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MASTER

LABORATORY MANUAL FOR STATIC PRESSURE DROP
EXPERIMENTS IN LMFBR WIRE WRAPPED ROD BUNDLES

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Nomenclature

A	Area
D	Rod diameter
De	Equivalent hydraulic diameter
e	Systematic error in subchannel static pressure measurements
F	Function defined by Eq. (5-1)
f	Friction factor
g _c	Gravitational constant ($g_c = 32.17 \frac{\text{ft-lbm}}{\text{lbf-sec}^2}$)
H	Wire wrap lead length
L	Axial distance over which static pressure drop is calculated (also electrical inductance in Appendix B)
L _o , L _r , L _u , L _l	Measured lengths (see Figs. 6, A-1, B-1)
l _a , l _b	
N	Total number of subchannels in bundle
N _i	Total number of type-i subchannels in bundle
N _R	Total number of rods in bundle
P	Rod pitch
P _i	Static pressure in i th subchannel
P _w	Wetted perimeter
Q	Volumetric Flow Rate
Re	Reynolds number

V	Velocity
X	Flow split parameter

Greek

ΔP	Static pressure drop
δf	Error in friction factor determination
δP_i	Error in subchannel static pressure measurement
$\delta \Delta P$	Error in pressure drop determination
δV	Error in velocity measurement
ρ	Fluid density
μ	Fluid viscosity

Subscripts

i	i = 1 for interior subchannel quantities i = 2 for edge subchannel quantities
j	j = i for type-i subchannel quantities j = b for bundle average quantities
l	denotes evaluation of quantity at the lower pressure tap location
u	denotes evaluation of quantity at the upper pressure tap location

1.0 Introduction

This manual describes the experimental apparatus, procedures, and data reduction associated with subchannel pressure drop experiments in LMFBR wire wrapped rod bundles. The fundamental procedures and data reduction techniques described herein can be applied to bundles with various geometric characteristics.

The purpose of this experiment is to determine both interior and edge subchannel axial pressure drops for a range of Reynolds numbers. The subchannel static pressure drop is used to calculate subchannel and bundle average friction factors, which can be used to verify existing friction factor correlations. The correlations for subchannel friction factors [1] are used as input to computer codes which solve the coupled energy, continuity, and momentum equations, and are also used to develop flow split correlations which are needed as input to codes which solve only the energy equation. The bundle average friction factor is used to calculate the overall bundle pressure drop, which determines the required pumping power.

2.0 Experimental Apparatus

This section describes the design of the apparatus used to gather subchannel static pressure data.

2.1 Loop Design

The reader is referred to Ref.[2] for information regarding the flow loop design, and to Ref.[3] and Ref.[4] for the details of specific test section bundles. It should be noted that Fig. 3 of Ref.[2] is incompletely labelled with respect to its corresponding text. Thus, a revised version of the figure is included as Fig. 1 of this report, and should be used in conjunction with the text of Ref.[2].

2.2 Subchannel Static Pressure Taps

The subchannel pressure drop is determined by measuring the subchannel static pressure at two locations, separated by the desired axial distance. The pressure taps are small (0.03125 in. diameter) holes drilled along the

length of a hollow rod at an angle of 30° from the vertical (see Fig. 2), with a separation between consecutive holes that varies axially. There is one interior pressure tap rod and one edge rod, which can be positioned as desired within the bundle (typical positions are shown in Fig. 3). These rods are each fitted with an end plug which can be removed for insertion of an injector device (see Section 2.3).

Before beginning, the experimenter must determine where the holes lie on the perimeter of the pressure tap rod. In order to easily reference their location, the holes all lie along an imaginary vertical line which passes through the point corresponding to the wire wrap position at the bundle exit (see Fig. 4). The radial position of the wire wrap relative to the pressure tap at each axial level is important, since the wire wrap gives a periodic nature to the subchannel axial static pressure gradient, as shown in Fig. 5. Thus, given the radial location of the vertical line of holes and the wire wrap lead length, the axial position of each hole must be ascertained. If these positions are not known, they can be determined by moving the injector (see Section 2.3) over its full range and noting the positions at which there exist pressure taps.

Section 3 outlines the procedures for determining when a tap is found and for referencing its position. Table 1 shows the distance below the bundle exit at which pressure taps were found by this method in a typical bundle [3].

Once the radial position of the wire wrap relative to each pressure tap is determined, the experimenter must choose which two taps at which to measure the static pressure in order to calculate a pressure difference. This decision should be based on the following criteria:

- (1) In order to minimize the percentage error due to specific absolute errors, the pressure drop should be maximized by maximizing the axial distance between the two pressure taps. This criterion is subject to the constraints imposed by the remaining criteria listed below. An axial separation between taps of about twice the wire wrap lead length is usually sufficient in this regard.
- (2) The lower of the two pressure taps should be a distance of at least 3 or 4 wire wrap lead lengths from the bundle inlet in order to guarantee flow stability, that is, a fully developed flow condition [5].

- (3) The optimal pressure tap locations are separated by an integral number of wire wrap lead lengths to avoid any periodic effects due to the wire wrap (Fig. 5). This condition is not perfectly rigid as long as the axial separation distance approximates an integral number of lead lengths. For example, it was found that an axial separation of 20.5 in. gave the same results (within the experimental error) as a 21.0 in. separation, for a bundle with a wire wrap lead length of 10.5 in.
- (4) Both pressure taps should be as far as possible radially (close to 180°) from the wire wrap at their respective axial levels, in order for the subchannel static pressure to correspond to the relatively flat portion of the pressure gradient (Fig. 5). This will minimize the periodic effects of the wire wrap in case the two taps are not separated exactly by an integral number of wire wrap lead lengths.

