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ABSTRACT

A proposed method for selecting and applying hot channel factors is presented along with some justification for these selections. The method is illustrated by example, and the sensitivity to some of the choices is examined. The uncertainty in the heat transfer coefficient is a major contributor to the reduction in thermal-hydraulic safety margins. The uncertainty introduced by the heterogeneity in the fuel is another important contributor and an area where more information may be useful in reducing this uncertainty.

INTRODUCTION

The selection of engineering hot channel factors for the thermal-hydraulic analysis of the limiting (hottest) channel can have a significant impact on reactor safety margins. Some reactor designs have large safety margins, and large uncertainties can be assumed without any particular difficulty. Even in these cases the choice of overly conservative peaking factors can unnecessarily limit the range and usefulness of the reactor. The safety documents for the current reactors show a variety of choices for peaking factors and often with little justification for those choices. There seems to be no generally accepted method for the selection of hot channel factors.

A method for the selection and application of hot channel factors is proposed here for consideration. The assumption here is that the fuel plate design has been set (perhaps through standardization), and the reactor operator must now evaluate this fuel for this reactor based on the given fabrication tolerances and uncertainties. The thermal-hydraulic limits of the fuel are not used to establish what tolerances can be allowed in the fuel fabrication. The method is illustrated by example, and the sensitivity to some of the choices is examined.

METHOD AND EVALUATION

Engineering hot channel factors may be broken down into three separate components corresponding to:

(1) Uncertainties that influence the heat flux, F_q

(2) Uncertainties in the temperature rise or enthalpy change in the channel, F_b

(3) Uncertainties in the heat transfer coefficient, F_h.

These factors should be introduced into the analysis as

$$q''_{hc} = F_q * q''_{nc}$$

$$\Delta T_b = F_b * Q/(C_p * MFR)$$

$$\Delta T_s = F_h * q''/h$$

where the notation hc refers to the hot channel value and nc refers to the nominal channel value for the heat flux (q”), and MFR is mass flow rate. The remaining notation is standard. F_b can be defined as the ratio $\Delta T_{hc}/\Delta T_{nc}$ for the bulk (b) coolant temperature, and F_h can be defined as a similar ratio in the clad surface (s) temperature. These components can be broken down further into sub-factors and combined either multiplicatively

$$F_b = f_{b1} * f_{b2} * f_{b3} * \cdots$$

or statistically

$$F_b = 1 + \sqrt{\sum_i (1 - f_{bi})^2}$$

Many of the sub-factors may be determined from the tolerances in the specifications for the fuel elements, pumps, and other related components. Other sub-factors may be determined from limitations in the ability to measure certain parameters accurately, such as, flow rates and temperatures. While still others may require some engineering judgment in the assessment of the quality of the data available. Some thermal-hydraulic analysis may be useful in determining the range of influence of certain variations.

The specifications for the fuel plates and elements that are used in the fabrication of the fuel usually contain tolerances on the fuel loading, the fuel density variation, plate thickness, and channel spacing. A portion of the fuel plate specifications for the University of Michigan[1] are quoted here for illustration and further discussions:

1) Fuel Loading - Each Fuel Plate shall contain 9.28 grams ± 0.18 gram U-235 based upon final weight of the final compact and chemical and isotopic analysis of the constituents.

2) Fuel Homogeneity - Density of the fuel per 0.08-inch-diameter Fuel Core area shall not differ by more than ± 20% from the average for all Fuel Core locations, except in the area one (1) inch from each end of the Fuel Core where the variance may be ± 30% in a region not to exceed 1/2 inch in the Fuel Plate longitudinal direction. A "high" region shall be defined as a location for which the fuel density per 0.080-inch-diameter Fuel Core area exceeds 20% of the Fuel Plate average. The average fuel density of the "high" region and four regions taken at the corners of a 1/2-inch-square symmetric about the "high" region shall be less than 20%. Between the minimum and maximum permissible fuel core length boundary, fuel underload condition shall not be evaluated.

