TECHNICAL REPORT

Pressure Drop Performance of Fuel Pin Bundle with Spiral Wire Spacer

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The pressure drop characteristics of a JEFR type fuel pin bundle were obtained from hydraulic tests. The coefficient of drag attributable to the spiral wire spacer wound round each fuel pin, as defined by de Stordeur, was found to be approximately 0.30 for the hexagonal lattice arrangement adopted. The coefficient is independent of spiral wire pitch, which ranged from 90 to 260 mm.

The pressure drop to be expected in a fuel pin bundle with spiral wire spacer, such as used in current fast breeder applications, can be satisfactorily estimated by using the coefficients reported.

I. INTRODUCTION

Most fuel assemblies of current fast breeder reactors are fabricated with use made of spiral wire or else grid type spacers to maintain the pins in their position. In the former case, the fuel pins are helically wound with a thin wire which serves as spacer to keep the predetermined gap between pins. In the latter case, various kinds of grid have been used, but this form of fuel spacing is more common in boiling water reactors. For fast reactor applications, this grid type spacing involves very severe technical requirements because of the small pin pitch of only about 6 mm. The coolant pressure drop induced by the grid has been considered generally higher than the case of spiral wire spacer. The pressure drop to be expected in a pin bundle with honeycomb grids, for instance, has been estimated from calculations to be 60% higher than with spiral wire system. This is one of the reasons why the spiral wire system has been adopted for the fuel assemblies of the JEFR (Japan Experimental Fast Reactor). Sufficient experimental data are, however, not today available for determining accurately by calculation the coolant pressure drop in a spiral wire type fuel assembly where the pins are arranged in a hexagonal lattice. We present below the experimental results and analyses on the pressure drop characteristics of a spiral wire pin bundle of this arrangement.

II. EXPERIMENTAL RESULTS

1. Outline of Apparatus and Experimental Method

A hydraulic test loop constructed in the laboratory was used for the experiments. The apparatus was a hot water circulation loop designed for water simulation of the high temperature liquid sodium used in practice as reactor coolant material. The loop water can be warmed up to 95°C, at which temperature the dynamic viscosity of water is approximately equal to that of liquid sodium at approximately 400°C. A conceptual flow sheet of this test loop is shown in Fig. 1. Its principal specifications are as follows.

- Circulating fluid: Water, (water temperature: 10°C ~ 95°C)
- Hydraulic pump head: 70 m
- Rated volumetric flow rate: 2 m³/min

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Max. static pressure at test channel inlet: 8 kg/cm²
Max. fluid velocity at fuel pin bundle: 10 m/sec
Fluid volume in the loop: Approximately 1.5 m³

The inside dimensions of the test channel are approximately equal to those of the hexagonal wrapper tube holding the pin bundle, as used in the JEFR fuel assembly. Ninety-one mock-up fuel pins of the same dimensions as the JEFR fuel pins were arranged hexagonally in the test channel as shown in Fig. 2. Particulars of the mock-up pins are as follows.

Number of pins: 91
Outer diameter of a pin: 6.30 ± 0.01 mm
Total length of a pin bundle: 1,460 mm
Spiral wire diameter: 1.20 ± 0.01 mm
Spiral wire lead: 90, 130, 190 and 260 mm

A schematic outline of the test channel and static pressure tap locations is given in Fig. 3. The test channel has a hexagonal flow area with an axial length of 1,640 mm, along which 6 static pressure taps 1.0 mm in diameter are drilled. The loop water flows upward as indicated in the figure. The pressure drop across the pin bundle was measured by Hg manometers.

2. Experimental Results

A series of preliminary experiments was conducted to determine the effects of the bundle inlet and of spiralling flow that might be induced by the spiral wire. The pressure drop between taps 3 and 4 and between 5 and 6 (see Fig. 3) were measured at room
temperature and compared with each other. The pressure drop between the two adjacent taps was practically equal, except in the case of 260 mm spiral pitch where the pressure drop between taps 5 and 6 was found approximately 2% higher than between 3 and 4. These results indicate that spiralling flow, even if existent, did not in the present case produce any significant rippling in the distribution of static pressure along the fuel bundle axis, as reported in Ref. (9).

The pin bundle pressure drop between taps 3 and 6 was measured for 90, 130, 190 and 260 mm spiral pitch. The distance between the two taps was 1,335 mm, as shown in Fig. 3, and the water temperature was maintained constant during the run at approximately 80°. The data obtained are plotted in Fig. 4, in logarithmic scale against flow rate. The plots are well aligned, with no apparent influence of inlet and outlet effects, so that the relation can be expressed by the equation, 

$$\Delta P = A Q^2$$

where A and n are constants to be determined empirically. In the present case,

$$\Delta P = A Q^{1.78 \pm 0.10},$$

the index of Q is independent of spiral pitch, but the parameter A increases with shortening pitch. The fact that the pressure drop $\Delta P$ was proportional to the 1.78th power of flow rate $Q$, and not to 1.75th, suggests that there may exist some effect of spiral wire on the hydraulic performance of the pin bundle, other than friction loss, which is embodied in the Blasius equation. The $\pm 0.10$ variance of the index was introduced by experimental error.

