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An Experimental Investigation of Side-Orifice Effects on Pressure Drop for Single-Phase Flow

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ABSTRACT

To investigate the effects of the side-orifice on the pressure drop for single-phase flow, a series of experiments have been carried out with 16 different downstream test sections with various combinations of side-orifice shapes, different numbers of side-orifices, and different arrangements of the side-orifice using water as a working fluid. From the measurements of the pressure drop and the flow rate, the pressure loss coefficient of the side-orifice(s) has been evaluated. Based on the total number of 529 present data, an empirical correlation for the pressure loss coefficient has been developed in terms of Reynolds number and geometric parameters, such as area ratio, equivalent diameter, leading edge, and average width of side-orifice.

1. Introduction

Each fuel assembly of liquid metal reactor is wrapped with a thin stainless steel duct. Coolant flow rates through fuel assemblies are regulated by side-orifices at the inlet module of each assembly. The hydraulic resistance with lateral flow entrance such as side-orifices is much higher than that with straight entrance [1].

The pressure loss coefficient is generally known as a function of component geometry and Reynolds number Re but has been frequently considered as a constant if Re is sufficiently large, i.e., greater than 10^5 [2]. When an abnormal event such as primary sodium pump trip occurs in a liquid metal reactor, the primary coolant flow changes from the forced flow to the transition flow, and subsequently to buoyancy induced flow. Thus, the pressure loss coefficient of the side-orifice needs to be studied over a wide range of flow rates and be correlated with Re.

The main objective of the present work is to investigate the effects of the side-orifice(s) on the pressure drop for single-phase flow and to develop an empirical correlation for the pressure loss coefficient as a function of Re and geometric parameters (i.e., number of side-orifices, their array and shape). Water at atmospheric pressure and room temperature has been selected as simulant of sodium because hydraulic characteristic of water is similar to sodium. A series of experiments have been carried out for a wide range of Reynolds numbers, i.e., $Re = 2{,}000 \sim 50{,}000$.

2. Experiments

As shown in Fig. 1, the upstream and the downstream test sections of the present experimental facility simulate the lower plenum and the inlet module of assembly in a liquid metal reactor, respectively. The upstream test section is made of 20mm thick acryl cylinder (300mm ID and 800mm height) and the downstream test sections are made of 5 mm thick acryl pipes (80mm ID and 530mm height). These test sections have various shapes, numbers, and different arrangements of the side-orifices. Downstream test sections with three different shapes of the side-orifice (i.e., circle, rounded rectangle, and rectangle) are designed to investigate the geometric effect of the side-orifice on the pressure drop as shown in Fig. 2. To examine the effect of number of the side-orifices on the pressure drop, five different numbers (i.e., 1, 2, 3, 4 and 6) of the side-orifice are designed as shown in Figs. 3 and 4. Two different arrangements, regular and staggered array, are designed to examine the effect of arrangements on the pressure drop in the case of six circular and rounded rectangular side-orifices. Figures 3 and 4 show 8 downstream test sections of total 16 downstream test sections. The present test matrix is shown in Table 1.

Table 1. Test Matrix of the Experiment

Shape of the Side-Orifice	Circle, Rounded Rectangle, and Rectangle
Number of the Side-Orifice	1, 2, 3, 4, and 6
Arrangement (with Six Side-Orifices)	Regular and Staggered Array
Reynolds number	2,000 ~ 50,000

The volumetric flow rate of water is measured by a magnetic flowmeter with a range of 2.3~530 lpm (0.316~32m^3/h) and controlled by pump and bypass valve. To measure the pressure drop through the side-orifice(s), two differential pressure transmitters are installed in parallel. One of the differential pressure transmitter has the maximum range of 7,446Pa (30"H_2O) and the other has 1,245Pa (5"H_2O). Two pressure taps are installed, one is located at the same level with the side-orifice and the other at 450mm height from the bottom of the downstream test section.

3. Results and Discussion

3.1 Loss Coefficient of Side-Orifice

It is difficult to directly measure the pressure drop due to side-orifices. In the present experiments, however, it is assumed that the pressure drop through the side-orifice can be determined by measuring the static pressure difference between the upstream and the downstream test sections. The pressure loss coefficient K can be expressed in terms of the pressure drop, downstream mean velocity, and area ratio between the side-orifices and the upstream test section.

$$K = \frac{2}{\rho u_2^2}\Delta P - (1 - \beta^2 - f\beta^2) \tag{1}$$

where ρ is the density of water, u_2 is the mean velocity at downstream test section, ΔP is the static pressure difference between the high and low pressure taps, β is the ratio of total side-orifice(s) area to the cross-sectional area of the downstream test section, and f is the wall friction factor of downstream test section.

The last term in Eq. (1) describes the pressure drop due to wall friction through downstream section. This term is negligible since it is much smaller than that of the form loss by order of 10^3. Thus, the pressure loss coefficient K can be calculated as follows :

$$K = \frac{2\rho}{G_2^2}\Delta P - (1 - \beta^2) \tag{2}$$

where G_2 is the time averaged mass flux at downstream. From the measurements of the pressure drop and the volumetric flow rate, therefore, the pressure loss coefficient through the side-orifice(s) can be evaluated using Eq. (2).