From these specifications, the fuel loading in a plate can be higher than nominal by nearly 2%, and the density can be 20% higher in the X-ray scan. The tolerances on plate and channel dimensions may be extracted from the associated blue prints used in fuel fabrication. From these data the uncertainty in the plate thickness is slightly more than 3%, and the channel spacing can be almost 6% smaller than nominal. The channel spacing does not include bowing of the plates.

These fuel plate and channel tolerances can be translated into subfactors in most cases without difficulty. The presence of a higher fuel loading in a plate will result in both an increase in the heat flux from the plate and a temperature rise in the channel. A fuel loading specification of M per plate with a tolerances of Δm translates into the following sub-factors:

$$f_q = 1.0 + \Delta m/M$$

$$f_b = 1.0 + \Delta m/M$$

The fuel plate tolerances with upper and lower thicknesses specified for the entire fuel plate can conservatively be assumed to be the result of variation in the fuel meat thickness. A thicker fuel meat region results in an increase in the local heat flux. Here one could also assume that the meat is thicker over the entire length of the plate and that the bulk temperature is also affected by this variation in thickness. This overall variation is addressed under density uncertainties. If the nominal meat thickness is t_m and the tolerance on the plate is $\pm \Delta t_p$, the heat flux sub-factor may be expressed as:

$$f_q = 1.0 + \Delta t_p/t_m.$$

The potential reduction in the flow channel spacing results in both a bulk temperature rise (ΔT_b) over the channel and a reduction in the heat transfer from the clad to the coolant (ΔT_s). For turbulent flow the change in channel thickness can be related to these temperature changes through basic principles[2]. First it is useful to develop an expression relating the change in flow in the hot channel to the nominal. The pressure drop across the hot channel is assumed to be equal to that of the nominal channel (a good assumption with forced flow), and the pressure drop can be expressed as

$$\Delta p = fr * \frac{L}{De} * \frac{\rho v^2}{2}$$

where fr is the friction factor for the channel. Thus, the velocity (v) is proportional to $(De/fr)^{1/2}$, and the hot to nominal velocity ratio can be written as

$$\frac{v_{hc}}{v_{nc}} = \left[\frac{De_{hc}}{De_{nc}}\right]^{1/2} * \left[\frac{fr_{nc}}{fr_{hc}}\right]^{1/2} .$$

The friction factor may be expressed in terms of the Reynold's number ($Re^{-\alpha}$) where Re = $\rho * v * De/\mu$. With the assumption that ρ and μ are constant, the velocity ration can be rewritten as

$$\frac{v_{hc}}{v_{nc}} = \left[\frac{De_{hc}}{De_{nc}}\right]^{(1+\alpha)/(2-\alpha)}$$

where the friction factor coefficient, α, is usually in the range of 0.2 - 0.25.

Now using the relation q" = h * ΔT_s, the sub-factor f_h, the ΔT ratio of hot to nominal at the clad surface, can be expressed as h_{nc}/ h_{hc}. The heat transfer coefficient for single-phase turbulent flow is usually represented by correlations that are proportional to $(Re)^{0.8}/De$, again Re is proportional to v*De, and the above heat transfer ratio can be written as $(v_{nc}/v_{hc})^{0.8}$ * (De_{hc}/De_{nc}). The velocity ratio can then be replaced by the expression derived above to give the hot channel sub-factor

$$f_h = \left[\frac{De_{nc}}{De_{hc}}\right]^{(0.4+\alpha)/(2-\alpha)}$$

In a similar fashion, a hot channel sub-factor for the bulk temperature rise due to a channel reduction can be derived. Using $Q = \rho * A * v * C_\rho * \Delta T_b$. ΔT_b is proportional to l/Av, and the flow area, A, is proportional to De. The ΔT ratio of hot to nominal, f_b, can be expressed as

