INPUT PARAMETERS TO THE ENERGY CODE
(TO BE USED WITH THE ENERGY CODES MANUAL)

by

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1.0 INTRODUCTION

The purpose of this report is to summarize recommended values of input data required by ENERGY code users. It is intended that this report will be updated as data analysis dictates (1) new input data for rod bundle geometries already surveyed or (2) input data for new rod bundle geometries.

1. Flow-Split

The division of flow at the inlet to the bundle (flow split) must be specified as a boundary condition. The porous body model of ENERGY requires, as input, the flow split between regions I and II. The subchannel analysis version of ENERGY requires, as input, the flow split between the various subchannels. The theoretical flow split suggested in Ref. 1 is not in complete agreement with the available data^(2,3,4,5,6) for wall channels(Fig.1). This discrepancy between the predicted and experimentally observed flow splits would also exist for central channels.

The flow split can be determined by (a) completely neglecting geometrical tolerance, and (b) allowing for geometrical tolerance. In reality, geometrical tolerance effect exists and must be taken into account. Following the method given by Hanson in Ref. 2 (appendix) if T is the diametrical tolerance across the flats of a bundle a fraction F of this would be accommodated within the bundle and a fraction (1 - F) in the wall region. Then the pitch, p, of the wire wrapped bundle must be increased by Δp due to the "looseness" caused by geometrical tolerance, where

$$\Delta P = TF/(\sqrt{3}.N_{RINGS})$$

The gap between the wire and the wall is given by

$$\Delta R = \frac{T}{2} (1 - F)$$

The two extreme cases for tolerance distribution are

Case I: $F = 0$ $\Delta P = 0$ $\Delta R = T/2$

Case II: $F = 1$ $\Delta P = T(\sqrt{3} \cdot N_{\text{RINGS}})$ $\Delta R = 0$

The actual tolerance will lie somewhere in between the two extreme cases mentioned above.

The effect of these two extreme cases on flow split in the wall channel are shown in Fig. 1 for the MIT 61-pin bundle which has a diametrical tolerance of 0.0195 in. in a duct with a distance across the hexagonal flats of 2.560 in.

In most bundles it is expected that Case II will exist where all the tolerance is accommodated within the bundle. Observation of the (Ref. 2) MIT bundle agrees with this suggestion as the pins were observed to contact the duct faces when the bundle was assembled. This was also observed in the AI 217 pin bundle (Ref. 4). Wherever there is a doubt as to which of the two limiting cases exists within a bundle, we have examined⁽⁷⁾ the two limits of flow splits for wall channel corresponding to the two cases.

It is interesting to note that for the 7-pin bundle

it was possible to predict both the wall channel and inner channel flow splits accurately. As the bundle size increased there appears to be a divergence between theoretical predictions and experimentally observed data on a similar geometry. Allowing the experimental predictions to have an associated error bar, it still appears that the theoretical flow split predicts higher axial velocities in the wall channels (and lower axial velocities in central and corner channels) than experimentally observed. If the divergence in the theoretical and experimental curves is in fact real then a correction factor on hydraulic diameter alone would not bring the two curves together. A bundle size effect exists in that case. If a bundle size effect exists it could be only due to a change in the basic flow field in going from a 7-pin to a 217-pin bundle.

The method of Novendstern¹ for determining flow division in the subchannels of a LMFBR bundle is briefly described below and it is shown how one can use this to determine the flow split between regions I and II of our model.