The friction factors of the pin bundle with spiral wire spacer can be determined from experimental data by applying the established expression of pressure drop for pipe flow, which is

$$\Delta P = \lambda \frac{L}{D_{eq}} \cdot \frac{\pi V_c^2}{2g},$$

In this equation, $V_c$ and $D_{eq}$ respectively are fluid velocity and the hydraulic equivalent diameter of a flow cell in the central zone, shown in Fig. 2. Adoption of the unit flow cell concept will permit neglect of the influence of the test channel wall. The flow distribution of the central and peripheral flow cells was calculated, assuming that the flow rate is proportional to the square root of the hydraulic equivalent diameter, as expressed by the following equations:

$$V_c = \frac{Q_e}{A_c} = \frac{Q_r}{A_r} \cdot \frac{n_s + n_w K_s}{n_s + n_w K_t},$$

$$K_c = \frac{Q_e}{Q_t} = \frac{A_c}{A_t} \sqrt{\frac{D_{eq}}{D_{eq}}},$$

$$K_s = \frac{A_c}{A_t}.$$

The calculated friction factors are plotted in Fig. 5 against Reynolds number $Re(=D_{eq} V_c/\nu)$ based on the central zone flow cell constants, where they are compared with the Blasius formula given for a round tube:

$$\lambda = 0.3164 Re^{-0.15}$$

The empirical correlation between the obtained friction factors and Reynolds number can be derived from experimental data:

$$\lambda = 1.03 \cdot (l/d)^{0.405} \cdot Re^{0.313},$$

where $8 \times 10^3 < Re < 6 \times 10^4$

$14 < l/d < 42.$

The effect of differences in spiral pitch is embodied in this equation as the factor $l/d$, the ratio of spiral pitch to pin diameter. It
is seen from Fig. 5 that the friction factor of a wire pin bundle with 260 mm spiral pitch is approximately equal to that of a round tube, and that the factor increases with shortening wire pitch. The friction factor for 90 mm spiral pitch is approximately 50% greater than for round tube.

The experimental data of Fig. 4 are used in the next chapter to calculate the drag coefficients for spiral wire spacer.

### III. Drag Coefficients of Spiral Wire

#### 1. Friction Factors for Fuel Pin Bundle without Spacer

A considerable amount of experimental and theoretical information is available today on the pressure drop performance of rod bundles\(^{[10] - [14]}\), but the data do not always agree with each other. The pressure drop of a pin bundle without wire spacer was first obtained, so that the influence of the wire spacer could be clearly separated from the total pin bundle pressure drop. Friction factors for a pin bundle without wire spacer can be determined from measurement by using Eq. (2), substituting \(D_{oc}\) for \(D_{w}\). The calculated friction factors based on experiments at water temperatures of 20°C and 80°C are presented in Fig. 6 against \(Re = D_{oc}V_\ell/\nu\) ranging from \(4 \times 10^4\) to \(8 \times 10^4\). The data obtained are seen to agree well with the straight line given by Blasius for a round tube, and that they are independent of water temperature. Some available data for a hexagonal lattice rod arrangement found in literature are shown in the same figure for comparison with the present experimental results. It can be concluded from the figure that the friction factors based on the Blasius formula can be applied to the JEFR type hexagonal lattice pin arrangement with a pitch-to-diameter ratio of approximately 1.2, which is close to the design value for fast breeders.

#### 2. Drag Coefficients of Spiral Wire

De Stordeur has derived drag coefficients\(^{[15]}\) for spiral wire spacer, assuming that the pressure drop through a pin bundle induced in the coolant flow can be separated into two elements (a) associated with and (b) independent of wire spacer pressure:

\[
\Delta P_T = \Delta P_n + \Delta P_s, \quad \text{Eq. (8)}
\]

\[
\Delta P_n = \lambda_n \frac{L}{D_{oc}} \frac{\nu}{2g} \frac{V_\ell^4}{A_e}, \quad \text{Eq. (9)}
\]

\[
\Delta P_s = C_s \frac{\nu}{2g} \frac{V_\ell^4}{A_f}, \quad \text{Eq. (10)}
\]

where \(\Delta P_n\) and \(\Delta P_s\) respectively are the pressure drop elements independent of and associated with wire spacer, \(\lambda_n\) is the friction factor calculated by the Blasius formula and \(C_s\) the drag coefficient of the spiral wire. Based on these equations, de Stordeur\(^{[15]}\) arranged the CVTR and APDA hydraulic test data, and derived drag coefficients. (Fig. 7) Now these data included those of square lattice arrangement as well as hexagonal, and the cited drag coefficients are seen to scatter quite widely above and below the proposed curve. It is of interest to note that the five groups of CVTR data seen at about 0.3 below the curve in the figure were obtained reportedly for a hexagonal pitch arrangement, while the APDA data were obtained for a square pitch arrangement. This suggests that the
pattern of pin arrangement has influence on the drag coefficients.