$$f_b = \frac{De_{nc}}{De_{hc}} * \frac{v_{nc}}{v_{hc}}$$

and again substituting for the velocity ratio gives the relation

$$f_b = \left[\frac{De_{nc}}{De_{hc}}\right]^{3/(2-\alpha)}$$

For plate geometry De is approximately equal to 2t, where t is the channel thickness, the above sub-factors can be written as

$$f_n = \left[\frac{t_{nc}}{t_{hc}}\right]^{(0.4+\alpha)/(2-\alpha)}$$

$$f_b = \left[\frac{t_{nc}}{t_{hc}}\right]^{3/(2-\alpha)}$$

For a friction factor coefficient of $\alpha = 0.2$, $f_h = (t_{nc}/t_{hc})^{1/3}$ and $f_b = (t_{nc}/t_{hc})^{5/3}$, and if the channel thickness in the hot channel is 10% less than the nominal value, $f_h = 1.04$ and $f_b = 1.19$. These expressions were derived under the assumption of turbulent flow and forced convection (ρ, μ, and C_p constant), and are not valid for other flow regimes.

The homogeneity specifications for the fuel are subject to some interpretation and may not really be used directly for choosing hot channel factors. The density measurements are a function of the apparatus used to make the measurements. In either a direct or indirect manner the instrument measures the transmission of X-rays through the fuel plate, and with proper calibration these may be translated into density values over the viewing area. The aperture in this example is 0.08 inches in diameter, and the densities are average densities within this aperture. Other instruments may have smaller apertures with larger tolerances or larger apertures with smaller tolerances, and all indicating the same degree of homogeneity. None of the instruments indicate the degree of heterogeneity within the aperture (the fuel particles may all be lumped into one portion of the aperture). The method outlined in this example seems to allow credit to be taken for the spot to be an isolated area of high density surrounded by areas of lower density (conduction away from the hot spot transverse to the clad surface may reduce the importance of the heterogeneity). The reasoning behind these particular choices of aperture size and tolerance seems to have been lost over the years. The density variations observed by these instruments is not only a function of the heterogeneity but also of the thickness of the meat. A thicker meat will also be indicated as a higher density. This uncertainty may duplicate the uncertainty already included for the fuel plate thickness.

The heterogeneity in the higher density fuels with LEU is more of a concern than was the case in the earlier HEU fuels. The conductivity is generally much lower with less aluminum in the matrix at the high densities, and the heat cannot be conducted away from the regions of higher fuel concentration as readily as was the case with HEU fuel. The uncertainty in the homogeneity of the fuel is also an important factor to include in the evaluation of hot channel factors for the LEU fuels. Clearly more work is needed to couple the density measured in the aperture to the actual heterogeneity this may represent in the fuel meat. This is not to say that these measurements are no longer adequate for the acceptance of the fuel plates as fabricated.

For an uncertainty in the local density of X%, the sub-factor for the heat flux can be expressed as f_q = 1.0 + X/100. In some assessments this same value is taken as an uncertainty applied to the factor f_h, but this seems to be a duplication and is not done here (in q" = h * ΔT_s, h is not reduced along with an increase in q"). The density variation of Y% from end-to-end may also be expressed in f_b = 1.0 + Y/100 for the temperature along the channel. At this time an uncertainty of 20% is believed to be a conservative estimate for the variation in the heat flux, and an additional 10% uncertainty is assumed for the variation in density end-to-end (including the dog bone region) and applied to the temperature rise along the channel.

Most of the other uncertainties can be related to uncertainties in measurements or tolerances in equipment. Some of these data can be taken from the specifications of the equipment, such as, pumps, meters, etc. Others may be taken from known uncertainties in measurements and methods of calibration.

Uncertainties in the flow can result from tolerances in pumping rate as the pump speed may vary with voltage fluctuations or load. There may be uncertainties in the instruments used to measure flow. There may also be uncertainties assigned to plenums, orifices, piping, etc. If these uncertainties are ± X%, the following factors can be set:

$$f_b = 1.0 + X/100)$$

$$f_h = (1.0 + X/100)^{0.8},$$

where the 0.8 exponent comes from the exponent on the Reynold's number in most single phase heat transfer correlations, and the Reynold's number is directly proportional to the flow rate.