2.3 Injector

The injector is a device which fits into a hollow pressure tap rod and can be moved axially therein. The reader should note that the term "injector" is a result of an alternate use of the device, namely to inject a salt solution in salt tracer mixing experiments. Similarly, the hollow pressure tap rods are sometimes referred to in the literature as "injection rods" because of their function in mixing experiments. For the purpose of this subchannel pressure drop laboratory manual, the term injector will be retained, however the "injection rods" will be referred to as "pressure tap rods."

The injector (see Fig. 2 and Fig. 6) consists of two pieces which fit together after the lower piece is inserted into the hollow pressure tap rod, thus eliminating any bending of the injector shaft during insertion due to the relatively low ceiling clearance above the upper plenum. A schematic of the lower injector piece is shown in Fig. 2. The injector end hole, when aligned with a particular hole in the pressure tap rod, transmits the subchannel static pressure at that pressure tap to the appropriate measuring

instrument (see Section 2.4). The end hole is located between two pairs of o-rings to prevent the disturbance of the local subchannel static pressure at the desired measuring location by the static pressure at taps either upstream or downstream. As shown in Fig. 2, part of the lower injector shaft above the end piece is enclosed in a neoprene tubing. The purpose of this tubing is to provide a good fit for the injector shaft, in order to prevent the recirculation of water into the gap between the hollow pressure tap rod and the inserted injector.

2.4 Pressure Measuring Instruments

A length of clear plastic tubing (Fig. 6) is used to connect the upper end of the injector to the desired static pressure measuring instrument. The primary instrument is a differential pressure gage with a range of 0 - 150 in. of water (a differential pressure gage with a range of 0 - 400 in. of water is needed for highly turbulent flow). In addition, a manometer was implemented in order to make static pressure measurements in laminar flow, since the pressure gage graduations were not sufficient to distinguish between the subchannel static pressures at consecutively

tested flow rates in the laminar regime. These pressures were later found to differ by almost an order of magnitude less than the 1.0 in. of water separation between graduations on the 0 - 150 in. of water range pressure gage. The manometer (Fig. 7) was constructed simply by mounting a meter stick at an appropriate height in order to determine the subchannel static pressure by balancing it with a measurable hydrostatic head in the clear plastic tube.

The differential pressure gage should be replaced by the manometer for determining small pressure drops. Ideally, the manometer should be utilized whenever the difference between the upper and lower static pressure readings (i.e., the subchannel static pressure drop) is less than the experimental error associated with the differential pressure gage. This is the case for the laminar and lower transition flow regimes. Currently, however, only the laminar ($Re < 400$) and turbulent ($Re > 10,000$) data are used to calibrate existing subchannel pressure drop and friction factor correlations [1]. Thus, the more tedious use of the manometer is necessary only for laminar flow, if the transition regime static pressure data is not required to the utmost accuracy.

3.0 Experimental Procedures

This section outlines the preparation, set-up, and running procedures involved in subchannel pressure drop experiments. It is assumed that the test section bundle is already assembled (refer to Refs.[3],[4], and [7] for bundle construction details).

3.1 Preparation

- (1) Prior to insertion of the injector, assemble it by connecting its upper and lower pieces.

NOTE: Refer to Fig. 6 for steps (1) - (6).

- (2) While the injector is assembled and still not inserted, measure the distance L_0 from the end hole to a convenient reference position near the top of the injector. The bottom edge of the black tape is chosen as the reference point to be used here.
- (3) Attach a ruler to the laboratory ceiling directly above the upper plenum.

- (4) Measure the distance L_r from the bottom of the ruler to the bundle exit.
- (5) Determine the distance below the bundle exit (L_l and L_u) of the two pressure taps to be utilized, based on the criteria set forth in Section 2.2.
- (6) Determine the two points on the ruler at which the bottom of the black tape should be located in order to correspond to the locations where the desired upper and lower pressure taps are aligned with the injector end hole. These points on the ruler will be referred to as position-u and position-l, respectively. From Fig. 6,

$$\text{position-u} = L_o - L_r - L_u$$

$$\text{position-l} = L_o - L_r - L_l$$

- (7) Disassemble the injector by separating its upper and lower pieces.
- (8) Choose a set of flow rates at which to gather the subchannel static pressure data. Consecutively tested flow rates should differ by an amount

ranging from 0.5 GPM to 10 GPM, depending on the magnitude of the flow rate. The data of previous experimenters (Ref. [3],[6], and [7]) provides a good basis for choosing a set of flow rates.

3.2 Set-Up

- (9) Initially, either the interior or the edge pressure tap rod is chosen for collecting data. Remove the end plug from the appropriate rod.
- (10) Clean the neoprene tubing and end piece (including the o-rings) of the lower injector with soap and water, then apply vacuum grease to all the newly cleaned surfaces. The experimenter should take care to remove all dirt from the injector end hole and avoid plugging it with vacuum grease.
- (11) Insert the lower part of the injector into the desired pressure tap rod. Push the lower injector deep enough into the bundle so that there is enough room between the top of the lower injector and the laboratory ceiling for the upper injector to be fit.

(12) Join the upper injector to the lower injector.

(13) Join the clear plastic tubing to the upper injector.

