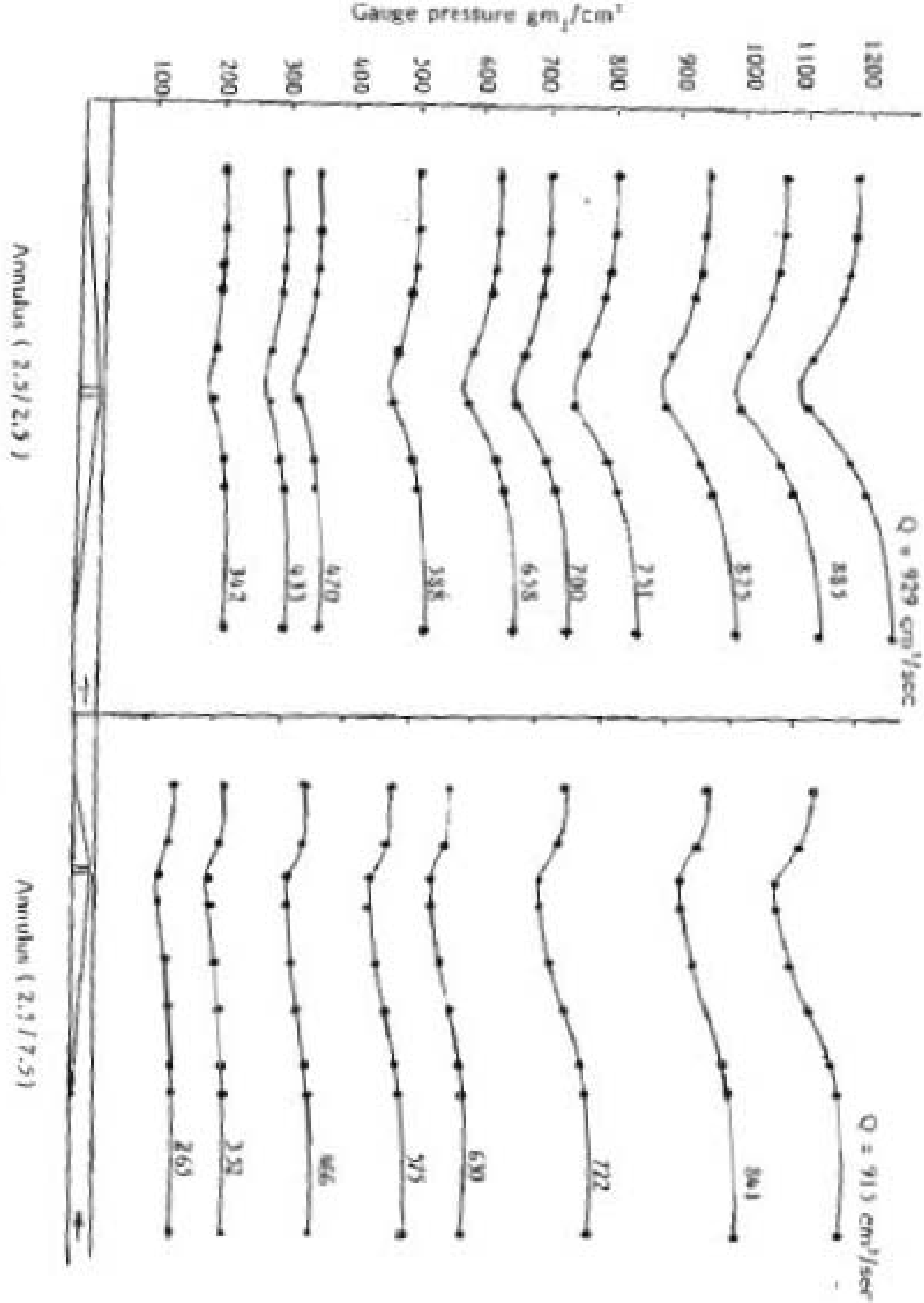

Fig. 2 Pressure profiles.

Total pressure loss over the whole annulus, ΔP_T, pressure loss over the forward section and throat (convergent portion), ΔP_1, and pressure loss over the backward section (divergent portion), ΔP_2, were deduced from these pressure profiles for each annulus at the different studied flow rates.

