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The Effects of Tube Arrangement and Inclination on the Pressure Drop in Tube Bundles of Intermediate Heat Exchanger in Liquid Meta Reactor

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액체금속로 중간열교환기 관다발에서의 튜브배열과 경사각도가 압력강하에 미치는 영향

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Keywords : *Liquid Metal Reactor(액체금속로), Intermediate Heat Exchanger(중간열교환기),Pressure Drop(압력강하), , Tube Arrangement(튜브배열), Incination(경사각도)*

Abstract

The present paper presents the experimental results for pressure drop in inclined tube bundles located in a rectangular duct. Measurements are made for pressure drop in triangular and rotated triangular tube arrays having P/d ratio of 1.6 and inclination angles of 30, 45, 60 and 90 degrees. The Reynolds number based on the free stream velocity and tube diameter ranges from 8×10^2 to 6.3×10^4. The experimental results show that the magnitude of dimensionless pressure drop decreases significantly when the inclined angle is less than 45 degree. The measured data are compared with two existing correlations available in the literatures. The ESDU correlation agrees well with the present data for the triangular arrays. But some discrepancies are observed for the rotated triangular arrays when the inclined angles are 30 and 45 degrees. The Idel'chik correlation generally agrees well with the measured data for the rotated triangular arrays except for the inclined angle of 30 degree. The Idel'chik correlation needs modification for the triangular arrays. The modified Idel'chik correlation agrees well with the measured data within 10%. It is found that the present measured data can be applied to the evaluation and modification of previous correlations.

1. Introduction

The pressure drop across the inclined tube bundles is one of the important parameters in the design of the intermediate heat exchanger in a liquid metal reactor. Due to the complex geometry of the intermediate heat exchanger in a liquid metal reactor, the porous media approach is generally used to calculate the fluid flow and heat transfer. In the porous media approach, the accurate correlations of frictional force that take into account of the flow inclination to the tubes are essential for better prediction of fluid flow and heat transfer. The main objective of the present study is to develop an accurate friction factor correlation that can be applicable to the design purpose as well as the computation of flow field in the intermediate heat exchanger in a liquid metal reactor.

There exist several previous studies for measuring the pressure drop in a tube bundle. Most of the early studies provided the experimental data for purely cross flow. The pressure drop and heat transfer coefficient were measured with respect to different tube arrangements for a wide range of flow regimes. An excellent review of such studies is given in Zukasukas [1].

Since the main emphasis of the present study is placed on the flow over inclined tube bundles, it is desirable to survey the previous studies for the inclined tube array flows. Kazakevich [2] measured pressure drops of air flow across one to seven rows of rods for inclinations of 30, 45, 60 and 90 degrees. He measured the pressure drops in a six in-line and eight staggered rod arrangements for free stream Reynolds numbers from 7,000 to 100,000. Groehn [3] measured pressure drops across one to ten rows of rods for a more wide range of inclinations, 15, 30, 45, 60, 75, 90 degrees. Mueller [4] made measurements for both parallel and perpendicular pressure drops in inclined irregular arrays and developed a rod arrangement independent resistance correlation. However, he obtained data points only up to Reynolds number of 1,100. Boettgenbach [4] measured both resistance components across one to ten rows of rods for inclinations of 30, 45, 60 and 90 degrees in a squared array of P/d=1.2. His results ranged from Reynolds number of 5,500 to 550,000 based on the hydraulic diameter. However, his data scattered large. In 1984, Derek [5] made extensive experiments for single and two-phase flow in inclined rod arrays and in square arrays of P/d=1.5 for 0, 30, 45, 60 and 90 degrees. He also measured both resistances and constructed rod array independent constitutive relations for use in thermal-hydraulic codes.

The previous experimental correlations were made often from extrapolated data beyond their region of validity or some of them have significant errors. Therefore, for the use of correlations for design purpose, more accurate correlations

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should be selected or developed. The purpose of present study is to add new data for pressure drop in inclined tube banks for both triangular and rotated triangular tube arrays, to evaluate the previous correlations, and to develop a more accurate correlation for design and computation of flow field in a heat exchanger. For this purpose we made a set of experiments in triangular and rotated triangular tube arrays of P/d=1.6 at 30, 45, 60 and 90 degree inclinations to the flow direction in the range of Reynolds numbers between 8×10^2 and 6.3×10^4.