NOTE: Tape dope should be used to seal the threads at the connections formed in steps (12) and (13), thereby preventing air from leaking into the injector.

3.3 Running Procedures

(14) Turn on the pumps and adjust the appropriate valves (see Section 2.1) so that the flowmeter indicates a flow corresponding to the highest flow rate to be tested, as determined in step (8).

NOTE: It is advisable to start at the highest flow rate and proceed in a decreasing fashion, since the higher static pressure associated with higher flow rates will help in expelling any dirt or grease which may be blocking the

injector end hole at the start of the experiment. Since the static pressure is higher for a lower axial level in the bundle, it is also recommended to start at the lower of the two pressure tap locations.

- (15) Use a thermometer to measure the temperature of the water in the tank. This is necessary for determining the fluid density and viscosity, which in turn are needed to calculate the Reynolds number from the flow rate and geometric characteristics.
- (16) Move the bottom of the black tape to the ruler's position-1.
- (17) Each time the injector reference point is at position-1 or position-u, the experimenter should observe water passing through the clear plastic tubing. Once water begins to exit the free end of the tubing, the experimenter should wait about 1 min. for any air bubbles (which may result from the injector's movement) to propagate and exit the tubing.

NOTE: If there is no water in the clear plastic tubing (or if there is water which doesn't propagate and exit the free end of the tubing), it is probably because the injector end hole is not aligned exactly with the desired pressure tap. In this case, the injector should be moved slightly up and down by trial and error until water appears (or begins to propagate) in the tubing. This vertical movement should be for a distance of less than the pressure tap separation distance at that elevation to insure that the desired pressure tap, and not an adjacent one, has been found.

(18) Attach the free end of the clear plastic tubing to the appropriate differential pressure gage or the manometer scale (see Section 2.4).

(19) Read and record the observed static pressure.

NOTE: When a differential pressure gage is used, the face of the gage should be tapped lightly between steps (18) and (19) to insure that friction has not inhibited the functioning of

the internal mechanism. When the manometer is used, the experimenter should allow sufficient time (about 30 sec.) between steps (18) and (19) for the water to overcome the wall friction of the tube surface as it rises or falls and finally comes to rest.

(20) Detach the clear plastic tubing from the pressure gage or manometer scale.

(21) Move the bottom of the black tape to the ruler's position-u.

(22) Repeat steps (17) - (20).

(23) Adjust the appropriate valves so that the flowmeter indicates the next flow rate to be tested.

(24) Repeat steps (17) - (20).

(25) Repeat steps (16) - (20).

(26) Repeat step (23).

(27) Repeat steps (17) - (23).

- (28) Repeat steps (24) - (27) until all flow rates have been tested at both position-l and position-u.

NOTE: The recommended sequence of experimental procedures is illustrated more compactly in the flow chart of Fig. 8.

4.0 Data Reduction

This section presents the methods for calculating interior subchannel, edge subchannel, and bundle average friction factors from experimental subchannel static pressure data.

4.1 Subchannel Friction Factors

The subchannel friction factor, f_i , is defined according to the following equation:

$$\Delta P_i = f_i \frac{L}{De_i} \frac{\rho V_i^2}{2g_c} \quad (4-1)$$

The parameters in this equation are determined as follows:

L is simply the separation distance between the ruler's position- u and position- l .

ΔP_i , taken as a positive quantity, represents the difference between the subchannel static pressure measured at the two locations referenced by position- l and position- u .

ρ is known as a function of the temperature of the water (see step (15) of Section 3.3). The water temperature also determines μ , which is used to calculate $Re_i = \frac{\rho V_i De_i}{\mu}$.

$De_i = \frac{4A_i}{P_{wi}}$ is calculated from the geometric characteristics of the subchannel.

V_i can be deduced from V_b given the appropriate flow split parameter, X_i (see Ref.[1]), since $X_i = \frac{V_i}{V_b}$. V_b , in turn, follows from the known bundle flow rate and bundle geometry since $V_b = \frac{Q_b}{A_b}$.

Thus, f_i can be calculated from Eq.(4-1), given the values of the above parameters. For example, with the

following data for a 37 pin bundle with $P/D = 1.15$ and $H/D = 21.0$,

$$Q_b = 101.1 \text{ GPM} = 0.2253 \text{ ft}^3/\text{sec}$$

$$A_b = 4.160 \text{ in}^2 = 0.02889 \text{ ft}^2$$

$$X_1 = 0.9750$$

$$X_2 = 1.030$$

$$V_i = 7.604 \text{ ft/sec}$$

$$V_2 = 8.033 \text{ ft/sec}$$

$$De_1 = 0.1955 \text{ in} = 0.01629 \text{ ft}$$

$$De_2 = 0.2401 \text{ in} = 0.02001 \text{ ft}$$

$$\rho = 62.40 \text{ lbm/ft}^3$$

$$\mu = 3.026 \text{ lbm/hr-ft} = 8.406 \times 10^{-4} \text{ lbm/ft-sec}$$

$$L = 20.50 \text{ in} = 1.708 \text{ ft}$$

$$\Delta P_1 = 1.315 \text{ psia} = 189.4 \text{ lbf/ft}^2$$

$$\Delta P_2 = 1.337 \text{ psia} = 192.5 \text{ lbf/ft}^2$$

it follows that:

$$f_1 = 0.03221 \text{ at } Re_1 = 9,195$$

$$f_2 = 0.03604 \text{ at } Re_2 = 11,932$$

In order to calibrate and verify subchannel friction factor correlations, it is useful to plot f_i as a function of Re_i on a log-log scale ([3],[6]). The result is similar in nature to the plot of $\log f_b$ versus $\log Re_b$ (see Section 4.2) shown in Fig. 9.

