

STATISTICAL CALCULATION OF HOT CHANNEL FACTORS

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It is a conventional practice in the design of nuclear reactors to introduce hot channel factors to allow for spatial variations of power generation and flow distribution. Consequently, it is not enough to be able to calculate the nominal temperature distributions of fuel element, cladding, coolant, and central fuel. Indeed, one must be able to calculate the probability that the imposed temperature or heat flux limits in the entire core is not exceeded. In this paper, statistical methods are used to calculate hot channel factors for a particular case of a heterogeneous, Material Testing Reactor (MTR) and compare the results obtained from different statistical methods. It is shown that among the statistical methods available, the semi-statistical method is the most reliable one.

Keyword: "Hot-channel factors"- "Temperature"- "Thermal-hydraulic"

INTRODUCTION

In design of nuclear reactors, a number of uncertainties arise concerning variations in flow distribution, fuel element and coolant channel geometry, and neutron flux spatial distribution. To facilitate the determination of the effects of such variations upon the thermal performance, hot channel factors are introduced. That is, a factor is introduced which relates the nominal channel characteristics to the most unfavorable maximum conditions that might occur in the core [1].

The surface temperature is a function of two separate groups of variables. One group is composed of those variables that represent the physical characteristics of the fuel elements and the fuel channels; the other group is composed of those variables that

represent the parameters of the processes of heat generation and heat transfer excluding the physical dimensions which are part of the first group. Both of these groups of variables are essentially statistical variables. The statistical nature of the first group arises because of variations in the physical dimensions of the fuel element assembly due to manufacturing variations. The statistical nature of the second group arises from the uncertainty associated with the values of process parameters such as the heat transfer coefficient and the fission rate [2].

Since the variables are statistical in nature, it is not possible to uniquely determine the surface temperature at a point in a reactor before it is built. What can be done is to compute the probability that the temperature, at a fixed point, will be greater than a given value or lie between given limits. This paper is concerned with the techniques of computing such probabilities. Rude and Nelson [3] have applied some statistical considerations to the hot-channel factor approach to the surface temperature problem, while Tingey [4] proposed a statistical error analysis; however, in both papers the statistical variables were assumed to have Gaussian (normal) distribution function. The approach presented in this paper takes into consideration the effect of other variables that affect the nominal temperature distributions. In fact one calculates the overall factor due to its nature by the semi-statistical method, [5].

METHODS OF EVALUATION

Engineering hot channel factors may be split into three distinct components corresponding to:

- (i) Uncertainties that influence the heat flux, F_q
- (ii) Uncertainties in the temperature rise or enthalpy in the channel, F_b
- (iii) Uncertainties in the heat transfer coefficient, F_h .

These factors should be introduced into the analysis as

$$q''_{hc} = F_q \times q''_{nc} \quad (1)$$

$$\Delta T_b = F_b \times \frac{Q}{(c_p \times \dot{m})} \quad (2)$$

$$\Delta T_{cs} = F_h \times \frac{q''}{h} \quad (3)$$

where the notation *hc* refers to the hot channel value and *nc* refers to the nominal channel value for the heat flux (q''), and \dot{m} is the mass flow rate. The remaining notation is standard. F_b can be defined as the ratio $\frac{\Delta T_{hc}}{\Delta T_{nc}}$ for the bulk (*b*) coolant temperature, and F_h can be defined as a similar ratio in the clad surface (*cs*)

temperature. These components can be broken down further into sub-factors and combined either multiplicatively

$$F_b = f_{b1} \times f_{b2} \times f_{b3} \times \dots \quad (4)$$

or statistically

$$F_b = 1 + \sqrt{\sum_i (1 - f_{bi})^2} \quad (5)$$

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-factor may be determined from limitations in the ability to measure certain parameters accurately, such as, flow rates and temperatures. Other sub-factors may still 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 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:

$$f_q = 1.0 + \frac{\Delta t_p}{t_m} \quad (6)$$

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_{cs}). For this 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 that is a good assumption with forced flow, and the pressure drop can be expressed as

$$\Delta p = fr \frac{L}{De} \left(\frac{\rho v^2}{2} \right) \quad (7)$$

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

$$\frac{v_{hc}}{v_{nc}} = \left[\frac{De_{hc}}{De_{nc}} \right]^{1/2} \times \left[\frac{fr_{nc}}{fr_{hc}} \right]^{1/2} \quad (8)$$

The friction factor may be express in terms of the Reynolds's number $\left(\frac{1}{Re^a} \right)$, where $Re = \frac{\rho v De}{\mu}$. With the assumption that ρ and μ are constant, the velocity ratios can be rewritten as:

$$\frac{v_{hc}}{v_{nc}} = \left[\frac{De_{hc}}{De_{nc}} \right]^{(1+a)/(2-a)}, \quad (9)$$