2. Experimental Apparatus

2.1 Test Section

Four stainless steel tube bundles which have 30, 45, 60 and 90 degree inclined angles enclosed by the rectangular duct are fabricated as shown in Fig.1. The duct has a rectangular cross section (140.7 × 203.2mm) and the length of duct is 1,600mm. Fig.2 shows two kinds of tube arrangements, triangular and rotated triangular arrays, considered in the present study. The detailed explanation of the test section for the triangular tube arrays is given in Choi et al. [6]. In the present experiment for the rotated triangular tube arrangement, the longitudinal and transverse pitches are $10.15\sqrt{3}$ mm and 20.3 mm respectively. Each tube bundle consists of 41 rows in the direction of flow. The tube diameter is 12.7 mm. There are four tubes in each row and the odd numbered rows include three whole tubes and two half tubes whose half part is embodied in the sidewalls of the duct. At least five rows are needed to avoid the entrance effects and the exit effects, and the pressure drop measurements are carried out across 21 rows from the 14-th row upstream to the 34-th row downstream. Five OMEGA and ROSEMOUNT™ differential pressure meters (6. 10, 30, 100, 250 inch H_2O) are used and connected to the 1 mm diameter hole of pressure taps located at the duct wall. The taps are installed midway between the rows on the sidewall of the duct. Most of the measurements are taken at the center region of the tube bank to simulate the conditions of an infinitely long tube bank. Temperatures are measured using the OMEGA™ J-type thermo couples immersed directly in the water at the inlet and outlet of the duct.

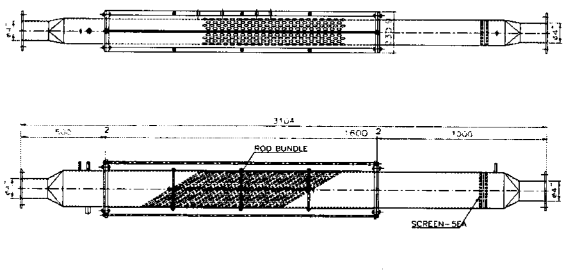

Fig. 1 Schematic diagram of the test section

2.2 Water Circuit

The water circuit consists of a water tank, a pump, a damper, a flow manifold and some a test section, as shown in Fig.3. The water tank can contain about five tons of water. The pump can supply water at a maximum flow rate of $3m^3$/min, which is controlled by ae control unit. The damper is installed to reduce the riffling of the flow, which is electrically controlled by the pressure of nitrogen cover gas. The wire mesh with screens is installed in the damper. The flow manifold has 3 turbine type flow meters, which are operated manually by valves to supply the required flow rate.

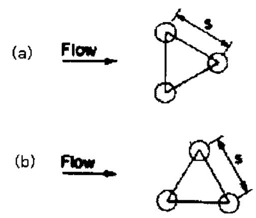

Fig. 2 Tube arrangements. (a) triangular array and (b) rotated triangular array

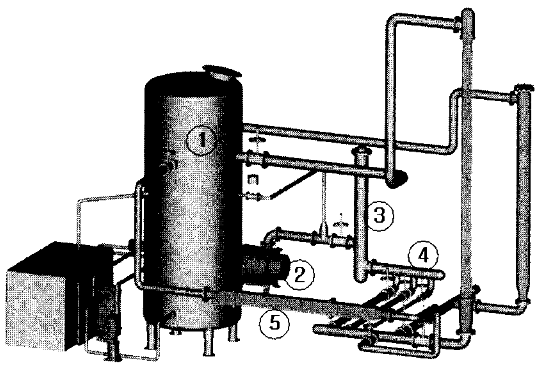

Fig. 3 Schematic diagram of the water circuit : ① water tank, ② pump, ③ damper, ④ flow manifold, and ⑤ test section.

3. Results and Discussion

3.1 Method of Measurement

Pressure drop measurements in the inclined tube bundles in a rectangular duct are carried out changing the test sections, which have four different inclined angles: 30, 45, 60 and 90 degrees. The range of flow rate at inlet is 0.97-50 liter/sec. This flow rate range is divided into about 30 intervals by logarithmic scale for each test section, and about 200 sets of data are collected in each flow rate. The flow rate is measured by three turbine type flow meters. The density and viscosity are calculated using the average temperature between inlet and outlet. There exist many correlations for the pressure drop in the tube bundle. Two correlations of Idel'chik [7] and ESDU Item NO.79034 [8] are compared with the present measured data.