4.2 Bundle Average Friction Factor

The bundle average friction factor, f_b , is defined according to the following relation:

$$\Delta P_b = f_b \frac{L}{De_b} \frac{\rho V_b^2}{2g_c} \quad (4-2)$$

The parameters in this equation are determined as follows:

L , ρ (and μ), and V_b are calculated according to the discussion of Section 4.1.

$De_b = \frac{4A_b}{P_{wb}}$ is calculated from the geometric characteristics of the bundle.

ΔP_b is calculated from a force balance as follows [6]:

$$\Delta P_b = \sum_{i=1}^N \frac{\Delta P_i A_i}{A_b} \quad (4-3)$$

If the force due to the pressure difference acting over the relatively small area of the corner subchannels is neglected, and if one assumes that the pressure drops for all interior subchannels are identical and the pressure drops for all edge subchannels are identical, then Eq.(4-3) becomes:

$$\Delta P_b = \frac{N_1 A_1 \Delta P_1 + N_2 A_2 \Delta P_2}{N_1 A_1 + N_2 A_2} \quad (4-4)$$

Eq.(4-4) is used to calculate ΔP_b from ΔP_1 , ΔP_2 , and the geometry.

A sample calculation with data for the same 37 pin bundle referred to in Section 4.1,

$$Q_b = 0.2253 \text{ ft}^3/\text{sec}$$

$$A_b = 0.02889 \text{ ft}^2$$

$$V_b = 7.799 \text{ ft/sec}$$

$$De_b = 0.2090 \text{ in} = 0.01742 \text{ ft}$$

$$\rho = 62.40 \text{ lbm/ft}^3$$

$$\mu = 8.406 \times 10^{-4} \text{ lbm/ft-sec}$$

$$L = 1.708 \text{ ft}$$

$$\Delta P_1 = 189.4 \text{ lbf/ft}^2$$

$$\Delta P_2 = 192.5 \text{ lbf/ft}^2$$

$$A_1 = 0.0442 \text{ in}^2 = 3.069 \times 10^{-4} \text{ ft}^2$$

$$A_2 = 0.0890 \text{ in}^2 = 6.181 \times 10^{-4} \text{ ft}^2$$

$$N_1 = 54$$

$$N_2 = 18$$

yields:

$$\Delta P_b = 190.65 \text{ lbf/ft}^2 \text{ (from Eq.(4-4))}$$

and

$$f_b = 0.03296 \quad \text{at } Re_b = 10,085 \quad (\text{from Eq. (4-3)})$$

A typical plot of $\log f_b$ versus $\log Re_b$ is shown in Fig. 9. This plot exhibits the characteristic linear relation between $\log f_b$ and $\log Re_b$ for both the laminar and turbulent regimes, with a different slope for each regime.

5.0 Error Analysis

This section attempts to quantitatively evaluate the inaccuracy involved in the determination of friction factors from subchannel static pressure measurements. This discussion which follows applies to both bundle average and local subchannel friction factors.

5.1 Combination of Component Errors in Friction Factor Overall Inaccuracy

The overall error in the experimentally determined friction factor is a result of several component errors. If one assumes that the friction factor is only a function

of the velocity and the static pressure drop, then:

$$f_j = F(\Delta P_j, V_j) \quad (5-1)$$

where $j=1,2$, or b , and:

$$f_j + \delta f_j = F(\Delta P_j + \delta \Delta P_j, V_j + \delta V_j) \quad (5-2)$$

where $\delta \Delta P_j$ and δV_j (taken as positive quantities) are the errors in static pressure drop and velocity measurements, respectively. Expanding the function F in a Taylor series yields:

$$\begin{aligned} F(\Delta P_j \pm \delta \Delta P_j, V_j \pm \delta V_j) &= F(\Delta P_j, V_j) + \delta \Delta P_j \frac{\partial F}{\partial \Delta P_j} + \delta V_j \frac{\partial F}{\partial V_j} \\ &+ \frac{1}{2}[(\delta \Delta P_j)^2 \frac{\partial^2 F}{\partial \Delta P_j^2} + \dots] + \dots \end{aligned} \quad (5-3)$$

However, since $\delta \Delta P_j$ and δV_j are experimental errors and as such represent small quantities, the terms in Eq.(5-3) which include $(\delta \Delta P_j)^2$ and $(\delta V_j)^2$, as well as all higher order terms, are negligible. Thus, the maximum error in f_j is given by Eqs.(5-3), (5-2), and (5-1) as follows:

$$\delta f_j = \delta \Delta P_j \left| \frac{\partial F}{\partial \Delta P_j} \right| + \delta V_j \left| \frac{\partial F}{\partial V_j} \right| \quad (5-4)$$

The absolute value signs are used so that the two terms on the right hand side of Eq. (5-4) will sum to a maximum positive value of δf_j , regardless of the signs of the individual terms $\frac{\partial F}{\partial \Delta P_j}$ and $\frac{\partial F}{\partial V_j}$. By definition,

$$f_j = F(\Delta P_j, V_j) = \frac{2g_c}{\rho V_j^2} \frac{De_j}{L} \Delta P_j \quad (5-5)$$