Uncertainties in the power level and the power density may be attributed to the various sources. There may be uncertainties in the power level due to limitations in the calibration of the instrumentation or in the sensitivity of the equipment used for measurements. Uncertainties in the computed power density data may be assigned based on uncertainties in the basic data, dimensions, method, etc. With an uncertainty of ± X%, the following factors can be specified:

$$f_q \text{ and } f_b = 1.0 + X/100$$

The last major uncertainty to be discussed is in the heat transfer coefficient. This uncertainty may be based on the spread of data and the fit of the data by the selected correlation. The experimental data generally fit within a band of ± 20% for any of the single phase correlations commonly used. For an uncertainty of X%, the sub-factor f_h = 1.0 + X/100 is assigned.

Some of the other factors that might be considered, such as, conductivity and heat capacity have been found to have little impact on the results. Uncertainties in these properties are neglected. Also in some of the derivations, the density and viscosity are assumed constant. These assumptions are not valid for reactors under natural convection flow conditions. Other factors may need to be considered is some special cases.

The following tabulation provides a summary of the proposed subfactors:

Fuel loading/plate - M ± Δm

$$f_q \text{ and } f_b = 1.0 + \Delta m/M$$

Fuel plate thickness - ± Δt_p

$$f_q = 1.0 + \Delta t_p/t_m, \text{ where } t_m = \text{nominal meat thickness}$$

Fuel density - ± X%, local and ± Y%, end-to-end

$$f_q = 1.0 + X/100 \text{ and } f_b = 1.0 + Y/100$$

Channel thickness - t ± Δt

$$f_h = (1.0 - \Delta t/t)^{-(0.4+\alpha)/(2-\alpha)} \text{ and } f_b = (1.0 - \Delta t/t)^{-3/(2-\alpha)}$$

where α = friction factor coefficient

Flow rate - ± X%

$$f_b = 1.0 + X/100 \text{ and } f_h = (1.0 + X/100)^{0.8}$$

Power and power density - ± X%

$$f_q \text{ and } f_b = 1.0 + X/100$$

Heat transfer coefficient - ± X%

$$f_h = 1.0 + X/100$$

APPLICATION

The fuel specifications for the University of Michigan as quoted in the previous section are used as an example. This fuel design is proposed for the 10 kW reactor at Worcester Polytechnic Institute (WPI). The reactor is pool type and cooled by natural convection. Thus, some of the expressions do not apply to this example. The assumptions of turbulent flow, constant density, and constant viscosity are no longer valid with natural convection. There is no pump associated with the coolant flow, and the flow rate in the channel changes as the heat flux changes. The sub-factors associated with a reduction in the channel spacing have been obtained from a natural convection thermal-hydraulics code.

The fuel plate specifications and blue prints for fabrication give the following data:

Plate thickness, in	0.062/0.058
Channel spacing, in	0.123/0.103
^{235}U loading/plate, g	9.28 ± 0.18

The fuel plate variation is ± 0.002 in., the nominal meat thickness is 0.030 in., and the meat thickness variation is then taken to be ± 7%. The nominal channel spacing is 0.109 in., and the reduction in spacing allowed is about 6%. However, a variation of 10% was assumed and introduced in a steady-state thermal-hydraulics computation. This resulted in a 16% rise in the bulk temperature in the channel, and a 14% increase in the temperature difference at the clad surface. The uncertainties in the fuel density are taken to be ± 20% over the fuel core and ± 10% end-to-end.

Since data were not available for uncertainties in power, power density, and flow in this case, the following assumptions were made:

Uncertainty in power measurement	± 5%
Uncertainty in power density	± 10%
Uncertainty in flow measurement	± 10%

The uncertainty in the heat transfer coefficient for this natural convection case was taken to be ± 20%.