Values of (ΔP_T) were read directly from pressure profiles while (ΔP_1) values were calculated using Bernouilli's equation (by making a mechanical energy balance for flow along a streamline from the annulus inlet to the annulus throat). Differences between corresponding values of (ΔP_T) and (ΔP_1) gives values of (ΔP_2).

In the convergent portion pressure loss (ΔP_1) is due to friction losses. In the divergent portion flow velocity decreases and hence pressure increases. The energy of layers at the boundary here is so small that the increased pressure may stop the flow there or even reverse it. As a result, eddies form and the flow separates from the walls. So, pressure loss in this portion is expended on eddy formation (eddy losses), besides there exist ordinary friction losses.

Due to the fact that eddy losses are not amenable to analysis as skin-friction losses, particularly in the case of turbulent flow, pressure losses mentioned were treated in terms of empirical loss coefficients.

So, $\Delta P_T = \dot{K} \left(\frac{U^2}{2g_c} \right)$, $\Delta P_1 = \dot{K}_1 \left(\frac{U^2}{2g_c} \right)$ and $\Delta P_2 = \dot{K}_2 \left(\frac{U^2}{2g_c} \right)$

where, $\dot{K}$, $\dot{K}_1$ and $\dot{K}_2$ are empirical loss coefficients and U is the velocity at the throat (maximum velocity).

Point values of $\dot{K}$, $\dot{K}_1$ and $\dot{K}_2$ were calculated for each annulus then general empirical formule were deduced as,

$$\dot{K} = K \cdot Re^{-0.5}$$

$$\dot{K}_1 = K_1 \cdot Re^{-0.5}$$

and $$\dot{K}_2 = K_2 \cdot Re^{-0.5}$$

where $$K = 62 \left(1 + \frac{\alpha_1}{\alpha_2} \right) \alpha_1^{-0.274} + 56 \left(1 - \frac{\alpha_1}{\alpha_2} \right) \alpha_2^{-0.738}$$

$$K_1 = 72.9 \left(1 + \frac{\alpha_1}{\alpha_2} \right) \alpha_1^{-1.38} - 31.7 \left(1 - \frac{\alpha_1}{\alpha_2} \right) \alpha_2^{-3.1}$$

and $$K_2 = 23.6 \left(1 + \frac{\alpha_1}{\alpha_2} \right) \alpha_1^{0.115} + 94 \left(1 - \frac{\alpha_1}{\alpha_2} \right) \alpha_2^{-0.76}$$

These formule correlate the experimental data within $\pm$ 4 % for Reynolds number values (based on the annulus outside diameter) greater than 10,000.

Figure (3) shows the correspondence between experimental and empirical data for (ΔP_T).

Effect of the convergence angle (α_1) and the divergence angle (α_2) on ΔP_T, ΔP_1 and ΔP_2 :

Figures (4) to (6) show the effect of the convergence angle (α_1) and the divergence angle (α_2) on K, K_1 and K_2.

1- From Fig. 4, K_1 and hence (ΔP_1) increases as angle (α_1) decreases. For the convergence portion losses are due to friction, so when angle (α_1) decreases, the friction surface-hence ΔP_1-increases accordingly.

2- From Fig. 5, when angle α_2 is less than 3.5 degrees, K_2 and hence (ΔP_2) decreases with angle α_1 increase. At angle $\alpha_2 \simeq$ 3.5 degrees, K_2 appears to be independent upon the value of angle α_1. For values of angle α_2 greater than 3.5 degrees, K_2 increases with angle α_1 increase.

For the backward portion, losses are due to eddy formation and friction. When angle α_2 is less than 3.5 degrees, the backward inner portion is more streamlined hence a small wake is formed-if flow separation occurs. Increase in the value of angle α_1 gives the flow stream a great chance to follow the contour of the backward inner portion. This leads to a smaller wake and a decrease in the value of (ΔP_2) accordingly.

When angle α_2 has a value around 3.5 degrees, changes in the value of angle α_1 appears to have no effect on the size of the wake formed and hence on the value of (ΔP_2).