Novendstern¹ considers a bundle with NN1 interior channels, NN2 wall channels and NN3 corner channels. Since the pressure drop in all subchannels is the same,

the velocity in each subchannel can be determined using the friction factor relationship. Thus for channels of type 1 (interior), type 2 (wall) and type 3 (corner) one can write

$$\frac{f_1}{de_1} \frac{\rho v_1^2}{2} = \frac{f_2}{de_2} \frac{\rho v_2^2}{2} = \frac{f_3}{de_3} \frac{\rho v_3^2}{2} \quad (1)$$

Assume if the friction factor is given by

$$f = \frac{C}{Re^m}, \text{ and substituting into the equation (1)}$$

$$\frac{v_1^{2-m}}{de_1^{1+m}} = \frac{v_2^{2-m}}{de_2^{1+m}} = \frac{v_3^{2-m}}{de_3^{1+m}} \quad (2)$$

The continuity equation is,

$$NN_1 V_1 A_1 + NN_2 V_2 A_2 + NN_3 V_3 A_3 = \bar{V} A_T \quad (3)$$

then from (2) and (3) eliminate V_2 and V_3 to get

$$\frac{V_1}{\bar{V}} = \frac{A_T}{[NN_1 A_1 + NN_2 A_2 \left(\frac{de_1}{de_2}\right)^\alpha + NN_3 A_3 \left(\frac{de_3}{de_2}\right)^\alpha]} \quad (4)$$

Similar equations for $\frac{V_2}{\bar{V}}$ and $\frac{V_3}{\bar{V}}$ can be easily derived.

Here

$$\alpha = \frac{1 + m}{2 - m}$$

The V's are the actual fluid velocities.

In the ENERGY series of codes the flow splits

$$\frac{U_1}{U} \text{ and } \frac{U_2}{U}$$

at the inlet must be specified by the user. In order to determine these, one may use Novendstern's method for subchannels as follows. For Region I the flow split is the same as for Novendstern's central channels, i.e.

$$\frac{U_1}{U} = \frac{V_1}{V} * \left(\frac{\lambda a_1}{\lambda a} \right)$$

if the boundary of Region I is taken to pass through the centers of rods adjacent to the wall. For region II the flow split $\frac{U_2}{U}$ may be calculated from equation 5.

$$\frac{U_2}{U} = \left[\left(\frac{V_2}{V} \right) F_2 + \left(\frac{V_3}{V} \right) F_3 \right] \frac{\lambda_{a2}}{\lambda_a} \quad (5)$$

where

$$F_2 = \frac{NN_2 \cdot A_2}{NN_2 A_2 + NN_3 A_3} ; F_3 = \frac{NN_3 \cdot A_3}{NN_2 A_2 + NN_3 A_3}$$

λ_{a1} = Average axial porosity of region I

λ_{a2} = Average axial porosity of region II

λ_a^- = Average axial bundle porosity

Until the question of the bundle size effect is fully resolved one needs to take into account the flow split effect discussed earlier while analyzing other data and in predicting temperatures for the full size bundle at power conditions. The ENERGY-I analysis of data has taken into account the uncertainty in flow split in calibrating the two constants ϵ^* and C.

The effect of this flow split uncertainty on the constants has been discussed explicitly ⁽¹⁾ only for those cases where it was found to have a measurable effect.

2. ϵ^* and C

Figures 2 and 3 give the variation of ϵ^* vs d/h for various values of p/d and the variation of C with d/h . These figures are taken from Ref. 7. For further details on the analysis of data see Ref. 7. Correlations were obtained for ϵ^* and C. These are given below. The use of these correlations is recommended within their range of applications.

Restrictions on Use of Correlations

(a) bundle must have all wire wraps of the same diameter wrapped in the same sense from the same start position.

(b) $14 \leq h/d \leq 52$

(c) $1.14 \leq p/d \leq 1.32$

The correlations for ϵ^* and C are as follows:

$$\epsilon^* = \{ 0.85 - 12.8[|p/d - 1.25|]^{1.424} \} (d/h)$$

Data correlated within $\pm 20\%$ at a 95% confidence level.

$$C = 0.09 + 2(d/h - 0.03)$$

Data correlated within $\pm 35\%$ at a 95% confidence level.