Thus,

$$\begin{aligned} \left| \frac{\partial F}{\partial \Delta P_j} \right| &= \frac{2g_c}{\rho V_j^2} \frac{De_j}{L} \\ \left| \frac{\partial F}{\partial V_j} \right| &= \frac{4g_c}{\rho V_j^3} \frac{De_j}{L} \end{aligned} \quad (5-6)$$

and

$$\delta f_j = (\delta \Delta P_j) \frac{2g_c}{\rho V_j^2} \frac{De_j}{L} + (\delta V_j) \frac{4g_c}{\rho V_j^3} \frac{De_j}{L} \Delta P_j \quad (5-7)$$

Rearranging Eq. (5-7) and using Eq. (5-5):

$$\frac{\delta f_j}{f_j} = \frac{\delta \Delta P_j}{\Delta P_j} + 2 \frac{\delta V_j}{V_j} \quad (5-8)$$

for $j = 1, 2$, or b .

Therefore, the overall fractional error in the experimentally determined friction factor $(\frac{\delta f_j}{f_j})$ can be computed from Eq.(5-8), given the fractional error in static pressure drop $(\frac{\delta \Delta P_j}{\Delta P_j})$ and the fractional error in velocity $(\frac{\delta V_j}{V_j})$.

5.2 Error in Subchannel Static Pressure Measurements

The error in subchannel static pressure measurements is a result of several individual inaccuracies, namely:

- (1) The random error associated with high frequency fluctuations in the local subchannel static pressure.
- (2) The random error associated with fluctuations in the loop flow rate.
- (3) The random error associated with the experimenter's uncertainty in reading the static pressure gage or manometer.
- (4) The systematic error (or bias) associated with the accuracy of the static pressure gage.

The effect of the high frequency (10 - 100 hz.) static pressure fluctuations can be neglected, since the gages (and manometer) used in the experiment do not respond to such high frequency fluctuations [6].

The loop flow rate fluctuations, on the other hand, are observed to have a frequency on the order of 1 hz. (with an amplitude of about 3% of the mean flow rate). One would expect to observe a corresponding low frequency fluctuation in the subchannel static pressure readings. In order to estimate the magnitude of the low frequency subchannel static pressure fluctuations, a steady state analysis was performed (see Appendix A) to calculate the static pressure at a point for two different flow rates. The result of this analysis was that the static pressures differed by about 2.1 in. of water for the steady state flow rates Q (101.1 GPM) and $1.03 Q$ (104.1 GPM). However, it is experimentally observed that the pressure gage reading does not fluctuate while measuring the subchannel static pressure, yet a 2.1 in. of water fluctuation would certainly be noticed. Thus, it was deduced that the steady state analysis of Appendix A gives an overly conservative value for the static pressure inaccuracy from loop flow rate fluctuations, and it was concluded that a dynamic analysis was required.

Appendix B represents an attempt to reduce the conservatisms of Appendix A by performing an unsteady analysis. The system is modeled electrically as an inductor and a resistor in series, analagous to a fluid inertance and friction, respectively. The result is that velocity fluctuations of 3% at a frequency of 1 hz. are calculated to produce a static pressure fluctuation with an amplitude of about 0.15 in. of water (at a flow rate of 101.1 GPM), which is well within the accuracy to which the differential pressure gage can be read. Thus, it is concluded that the loop flow rate fluctuations produce a negligible subchannel static pressure fluctuation. This conclusion (which the reader should note is in conflict with the error analysis given in Ref.[6]) is supported by the previously mentioned observation that the differential pressure gage exhibits very stable subchannel static pressure readings.

The random error due to the uncertainty in reading the pressure measuring instruments is estimated to be:

± 0.02 in. of water for the manometer

± 0.25 in. of water for the 0-150 in. of water range gage

± 1.0 in. of water for the 0-400 in. of water range gage

These values are based simply on the separation between adjacent graduations on the scale of each individual instrument.

The systematic error associated with the accuracy of the pressure gages is given by the manufacturer as $\pm 0.5\%$ of the total gage scale. Thus, the maximum expected systematic error is:

nonexistent for the manometer

± 0.75 in. of water for the 0-150 in. of water range gage

± 2.0 in. of water for the 0-400 in. of water range gage

When the value of the statistical combination of the random errors is combined linearly with the systematic error, the result is the overall error in the subchannel static pressure measurement, δP_i (for $i=1$ or 2). Thus, denoting the individual inaccuracies introduced at the beginning of Section 5.2 as (1), (2), (3), and (4):

$$\delta P_i = \sqrt{(1)^2 + (2)^2 + (3)^2} + (4) \quad (5-9)$$

Table 2 shows the overall error in subchannel static pressure measurements (δP_i) as calculated by Eq.(5-9), for each pressure measuring instrument.

5.3 Error in Subchannel Static Pressure Drop

The subchannel pressure drop is the difference between two static pressure measurements, each with the random and systematic inaccuracies noted in Section 5.2. Since the random error can be positive for one static pressure measurement and negative for the other, the maximum random inaccuracy of their difference (i.e., $\delta\Delta P_i$) must be taken to be twice the random error of a single static pressure measurement.