When angle α_2 is greater than 3.5 degrees, the backward inner portion is short and separation effects are more pronounced. The wake formed grows in size with angle α_1 increase. Angle α_1 increase makes the flow stream to follow a certain contour that exceeds the size of the backwark inner portion. So, the value of (ΔP_2) increases with angle α_1 increase.

3- From Fig. 6, K and hence (ΔP_T) decreases with angle α_1 increase. The resultant of the effect of angle α_1 increase on (ΔP_1) and (ΔP_2) lead to a decrease in the value of (ΔP_T).

For angle $\alpha_2 \geqslant 10$ degrees and angle $\alpha_1 \geqslant 7.5$ degrees, K or (ΔP_T) appears to be independent upon angle α_1. In this range the decrease in the value of (ΔP_1) due to angle α_1 increase (friction surface decrease), is compensated by a nearly equal increase in the value of (ΔP_2) (eddy losses increase).

4- From Fig. 4, K_1 and hence (ΔP_1) decreases with angle α_2 increase. As flow through the backward portion causes back pressure effects upon the forward portion. As angle α_2 increases these back pressure effects diminish and the flow finds a less resistance through the forward portion and hence (ΔP_1) decreases.

5- From Fig. 5, K_2 and hence (ΔP_2) increases as angle α_2 increases till a certain value of angle α_2 behind which (ΔP_2) decreases with angle α_2 increase. For (ΔP_2) eddy losses are controlling. As angle α_2 increases the backward portion becomes shorter, hence separation effects and eddy losses are more pronounced. At a certain value of angle α_2 that depends upon the value of angle α_1 the wake formed due to flow separation reaches a certain maximum size. With angle α_2 increase this wake decreases in size hence eddy losses and (ΔP_2) also decreases.

6- From Fig. 6, K and hence (ΔP_T) increases with angle α_2 increase (eddy losses are the controlling losses) till a certain value of angle α_2 -that depends upon the value of angle α_1 -then K and hence (ΔP_T) decreases with angle α_2 increase. As eddy losses are controlling, values of (ΔP_T) are determined by (ΔP_2) values and the effect of angle α_2 on (ΔP_T) is similar to its effect on (ΔP_2).

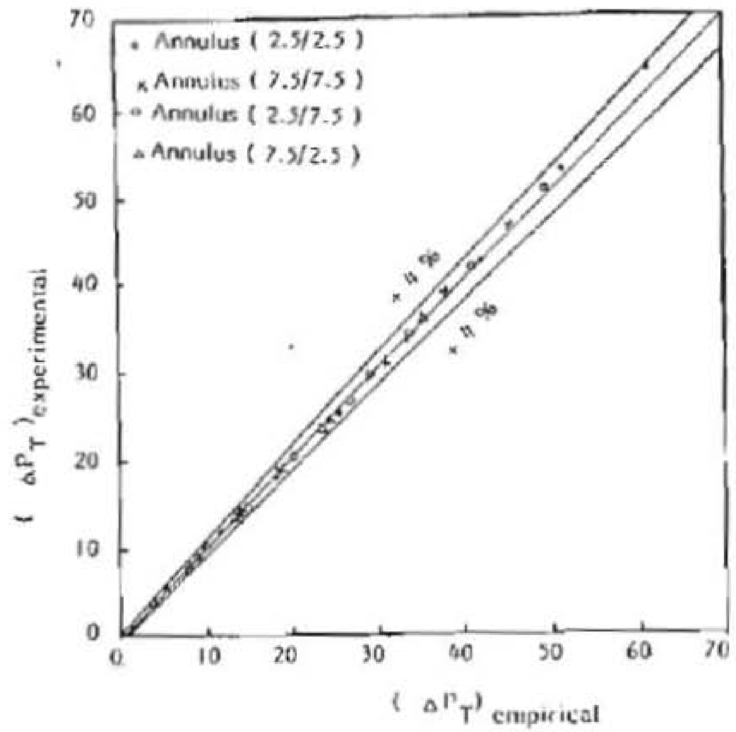

Fig. 3 Correspondence between experimental and empirical data for (ΔP_T).