The parameters ϵ_1^* and C_1 , for use in subchannel

analysis codes can be determined from ϵ^* and C as follows:

$$\epsilon^* = \epsilon_1^* \frac{\lambda_{LI}}{\lambda_a}$$

$$C = C_1 \frac{\lambda_s}{\lambda_a}$$

For definitions of λ 's and derivation of these two relationships see Appendix 1, taken from Ref. 7.

IMPORTANT NOTE

The listing of the ENERGY codes uses "d" the rod diameter as the non-dimensionalising parameter. However it was later decided to use d_e the hydraulic diameter of the inner channel as the characteristic dimension (as opposed to d) in order to maintain the same definition of Reynolds number as commonly used in literature. Thus Reynolds number is defined as $\frac{\rho \bar{U} d_e}{\mu}$ and ϵ^* is defined as $\frac{\epsilon}{\bar{U} d_e}$. The code requires $\epsilon^* \left(= \frac{\epsilon}{\bar{U} d_e} \right)$ as input but converts it to $\frac{\epsilon}{\bar{U} d}$ for use in the ENERGY code. The correlation presented for ϵ^* also uses d_e as the characteristic dimension.

3. Criterion To Determine When Buoyancy Effects Are Important

In Ref. 7 a criterion has been found to determine when buoyancy effects are important in a wire wrapped fuel or blanket assembly operating in steady state mixed convection flow.

Buoyancy effects were determined to be important when $Gr^* \geq Gr_c^*$. The critical value of this dimensionless group, called Gr_c^* , has been found to be approx. 0.02(Ref.7).

For an assembly operating in steady state conditions, the definition of Gr^* was determined to be as follows:

$$Gr^* = \frac{Gr}{fRe^2} \times$$

where

$$\times = \frac{1}{M} \frac{Q_p^{-1}}{2} \frac{1}{\gamma L}$$

$$Gr = \frac{g_o \beta (T_M - T_{1N}) d_e^3}{\gamma_k^2}$$

$$\gamma = \frac{(p/d-1)}{\pi} \frac{16}{D} (\epsilon_1^* + \alpha^*)$$

$$(T_M - T_{1N}) = \text{average axial temperature rise across the bundle of height } L$$

$$\hat{Q}_p = \text{radial power skew (peak/avg)}$$

$$Re = \text{Reynolds number in bundle based on } d_e \text{ and interior channel axial velocity and bundle mean axial temperature}$$

$$D = \text{duct flat to flat distance}$$

de = hydraulic diameter of an interior channel

f = friction-factor determined from smooth tube conditions at Re based on definition

$$\frac{\Delta p}{\frac{L}{de} \frac{\rho v^2}{2}} \equiv f$$

v = interior channel axial velocity

L = bundle length

p/d = pitch/diameter of interior channel

ϵ_1^* = mixing coefficient (subchannel analysis); function of h/d, p/d

α^* = 1/Re Pr based on bundle mean axial temperature

γ_k = kinematic viscosity evaluated at mean bundle temperature $(T_M + T_{1N})/2$

β = volume expansion coefficient, evaluated at mean bundle temperature

M = Novendstern's multiplication factor for wire wrapped bundles

$$M = \left\{ \frac{1.034}{(p/d)^{0.124}} + \frac{29.7(p/d)^{6.94} Re^{0.086}}{(h/d)^{2.239}} \right\}^{0.885}$$

g_o = acceleration due to gravity

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LIST OF FIGURES

1. Theoretical Flow Split for Wall Channels vs Wire-Wrapped Bundle Size
2. Variation of ϵ^* with d/h for Various Values of p/d
3. Variation of C with d/h