However, one would expect the systematic error for each individual pressure measurement to be of the same sign, and approximately the same percentage of the true reading in magnitude. That is, if the true subchannel static pressures at two axial locations are indicated by P_{iu} and P_{il} , and if the systematic error is given by $\pm e$, then the most inaccurately measured values are $(1 \pm e)P_{iu}$ and $(1 \pm e)P_{il}$ where both coefficients are the same (either $(1 + e)$ or $(1 - e)$). The difference between the two measured static pressures is then given by $(1 \pm e)(P_{il} - P_{iu})$, or $(1 \pm e)\Delta P_i$. Thus, it follows that the maximum inaccuracy of the subchannel static pressure drop calculation is simply the

maximum systematic error of a subchannel static pressure measurement, $\pm e$, for the case when only the systematic error is accounted for.

Finally, the total inaccuracy of the subchannel pressure drop ($\delta\Delta P_i$) is given by the linear combination of twice the random error and the systematic error, where the random and systematic errors referred to are those of the individual subchannel static pressure measurements discussed in Section 5.2. Table 2 shows the values of $\delta\Delta P_i$ computed in the aforementioned manner.

5.4 Error in Bundle Average Pressure Drop

The bundle average pressure drop is given by Eq. (4-4) as:

$$\Delta P_b = \frac{N_1 A_1 \Delta P_1 + N_2 A_2 \Delta P_2}{N_1 A_1 + N_2 A_2} \quad (4-4)$$

The overall inaccuracy in the calculation of the bundle average pressure drop is determined according to the analysis presented in Section 5.1. That is, by analogy with Eq. (5-4),

$$\delta\Delta P_b = \delta\Delta P_1 \left| \frac{\delta F}{\delta\Delta P_1} \right| + \delta\Delta P_2 \left| \frac{\delta F}{\delta\Delta P_2} \right| \quad (5-10)$$

where in this case,

$$F = \Delta P_b(\Delta P_1, \Delta P_2) \quad (5-11)$$

Evaluating the partial derivatives of F via Eq.(4-4), and subsequent substitution into Eq.(5-10) yields:

$$\delta\Delta P_b = \delta\Delta P_1 \left[\frac{N_1 A_1}{N_1 A_1 + N_2 A_2} \right] + \delta\Delta P_2 \left[\frac{N_2 A_2}{N_1 A_1 + N_2 A_2} \right] \quad (5-12)$$

But $\delta\Delta P_1 = \delta\Delta P_2 = \delta\Delta P_i$, thus:

$$\delta\Delta P_b = 2\delta\Delta P_i \quad (5-13)$$

The values of $\delta\Delta P_b$ computed from Eq.(5-13) using the previously calculated values of $\delta\Delta P_i$ for each pressure measuring instrument are presented in Table 2.

5.5 Error in Subchannel and Bundle Average Friction Factors

Now that the component error due to the static pressure drop (see Sections 5.3 and 5.4) and the component error due

to the velocity measurement ($\pm 3\%$ of the measured velocity) have been determined, the overall inaccuracy of the bundle average and local subchannel friction factors can be calculated from Eq.(5-8). The resulting values of $\frac{\delta f_j}{f_j}$ appear in Table 2 as a function of the pressure measuring instruments, for Reynolds numbers within the range of operation for each instrument. Fig. 9 shows the error bars for f_b at these same Reynolds numbers.

5.6 Discussion

It should be noted that Chiu [6] calculates a "data reduction error," based on the maximum expected error resulting from the assumption that ΔP_1 is the same for all interior subchannels. This implies that Eq.(4-4) does not follow exactly from Eq.(4-3). Chiu uses the difference between ΔP_1 and ΔP_2 as a measure of the variation in static pressure drop between individual interior subchannels. However, Table 3 shows that the difference between ΔP_1 and ΔP_2 is considerably less than the estimated subchannel static pressure drop error ($\delta \Delta P_i$, as indicated in Table 2) for $Re > 500$, while the difference between ΔP_1 and ΔP_2 is approximately equal to $\delta \Delta P_i$ for the laminar flow regime.

On the basis of this observation, it was concluded that any variation in ΔP_1 among interior subchannels is already within the experimental error, hence Chiu's "data reduction error" was not considered.

APPENDIX A

Steady State Formulation of the Flow Rate Induced Error
In Static Pressure Measurements

This appendix presents a steady state analysis of the estimated error in static pressure measurements due to low frequency loop flow rate fluctuations. The analysis assumes that the system's response to these low frequency fluctuations is so quick that an upper bound on the variations in static pressure can be determined simply by a steady state calculation. Two constant flow rates (which differ by the amplitude of the maximum observed fluctuation) will be chosen, and the resulting difference in static pressure at a particular point in the bundle will be examined.

The system model to be used in this analysis is illustrated in Fig. A-1 (the relevant nomenclature is also presented in the figure). The first law of thermodynamics for the case of steady, incompressible flow, in the absence of work, is as follows:

$$\begin{aligned}
P_a + \frac{\rho V_a^2}{2g_c} &= P_b + \frac{\rho V_b^2}{2g_c} + \rho(l_a + l_b) \\
&+ f_a \frac{l_a}{De_a} \frac{\rho V_a^2}{2g_c} + f_b \frac{l_b}{De_b} \frac{\rho V_b^2}{2g_c} + K_e \frac{\rho V_a^2}{2g_c}
\end{aligned} \quad (A-1)$$

where K_e is the appropriate expansion loss coefficient. If the terms containing V_b^2 are assumed negligible in comparison with the corresponding terms containing V_a^2 (since $V_a A_a = V_b A_b$, but $A_a \ll A_b$), then Eq.(A-1) reduces to:

$$P_a = P_b + \rho(l_a + l_b) + \left[f_a \frac{l_a}{De_a} + K_e - 1 \right] \frac{\rho V_a^2}{2g_c} \quad (A-2)$$