![Fig. 7 Drag coefficient of spiral wire spacer (From A.N. de Stordeur(15))](image)

Some authors have reported experimental results and analyses on banks of rods or tubes wrapped with spiral wire(16)–(18) but their results are applicable to particular designs and would not be utilizable for a close-packed fuel pin bundle such as used in current fast breeders.

The drag coefficients for a spiral wire spacer defined by Stordeur's equation were calculated on the basis of the present experiments. The results are shown in Fig. 8. The pin bundle used is composed of 91 mock-up pins, 6.30 mm in diameter, each wound with a helical wire 1.20 mm in diameter and arranged in a hexagonal lattice.

![Fig. 8 Drag coefficient of spiral wire spacer for various spiral pitches](image)

The drag coefficient has been found to be 0.3–0.4, independent of wire spiral pitch, and governed by the Reynolds number $Re_s$, ranging from $2 \times 10^4$ to $2.3 \times 10^4$ as defined by

$$Re_s = \frac{d_s V_s}{\nu}, \quad (11)$$

where $d_s$ is the spiral wire diameter. The drag coefficients thus obtained are seen to be somewhat lower than reported for the APDA core model and are close to the 5 group data for the CVTR model. In the calculation of the drag coefficients from experimental data, an electronic computer was used for convenience, to maintain accuracy and to diminish personal error. Fairly good convergence of calculated data can be seen in the figure.

IV. CONCLUSIONS

Hydraulic tests have been performed on JEFR type spiral wire pin bundle in a water loop, from which the following conclusions can be drawn:

(1) The friction factors for pin bundle without spacer, composed of 91 pins 6.30 mm in outside diameter and arranged in a hexagonal lattice of 7.69 mm pitch, were found to agree well with Blasius' curve for Reynolds number ranging from $7 \times 10^3$ to $8 \times 10^4$, applying the flow area and the hydraulic equivalent diameter of a flow cell in the central zone of the assembly.

(2) The drag coefficients of the spiral wire spacer defined by Stordeur's equation were determined from observed data by calculation on computer, and found to be approximately 0.30, independent of the spiral pitch of the wire, ranging from 90 to 260 mm. Fairly good convergence of the calculated drag coefficients was obtained.

[Nomenclature]

- $A_c$: Flow area of flow cell in central zone of assembly, without wire, $A_c = \sqrt{3} P^4/2 - \pi d^4/4$
- $A'c$: Flow area of flow cell in central zone of assembly, with wire, $A'c = A_c - (\pi/4)d_s^2$
- $A_w$: Flow area of flow cell in peripheral zone of assembly, without wire, $A_w = 0.42P - \pi d^2/8$
- $A_w'$: Flow area of flow cell in peripheral zone of assembly, with wire, $A_w' = A_w - (\pi/8)d_s^2$
- $A_T$: Total flow area in pin bundle
- $C_d$: Drag coefficient of spiral wire
- $D_{sc}$: Hydraulic equivalent diameter of flow cell in central zone, without wire, $D_{sc} = 4A_s/\pi d$
- $D_{sc}'$: Hydraulic equivalent diameter of flow cell in central zone, with wire, $D_{sc}' = 4A'c/\pi(d + d_s)$
$D_{ew}$: Hydraulic equivalent diameter of flow cell in peripheral zone, without wire, $D_{ew} = 4A_w/(\pi d/2 + P)$

$D'_{ew}$: Hydraulic equivalent diameter of flow cell in peripheral zone, with wire, $D'_{ew} = A'_{w}/(\pi d/2 + \pi d_s + P)$

$d$: Fuel pin diameter, $d = 0.630$ cm

$d_s$: Spiral wire diameter, $d_s = 0.120$ cm

$g$: Gravitational conversion factor, $980$ cm/sec$^2$

$K_1$: Ratio of $Q_w$ to $Q_c$, $K_1 = Q_w/Q_c$

$K_2$: Ratio of $A'_{w}$ to $A'_{c}$, $K_2 = A'_{w}/A'_{c}$

$L$: Distance between static pressure taps

$l$: Spiral pitch of spacer wire wound round rod

$N$: Number of spiral wire turns over unit pin bundle length

$n_w$: Number of peripheral flow cells, $n_w = 33$

$n_c$: Number of central flow cells, $n_c = 75$

$P$: Hexagonal lattice pin pitch, $P = 0.769$ cm

$\Delta P$: Fluid pressure drop

$\Delta P_k$: Total pressure drop

$\Delta P_s$: Pressure drop caused by bundle without spiral wire

$\Delta P_r$: Pressure drop caused by spiral wire

$Q_r$: Total gravitational flow rate

$Q_c$: Gravitational flow rate in flow cell in central zone

$Q_w$: Gravitational flow rate in flow cell in peripheral zone

$Re$: Reynolds number

$Re_{s}$: Reynolds number based on the spiral wire diameter

$S$: Spacer projected frontal area, $S = \pi (d + d_s) d_s N$

$V_c$: Fluid velocity in flow cell in central zone

$\eta$: Specific gravity of fluid

$\alpha$: Friction factor of pin bundle

$\alpha_B$: Friction factor taken from Blasius' formula

$\nu$: Dynamic viscosity of fluid

**References**

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