The hot channel factors and the hot channel sub-factors derived from the uncertainties for the WPI reactor are summarized in the following table:

Uncertainty	**F_q**	**F_b**	**F_h**
Fuel Meat Thickness	1.07	-	-
^{235}U Loading	1.02	1.02	-
^{235}U Homogeneity	1.20	1.10	-
Coolant Channel Spacing	-	1.16	1.14
Power Measurement	1.05	1.05	-
Calculated Power Density	1.10	1.10	-
Coolant Flow Rate	-	1.10	1.10
Heat Transfer Coefficient	-	-	1.20
Multiplicative Combination	1.51	1.65	1.50
Statistical Combination	1.24	1.24	1.41*

*Factors for coolant channel thickness and coolant flow rate are treated statistically. The factor for the heat transfer coefficient is multiplicative.

The multiplicative method of combining the sub-factors is conservative but somewhat unrealistic. The statistical method recognizes that all of these conditions do not occur at the same time and location. The uncertainty in the heat transfer coefficient is treated as a multiplicative bias. The hot channel factors with the statistical method are lower. The choice of hot channel factors strongly affects the design and safety margins. The WPI reactor power at the onset of nucleate boiling is predicted as:

No Factors	818 kW
Statistically Combined	442
Multiplicatively Combined	301

The sensitivity to the various components is illustrated for the WPI reactor at 200 kW in the following table:

	$\Delta \hat{q}''$, W/m^2	ΔT_{out}, °C	$\Delta \hat{T}_s$, °C	Δv_{out}, cm/s
No Factors	-	-	-	-
$F_b = 1.24$ only	-	2.63	3.29	-1.10
$F_q = 1.24$ only	5233	1.50	7.35	0.87
$F_h = 1.41$ only	-	-	13.14	-
All Factors	5233	4.38	27.74	-0.40

The heat transfer component, F_h, is the largest and has the largest effect on the clad surface temperature. This factor changes only the clad temperature. The uncertainty in the heat transfer coefficient is treated as a multiplicative sub-factor and is the largest contributor. If this uncertainty can be reduced, safety margins will increase.

The heat flux component is the next largest contributor, and the dominant sub-factor in this component is the heterogeneity of the fuel. Some further analysis may be helpful in reducing this uncertainty. In this natural convection example, the flow rate increases as the heat flux is increased in the hot channel. This improves the cooling of the plate in the channel and reduces the clad temperature.

This natural convection example may differ somewhat from the results one might expect in a reactor with forced convection. The impact of changes in the coolant channel spacing are probably larger in this case than with forced flow. With pumps and piping other uncertainties may be introduced.

CONCLUSION

The selection of hot channel factors has a large influence on the thermal-hydraulic performance and impacts the design and safety margins of the reactor. Thus, these factors should be selected with great care. The proposed selection process is an attempt to provide some guidance and rational for this task.

Hot channel factors should be divided into three separate components rather than only one factor applied to the heat flux. Hot channel factors are applied to the heat flux, the temperature or enthalpy change in the channel, and the heat transfer to the coolant at the clad-coolant interface. These factors can be broken down into sub-factors based on uncertainties in the manufacturing process, measurements, specifications, and methods.

These sub-factors may be combined by multiplying them together, by treating them statistically, or by a combination of the two previous options. The multiplicative method is overly conservative, and the statistical or combined method is recommended. Only the uncertainty in the heat transfer coefficient is treated as multiplicative in the example provided.

The sample results from the WPI reactor show that the power for the onset of nucleate boiling is reduced by almost a factor of two with the introduction of hot channel factors (statistically combined) and further reduced if the multiplictively combined factors are used. The increase in clad surface temperature with the introduction of hot channel factors is dominated by the heat transfer component, and the largest contributor to this factor is the uncertainty in the heat transfer coefficient.

A rather large uncertainty factor was also introduced for the heterogeneity in the fuel. This contributes directly to an increase in the heat flux. This is an area where further refinements would be useful in perhaps reducing this uncertainty.

REFERENCES

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