3.2 Comparison with the Idel'chik Correlation

Fig.4 and Fig.5 show the comparisons of the present data with a general empirical correlation by Idel'chik [7]. The Idel'chik correlation is given as follows:

$$f = \Psi[3.2 + 0.66(1.7 - \frac{S_1 - d_h}{S_2' - d_h})]\mathrm{Re}_m^{-0.27}(N+1)/N \qquad (1)$$

where Re is the Reynolds number, ψ is the correction factor for the inclinations, N is the number of rows between measuring locations, and S_1, S_2 and S_2' are pitches in the transverse, longitudinal and diagonal direction, respectively. The correlation gives the distributions of dimensionless pressure drop defined as $f = 2\Delta P / \rho U_m^2 N$ versus Reynolds number for different inclinations. The Reynolds number, $\mathrm{Re} = \rho U_m d / \mu$, is based on the maximum velocity, crossing the minimum area and the tube diameter. We can observe in Fig.4 that the pressure drop coefficient decreases with increasing Reynolds number, which is already observed in the literatures. We also observe that the flow becomes turbulent when the Reynolds number is approximately greater than 10^5. The slopes of pressure coefficient in the logarithmic plot show that the pressure drop coefficient decreases with nearly the same negative power of Reynolds number for all cases. It is noted that the pressure loss coefficient decreases with decreasing the inclined angle, and decreases rapidly when the inclination angle is less than 45 degree.

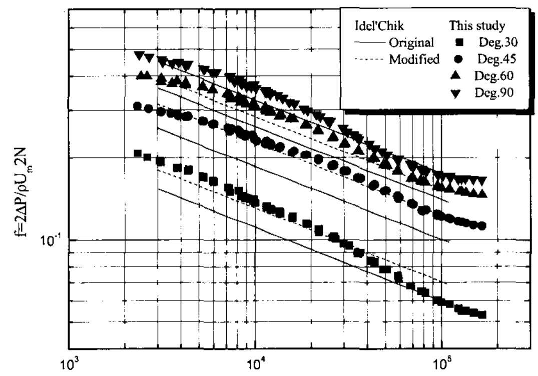

Fig. 4 Comparison of Idel'chik correlation with the measured data (triangular array).

Fig.4 shows the comparison of the present data with the Idel'chik correlation for the triangular arrays. The Idel'chik correlation is a general and simple correlation that takes into account the effects of the inclination. When this correlation is compared with our measured data, the correlation shows large discrepancies when the inclined angle is less than 90 degree. This correlation is in good agreement with the present data only for purely cross flow, that is 90 degree inclination. In this correlation the effect of inclined angle is given by the multiplication factor ψ. Therefore, if we modify the correction factor, ψ for the inclinations, the correlation would be more useful and accurate. The correction factors for triangular array are modified using our data as shown in Table 2. The solid lines are the original correlation and the dotted lines are the modified ones in Fig.4. As shown in Fig.4, the modified correlation agrees quite well with the present measured data, within 10%, for all cases of inclinations.

Table 2. The correction factors, ψ(triangular)

Degree	*Original*	*Modified*
90	1	1
60	0.8	0.87
45	0.57	0.7
30	0.34	0.4

Fig.5 shows the comparison of the present data with the Idel'chik correlation for the rotated triangular arrays. The correlation agrees quite well with the present data except for the 30 degree inclined angle. When the correction factor for the 30 degree inclined angle is modified for ψ=0.38, the correlation agrees much better with the present data as shown in Fig.5

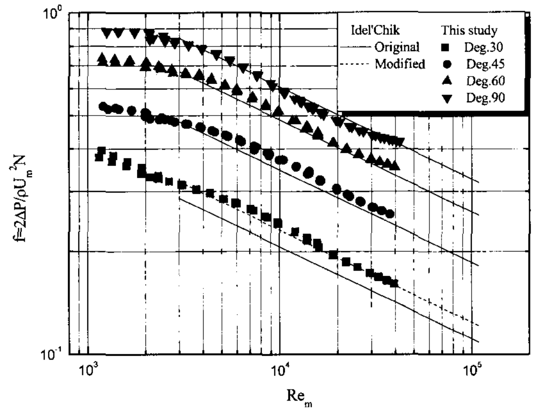

Fig. 5 Comparison of Idel'chik correlation with the measured data (rotated triangular array).