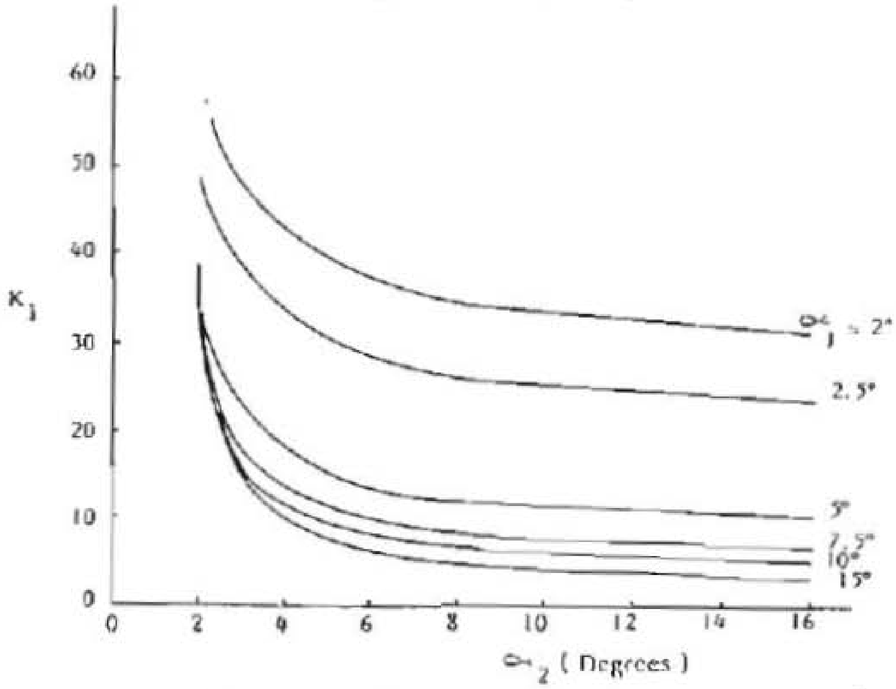

Fig. 4 Effect of angle of convergence and angle of divergence on the value of (K_1).