Rewriting Eq.(A-2) for the new velocity V_a^* :

$$P_a^* = P_b^* + \rho(l_a + l_b) + \left[f_a \frac{l_a}{De_a} + K_e - 1 \right] \frac{\rho (V_a^*)^2}{2g_c} \quad (A-3)$$

Subtracting Eq.(A-2) from Eq.(A-3) and noting that $P_b = P_b^* = P_{atm}$,

$$P_a^* - P_a = \left[f_a \frac{l_a}{De_a} + K_e - 1 \right] \frac{\rho}{2g_c} \left[(V_a^*)^2 - (V_a)^2 \right] \quad (A-4)$$

Using the following set of values for the parameters appearing in Eq.(A-4):

$$\rho = 62.4 \text{ lbm/ft}^3$$

$$g_c = 32.2 \text{ lbm} \cdot \text{ft/lbf} \cdot \text{sec}^2$$

$$V_a = 7.80 \text{ ft/sec (i.e., } Q_b = 101.1 \text{ GPM)}$$

$$V_a^* = 1.03 V_a = 8.03 \text{ ft/sec}$$

$$Re_b = 10,085$$

$$f_b = 0.0330$$

$$K_e = 0.8$$

The following result is obtained:

$$P_a^* - P_a = 0.0744 \text{ psia} = 2.1 \text{ in. of water}$$

Thus, based on the above analysis, one would expect a fluctuation in the static pressure reading of up to 2.1 in. of water for a bundle flow rate of 101.1 GPM.

APPENDIX B

Unsteady State Formulation of the Flow Rate Induced Error
In Static Pressure Measurements

This appendix presents an unsteady analysis of the estimated error in static pressure measurements due to low frequency loop flow rate fluctuations. The analysis assumes that the steady state formulation of Appendix A is overly conservative, hence a dynamic formulation is required.

Fig.B-1 illustrates the model to be utilized in this analysis. Fluid inertance is modeled as an inductor, and friction is modeled as a resistor. The volumetric flow of the fluid is considered analagous to electric current, while fluid pressure drop is considered analagous to an electric potential difference.

The governing equation for this model is as follows:

$$V = L \frac{di}{dt} + Ri \quad (B-1)$$

where:

$V \equiv$ voltage

$L \equiv$ inductance

$i \equiv$ current

$t \equiv$ time

$R \equiv$ resistance

Using the analagous fluid variables in Eq.(B-1) yields:

$$P_a - P_{atm} = I \frac{dQ}{dt} + R_f Q \quad (B-2)$$

where:

$P \equiv$ static pressure

$I \equiv$ fluid inertance

$Q \equiv$ volumetric flow rate

$t \equiv$ time

$R_f \equiv$ fluid resistance

For the case of a steady flow rate $\bar{Q}$ (i.e., $\frac{dQ}{dt} = 0$),
Eq.(B-2) reduces to:

$$P_a - P_{atm} = R_f \bar{Q} \quad (B-3)$$

If $\frac{dQ}{dt}$ is nonzero, however, and if Q fluctuates about $\bar{Q}$ by an amount ΔQ in a time interval Δt , then Eq.(B-2) can be approximated by:

$$P_a^* - P_{atm} = I \frac{\Delta Q}{\Delta t} + R_f \bar{Q} \quad (B-4)$$

where P_a^* is the static pressure at point "a" which results from the fluctuation in volumetric flow rate. Using Eq.(B-3) to eliminate $R_f \bar{Q}$ in Eq.(B-4), and subsequent rearrangement yields:

$$P_a^* - P_a = I \frac{\Delta Q}{\Delta t} \quad (B-5)$$

In order to calculate I , the physical significance of fluid inertance needs to be investigated. Thus, consider the force required to produce an acceleration $(\frac{dv}{dt})$ of the fluid in a pure fluid inertance element. Using Newton's second law:

$$\text{Force} = \Delta P \times A = \rho l A \left(\frac{dv}{dt} \right) = \rho l \frac{dQ}{dt} \quad (B-6)$$

where $\rho l A$ is the mass of the fluid. For a pure electrical

inductor,

$$V = L \frac{di}{dt} \quad (B-7)$$

Thus, by analogy, the inductance (I) of the fluid is simply $\frac{\rho l}{A}$. Substituting this value in Eq.(B-5),

$$P_a^* - P_a = \frac{\rho l}{A} \frac{\Delta Q}{\Delta t} \quad (B-8)$$

If the following values are used in Eq.(B-8),

$$\rho = 62.4 \text{ lbm/ft}^3$$

$$\frac{1}{a} = \frac{l_a}{A_a} + \frac{l_b}{A_b} = 5.11 \text{ ft}^{-1}$$

$$\Delta Q = 0.03 \bar{Q} = 3.03 \text{ GPM} = 0.00675 \text{ ft}^3/\text{sec} \text{ (for } \bar{Q} = 101.1 \text{ GPM)}$$

$$\Delta t = 1 \text{ sec}$$

the result is:

$$P_a^* - P_a = 0.000464 \text{ psia} = 0.013 \text{ in. of water}$$

Thus, based on the above calculation, one would expect a flow rate fluctuation with an amplitude of $0.03 \bar{Q}$ and a frequency of 1 hz. to produce a fluctuation in the static pressure reading of about 0.013 in. of water (for $\bar{Q} = 101.1$ GPM). In addition, the pressure fluctuations are proportional to ΔQ , hence they would be expected to decrease as $\bar{Q}$ is decreased (since $\Delta Q = 0.03 \bar{Q}$).