3.2 Comparison with the ESDU Correlation

The correlation in ESDU Item No. 79034 [8] is the most recent one among the numerous correlations available for the pressure drop in the tube banks with inclinations. This correlation is the most useful if it is validated by the experimental data since this correlation covers the whole flow range, from laminar to turbulent, by one equation. This correlation is given as follows;

defining the loss coefficients $C = 2\Delta PD / \rho U^2 N S_L$, then

$$C = C'\phi,$$

$$C' = Y(\frac{D_v}{D})\frac{1}{(X-1)^3} \qquad (2)$$

where

$$D_v = \frac{2\sqrt{3}X^2}{\pi} - \frac{\mathrm{Re}}{\mathrm{Re}+10}$$

$$Y = [\frac{3.61}{\mathrm{Re}^{0.7}}(1 + \frac{5}{\mathrm{Re}^{0.8}})^2 + 0.0625(1-a)^2 + 0.01]^{1/2}$$

$$a = \frac{\mathrm{Re}}{(\mathrm{Re}+10^4)},$$

$$\phi = (\sin\theta)^{a7},$$

$$a_7 = 1 + 1.55[\frac{Re}{Re+40}]^2,$$

$$Re = \frac{\rho U D}{\mu}$$

$$U = \beta U_m,$$

$$\beta = \frac{X-1}{X},$$

$$X = \frac{S}{D}$$

Fig.6 shows that this correlation fits well with the present measured data. In case of the triangular arrays, it is seen that the deviations between the measured data and the correlation are within ±5 % except in some regions. For 30 and 90 degree inclined angles, the maximum discrepancies are about 20 % near the transition to turbulent region. In case of the rotated triangular arrays, the discrepancies tend to increase when the inclined angle becomes small. The maximum discrepancy is about 20% when the inclined angle is 30 degree. Therefore, some corrections may be needed to take into account for some discrepancies in this region.

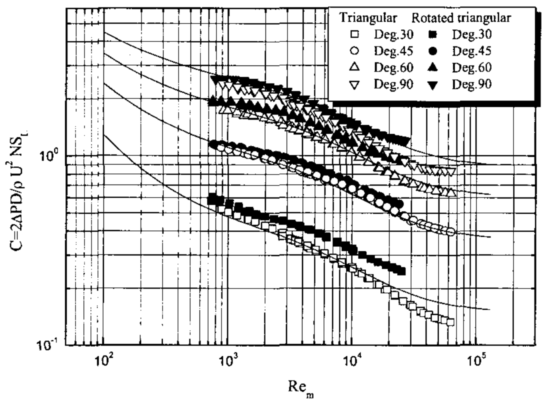

Fig. 6 Comparison of ESDU correlation with the measured data.

4. Conclusion

An experimental study of measurement of pressure drop in an inclined tube bundle is performed. Measurements are made for the pressure drop in the triangular and rotated triangular tube arrays of P/d=1.6 and inclination angles of 30, 45, 60 and 90 degrees for Reynolds numbers between 8×10^2 and 6.3×10^4. The experimental data show that the magnitude of dimensionless pressure drop increases with the increase of inclined tube angle. The measured data are compared with two previous correlations. Following conclusions are drawn from the results of comparisons:

(1) The ESDU correlation follows the trend of measured data, and it is accurate enough for use in engineering problems for the triangular arrays, although, this correlation shows some deviations from measured data in a region near the transition to turbulent when the inclined angle is 30 and 90 degrees. The ESDU correlation needs some modifications for the rotated triangular arrays when the inclined angle is less than 45 degree.

(2) The Idel'chik correlation needs modification for the triangular arrays when the inclined angles are less than 90 degree. But the modification is required only for the 30 degree inclination for the rotated triangular arrays. The modified correlation agrees well with the measured data.

It is found that the experimental data obtained from the present study can be applied to the evaluation and modification of previous correlations.

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