3.2 Effects of Key Parameters on the Pressure Loss Coefficient

Generally, the pressure loss coefficient has been considered to be a constant if Re is sufficiently large ($> 10^5$). As shown in Figs. 5~7, however, this coefficient is no longer a constant if Re is not sufficiently large. In the present work, the range of water Reynolds number is 2,000~50,000, where the Reynolds number is defined by [1]

$$Re = \frac{\rho u_i D_e}{\mu} \tag{3}$$

where u_i is the mean flow velocity at the side-orifice which is calculated from upstream mass flux using mass conservation and D_e is the equivalent diameter of the side-orifice. The present data for the pressure loss coefficient show the following dependency on the Reynolds number : (1) $K \propto Re^{-1.25}$ for $Re < 10{,}000$, (2) $K \propto Re^{-0.37}$ for $10{,}000 < Re < 30{,}000$, and (3) $K \propto Re^{-0.12}$ for $Re > 30{,}000$.

Figures 5~8 show the effects of shape and number of the side-orifices on the pressure loss coefficient. From these figures, it can be observed that the shape of the side-orifice does not affect the pressure coefficient significantly. Under the same condition, the pressure loss coefficient through the circular side-orifice(s) is largest although the difference is small when the number of the side-orifices is one or two. When the number of the side-orifices is three, four, or six, on the other hand, the pressure loss coefficient through the circular side-orifice(s) is smallest as shown in Fig. 8. Figures 5 and 6 also show the effect of the arrangement of six side-orifices on the pressure loss coefficient. Of two arrangements with six side-orifices(see Fig. 4), the regular arrangement shows the slightly larger pressure loss coefficient than that of staggered arrangement. The pressure loss coefficient is observed to be decreasing with the number of the side-orifices. This is mainly attributed to the fact that β in Eq. (2) is increased with the number of the side-orifices. It should be noted that the pressure loss coefficient decreases with increasing β as shown in Fig. 8. Although Idelchick[1] obtained the data by increasing area of a side-orifice, the present data for $Re \approx 5\times10^4$ show a good agreement with Idelchiks'.

3.3 Empirical Correlation for Pressure Loss Coefficient

Based on the present experimental data obtained from a total of 529 measurements, an empirical correlation for the pressure loss coefficient has been developed as follows :

$$K = CRe^{n_1}\beta^{n_2}\left(\frac{D_e}{D_2}\right)^{n_3}\left(\frac{l_e}{D_2}\right)^{n_4}\left(\frac{b}{h}\right)^{n_5} \tag{4}$$

where D_2 is the diameter of downstream test section, l_e is the leading edge from downstream test section, b is the average width of the side-orifice, and h is the average height of the side-orifice. C, n_1, n_2, n_3, n_4, and n_5 in Eq. (4) are listed in Table 2. The developed empirical correlation for the pressure loss coefficient of the side-orifice gives a good agreement with the data as shown in Fig. 9.

Table 2. Constant and Exponents in Eq. (4).

	C	n_1	n_2	n_3	n_4	n_5
$Re < 10{,}000$	43	-0.12	-2.	0.7	-2.39	0.26
$10{,}000 < Re < 30{,}000$	1292	-0.37	-2.	1.88	-0.86	0.05
$Re > 30{,}000$	59122.9	-1.25	-2.	1.0	1.63	0.12

4. Summary and Conclusions

Experiments to measure the pressure drop of side-orifice(s) for single-phase flow have been performed. A total of 529 data for pressure drop has been obtained within the range of $Re = 2{,}000 \sim 50{,}000$, with 16 downstream test sections that have 3 different side-orifice shapes, 5 different numbers of the side-orifice, and 2 different arrangements for the case of 6 side-orifices.

The present experimental study shows that the pressure loss coefficient decreases as Reynolds number increases and decreases in proportion to the inverse square of area ratio (β^{-2}). Under the same condition, pressure drop for staggered array is smaller than that for regular array. An empirical pressure loss coefficient has been developed in terms of Reynolds number, area ratio, equivalent diameter, leading edge, and average width of the side-orifice. The present empirical correlation for the pressure loss coefficient gives a good agreement with the experimental data.

References

1. I. E. Idelchik, *Handbook of Hydraulic Resistance*, Hemisphere, 1986, pp.113-136.
2. R. H. Sabersky, A. J. Ascosta and E. G. Haptmann, *Fluid Flow*, Macmillan, 1989, pp. 164-170

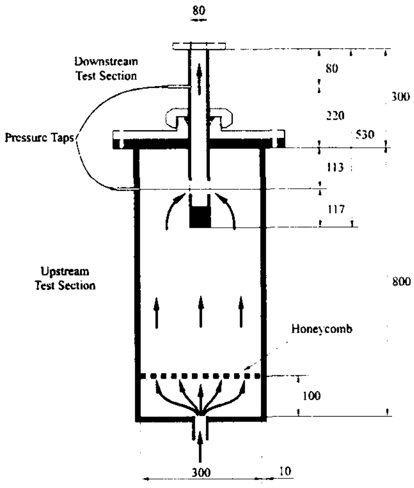


Fig. 1 Upstream and Downstream Test Section.