TABLE 1

Distance (in.) Below Bundle Exit of Pressure Taps
Found in the 37-Pin Bundle
(P/D = 1.15, H/D = 21.0)

*35.75	19.75
29.75	19.25
28.75	18.75
27.75	18.25
26.75	17.75
24.75	17.25
23.75	16.75
23.25	16.25
22.75	15.75
22.25	*15.25
21.25	14.75
20.75	14.25
20.25	13.75

* Denotes taps utilized in static pressure drop experiment

TABLE 2
Summary of Errors

Instrument	Sec 5.2	Sec 5.3	Sec 5.4	Sec 5.5	Sec 5.5	Sec 5.5	Reb
	δP_i (in. of water)	$\delta \Delta P_i$ (in. of water)	$\delta \Delta P_b$ (in. of water)	$\frac{\delta f_1}{f_1}$	$\frac{\delta f_2}{f_2}$	$\frac{\delta f_b}{f_b}$	
Manometer	0.02	0.04	0.08	0.29	0.40	0.58	204
				0.17	0.18	0.29	426
0-150 in. of water range gage	1.0	1.25	2.5	0.84	0.80	1.58	1,521
				0.14	0.14	0.23	6,087
0-400 in. of water range gage	3.0	4.0	8.0	0.13	0.13	0.20	13,039

TABLE 3

Experimentally Determined Bundle Average
Friction Factors for a Range of Reynolds Numbers

Q (GPM)	Re _b	ΔP_1 (psia)	ΔP_2 (psia)	ΔP_b (psia)	f_b
2.12	203.5	0.00640	0.00426	0.00554	0.3136
2.70	259.2	0.00712	0.00567	0.00654	0.2282
3.28	314.9	0.00853	0.00712	0.00796	0.1882
3.86	370.6	0.00997	0.00853	0.00939	0.1603
4.44	426.3	0.0128	0.012	0.0125	0.1613
6.08	609.6	0.0145	0.0217	0.0174	0.1197
7.03	704.9	0.0271	0.0289	0.0278	0.1431
7.98	800.2	0.0367	0.0271	0.0328	0.1310
8.93	895.4	0.0325	0.0289	0.0310	0.09890
10.07	1,010	0.0361	0.0343	0.0354	0.08881
11.02	1,105	0.0361	0.0470	0.0405	0.08484
11.97	1,200	0.0434	0.0470	0.0448	0.07954
12.92	1,295	0.0470	0.0524	0.0492	0.07498
14.06	1,410	0.0506	0.0524	0.0513	0.06602
15.17	1,521	0.0578	0.0614	0.0592	0.06544
15.91	1,595	0.0650	0.0632	0.0643	0.06462
17.02	1,707	0.0723	0.0723	0.0723	0.06349
18.13	1,818	0.0759	0.0741	0.0752	0.05820
19.98	2,003	0.0849	0.0957	0.0892	0.05684
21.83	2,189	0.1048	0.1138	0.1084	0.05787
24.05	2,411	0.1120	0.1246	0.1171	0.05150
25.90	2,597	0.1337	0.1391	0.1359	0.05154
28.12	2,820	0.1554	0.1481	0.1525	0.04906
29.97	3,005	0.1734	0.1734	0.1734	0.04911
31.82	3,191	0.1807	0.1861	0.1829	0.04595
34.78	3,487	0.2132	0.2150	0.2139	0.04498
36.99	3,709	0.2312	0.2493	0.2385	0.04434
41.81	4,192	0.2800	0.3035	0.2894	0.04212
46.31	4,644	0.3306	0.3577	0.3415	0.04051
51.28	5,142	0.4010	0.4191	0.4083	0.03950
60.71	6,087	0.5420	0.5456	0.5434	0.03751
70.37	7,056	0.7063	0.7100	0.7078	0.03637
80.62	8,084	0.8906	0.9087	0.8979	0.03514
88.60	8,884	1.0749	1.0749	1.0749	0.03484
101.12	10,139	1.3151	1.3368	1.3238	0.03294
109.69	10,999	1.5446	1.5536	1.5482	0.03273
119.93	12,025	1.7704	1.8065	1.7849	0.03157
130.04	13,039	2.0955	2.0775	2.0883	0.03142

FIGURE 1

Flow Diagram of the Main Water Circulation Loop (from Ref.[2])

FIGURE 2

Schematic of Hollow Pressure Tap Rod and Inserted Injector

i: interior pressure tap rod

e: edge pressure tap rod

FIGURE 3

Locations of Interior and Edge Pressure Tap Rods
In the Reference Bundle

FIGURE 4

Radial Location of the Pressure Taps Relative
To the Wire Wrap

FIGURE 5

Axial Static Pressure in a Peripheral Edge Subchannel

(from [5])

FIGURE 6

Schematic of Test Section and Measurement Apparatus

FIGURE 7

Schematic of Manometer

FIGURE 8

Flow Chart Showing Sequence of Experimental Procedures

FIGURE 9

Bundle Average Friction Factor
Vs. Bundle Average Reynolds Number
(including error bars)

FIGURE A-1

System Model for the Steady State Analysis of Appendix A

FIGURE B-1
System Model for the Unsteady State Analysis
Of Appendix B

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