THEORETICAL FLOW SPLIT FOR WALL CHANNELS VS WIRE-WRAPPED
BUNDLE SIZE USING METHOD OF REF. 1

FIG. 1

FIG. 2

FIG. 3

APPENDIX 1

Analysis of Data Using Subchannel Analysis

Version of ENERGY Code

Analysis of forced convection data reported in Ref. 7 was performed by using the subchannel analysis version of the ENERGY-I code called ENERGY-IS. The subchannel analysis form of ENERGY code maintains the basic region model discussed in Chapter 2.1^[7] where the bundle is divided into two predominant regions. In the central region (Region I) the mixing effect is modeled by an enhanced effective eddy diffusivity ϵ_1^* and in the wall region a uniform swirl flow C_1 (see nomenclature and Appendix 1^[7] for definition) is maintained along the duct wall. The axial velocities used in ENERGY-IS are the actual axial velocities in the voids of the bundle. Another difference between the two versions of ENERGY is the nodal network. The subchannel analysis requires each node to lie at the center of each subchannel and the area associated with each node is the actual subchannel area. The empirical constants ϵ_1^* and C_1 obtained from data analysis using ENERGY-IS can be related as follows to ϵ^* and C , obtained in Chapter 3, Ref. 7, using the porous body model, ENERGY-I.

Let λ_a^- be the average axial porosity of the bundle, defined as follows:

$$\lambda_a^- = \frac{\text{void area}}{\text{total area}}$$

Let λ_{L_1} and λ_S be the lateral porosities in region I and region II, respectively, defined as follows:

$$\lambda_{L_1} = \frac{p - d}{p} \quad (A.11)$$

$$\lambda_S = \frac{g}{t} \text{ where } t = g + \frac{d}{2} \quad (A.12)$$

The width of region II, t , as discussed in Chapter 2.4, Ref. 7, was taken in the analysis of data to be equal to $\frac{d}{2} + g$, where g = gap between the rod and wall and d = diameter of rod.

The energy equation in region I, for any node i , may be written as follows for the porous body version, ENERGY-I (subscript P represents the porous body model)

$$(\rho UA)_P \frac{dH}{dz} = (QA)_P + (EX1)_P \quad (A.13)$$

where

$$\begin{aligned} EX1 = & GBAR_P \cdot \left(\frac{d_e}{\eta}\right) \cdot (\epsilon^* + \kappa \alpha_P^*) \cdot (A_C)_P \\ & \cdot (H_1 + H_2 + H_3 - 3H) \end{aligned} \quad (A.14)$$

For the subchannel analysis version, ENERGY-IS

$$(\rho UA)_S \frac{dH}{dz} = (QA)_S + (EX1)_S \quad (A.15)$$

where

$$\begin{aligned} EX1 = & GBAR_S \left(\frac{d}{\eta} e \right) (\epsilon_1^* + SF \alpha_S^*) (AC)_S \\ & \cdot (H_1 + H_2 + H_3 - 3H) \end{aligned} \quad (A.16)$$

where SF = a shape factor used in subchannel analysis version, ENERGY-IS. It can be easily seen

$$(\rho UA)_P = (\rho UA)_S \quad (A.17)$$

$$(QA)_S = (QA)_P \quad (A.18)$$

$$(GBAR)_P = \lambda_a^- (GBAR)_S \quad (A.19)$$

$$(AC)_P = \left(\frac{1}{\lambda_{L1}^-} \right) (AC)_S \quad (A.20)$$

$$\alpha_P^* \left(= \frac{\alpha}{\bar{U} d_e} \right) = \frac{\alpha_S^*}{\lambda_a^-} \quad (A.21)$$

since

$$\bar{U} = \lambda_a^- \bar{V} \quad (A.22)$$

In order to obtain the same value of $\frac{dH}{dz}$ it is necessary that

$$\epsilon^* = \frac{\lambda_{L1}}{\lambda_a^-} \epsilon_1^* \quad (A.23)$$

and also

$$\kappa = \lambda_{L_1} * SF \quad (A.24)$$

In a similar fashion one can show that

$$C = C_1 \frac{\lambda_S}{\lambda_a} \quad (A.25)$$

Since ϵ^* , C and κ have already been determined in Chapter 2 and 3, the values of SF , ϵ_1^* and C_1 can be calculated using equations (A.23), (A.24) and (A.25). These calculated values must be used in the subchannel analysis version, i.e., ENERGY-IS.