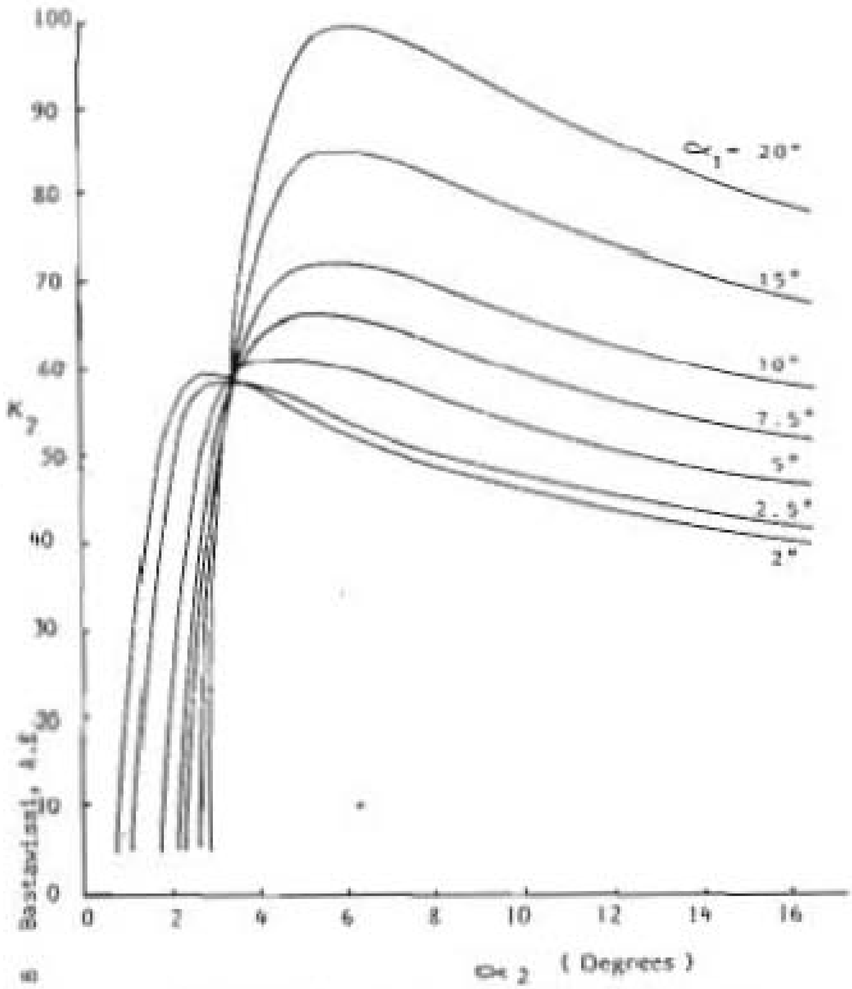

Fig. 5 Effect of angle of convergence and angle of divergence on the value of (K_2).

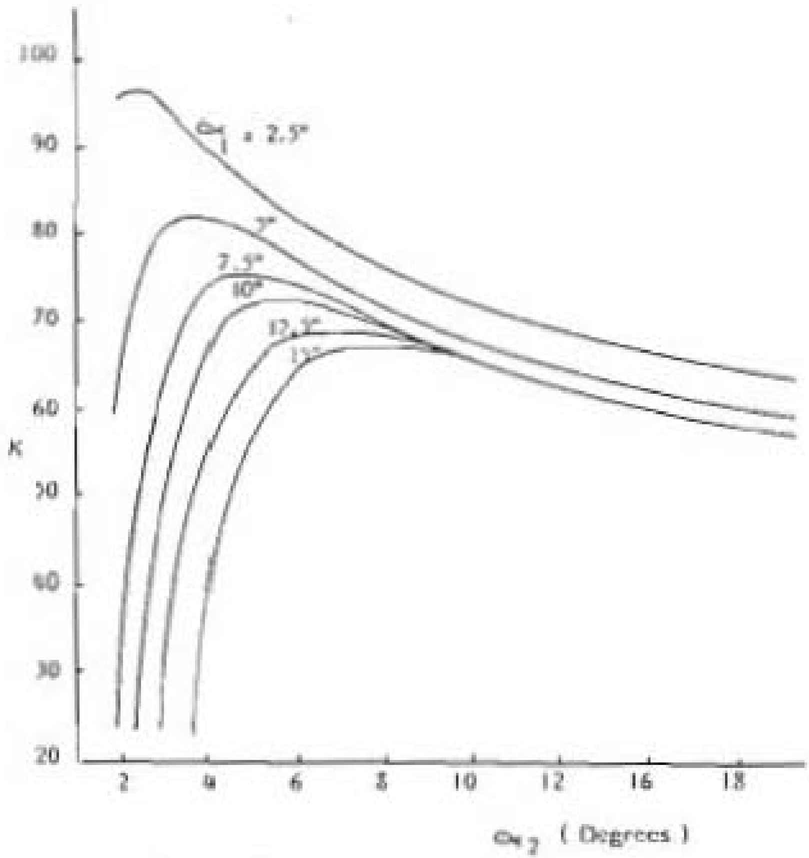

Fig. 6 Effect of angle of convergence and angle of divergence on the value of (K).

Conclusions

The main conclusions resulting from this study can be summarized in the following:

(1) Pressure losses for turbulent water flow (Re > 10,000) in convergent - divergent plain annuli can be treated in terms of empirical loss coefficients which are functions of flow rate beside convergence and divergence angles .

(2) Generalized empirical correlations are deduced to represent pressure losses for turbulent water flow in the convergent portion, in the divergent portion and in the whole annulus. They correlate the experimental data within ± 4%.

(3) When the divergence angle is greater than 10 degrees and the convergence angle is equal to or greater than 7.5 degrees, pressure loss over the whole annulus is function of the divergence angle only.

(4) When the divergence angle is about 3.5 degrees, pressure loss over the divergent portion takes a certain value irrespective the value of the convergence angle.

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