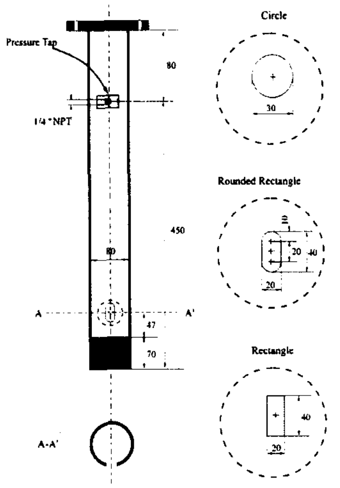


Fig. 2 Downstream Test Section and
3 Types of Side-Orifice Shape.

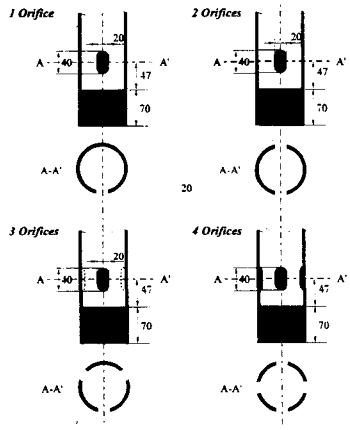
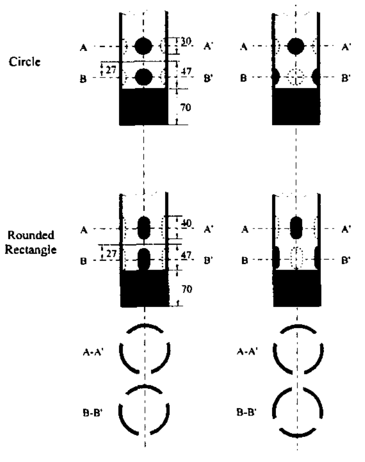


Fig. 3 Designs for Side-Orifice(s) with
Rounded Rectangle Shape.



Regular Array Staggered Array

Fig. 4 Arrangements of 6 Side-Orifices.

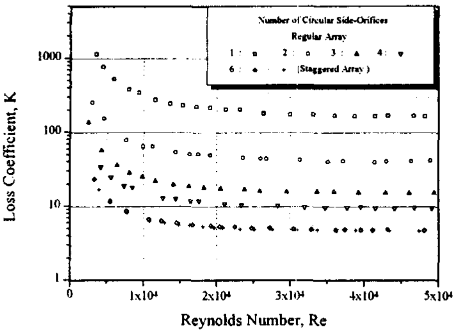


Fig. 5 Effects of Circular Side-Orifice(s) on K .

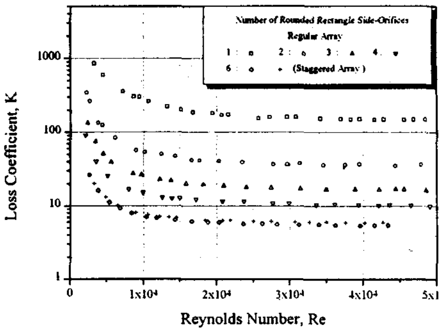


Fig. 6 Effects of Rounded Rectangular Side-Orifice(s) on K .

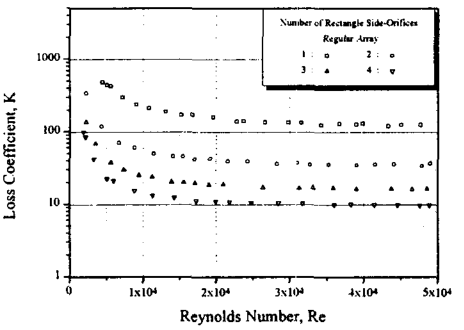


Fig. 7 Effects of Rectangular Side-Orifice(s) on K .

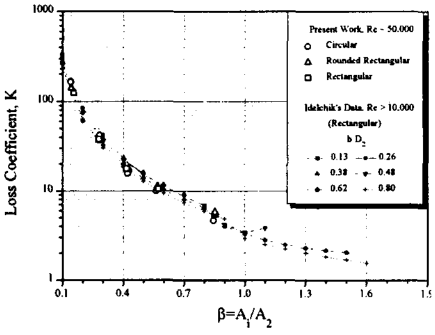


Fig. 8 Comparison between the Present Experimental and Idelchik's Data [1]

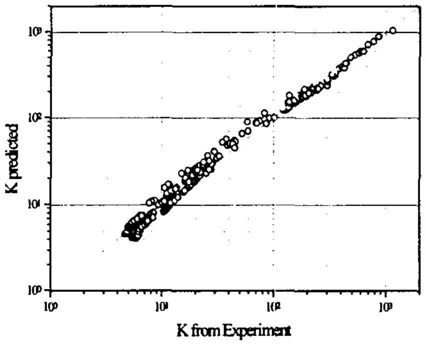


Fig. 9 Comparision of the Empirical Correlation for K with Experimental Data.