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

Now using the relation $q'' = h \times \Delta T_{cs}$, the sub-factor f_h , the ΔT ratio of hot to nominal at the clad surface, can be expressed as $\frac{h_{nc}}{h_{hc}}$. The heat transfer coefficient for single-phase turbulent flow is usually represented by a correlation that is proportional to $\frac{(Re)^{0.8}}{De}$, again Re is proportional to vDe , and the heat transfer ratio can be written as $\left(\frac{v_{nc}}{v_{hc}} \right)^{0.8} \times \left(\frac{De_{hc}}{De_{nc}} \right)$. The velocity ratio can then be replaced by the expression derived above to give the hot channel sub-factor

$$f_h = \left[\frac{De_{nc}}{De_{hc}} \right]^{(0.4+a)/(2-a)} \quad (10)$$

In a similar manner, a hot channel sub-factor for the bulk temperature rise due to a channel reduction can be derived. Using $Q = \rho \times A \times v \times c_p \times \Delta T_b$,

where ΔT_b is proportional to $\frac{1}{Av}$, and the flow area, A , is proportional to De . The ΔT ratio of hot to nominal, f_b , can be expressed as:

$$f_b = \frac{De_{nc}}{De_{hc}} \times \frac{v_{nc}}{v_{hc}} \quad (11)$$

and again substituting for the velocity ratio the relation

$$f_b = \left[\frac{De_{nc}}{De_{hc}} \right]^{\frac{3}{(2-a)}} \quad (12)$$

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

$$f_n = \left[\frac{t_{nc}}{t_{hc}} \right]^{\frac{(0.4+a)}{(2-a)}} \quad (13)$$

$$f_b = \left[\frac{t_{nc}}{t_{hc}} \right]^{\frac{3}{(2-a)}} \quad (14)$$

For a friction factor coefficient of $a = 0.2$, $f_h = \frac{(t_{nc})^{1/3}}{t_{hc}^{1/3}}$ and $f_b = \frac{(t_{nc})^{5/3}}{t_{hc}^{5/3}}$.

Should 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.

APPLICATION

The statistical calculation of temperature hot channel factors can best be illustrated by considering a specified reactor such as a MTR type. Calculations of the expected statistical variations of temperature and other process variables have been made for Tehran Research Reactor (TRR). The TRR is a pool-type reactor, operating with maximum 5 MW, water-cooled and moderated reactor. The reactor core is rectangular in geometry with vertical fuel channels parallel to the core axis. The coolant is gravity driven through the coolant channels to an external heat exchanger and is eventually returned to the bottom of the reactor pool. The general arrangement of the reactor cooling circuit, typical standard fuel element, components along with their positions and details of relative information can be found in Safety Analysis Report (SAR, AEOI)[6].

The thermal-hydraulic calculations were done using standard codes such as thermique by Fabrega [7]. The TRR maximum thermal-hydraulic values for critical condition and phenomena are as follow:

Maximum clad temperature 93.0 °C

Onset of nucleate boiling heat flux 55.0 W/cm²

Critical heat flux (DNB) 126.0 W/cm²

The hot channel factors and the hot channel sub-factors derived from the uncertainties for the TRR are summarized in Table 1.

Table 1. Components of hot-channel factors for the TRR

Physical uncertainty	F_q	F_b	F_h
Nuclear:			
^{235}U Loading	1.02	1.02	1
^{235}U Homogeneity	1.08	1.08	1
Engineering:			
Fuel meat thickness	1.05	1	1
Coolant Channel area	1	1.075	1.075
Power measurement	1.05	1.05	1.05
Calculated Power density	1.10	1.10	1
Coolant flow rate	1	1.11	1.08
Heat transfer coefficient	1	1	1.33
Multiplicative combination	1.33	1.51	1.62
Statistical combination	1.14	1.19	1.35

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 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. Should this uncertainty could be reduced, safety margins will increase.

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

Table 2. The effect of hot channel factors on the selected temperatures (5MW)

Physical uncertainty	Factor for coolant temperature rise $\Delta t_c = 12.7^\circ\text{C}$		Factor for temperature rise through film $\Delta t_f = 21.48^\circ\text{C}$		Factor for temperature rise through clad $\Delta t_c = 0.61^\circ\text{C}$		Factor for temperature rise through gap $\Delta t_g = 0.0001^\circ\text{C}$		Factor for temperature rise through fuel $\Delta t_f = 4.77^\circ\text{C}$	
	f	3σ	f	3σ	f	3σ	f	3σ	f	3σ
Cumulative product	2.040	65.80	2.122	111.38	1.325	112.19	1.000	112.19	1.377	118.76
Cumulative sum	1.745	62.07	1.815	101.06	1.290	101.85	1.000	101.85	1.333	108.20
Statistical vertical	1.262	55.97	1.383	85.67	1.135	86.37	1.000	86.37	1.162	91.91
Statistical horizontal	1.262	55.97	1.312	84.15	1.054	84.80	1.000	84.80	1.060	89.85
Semi-statistical vertical	1.528	59.33	1.691	95.64	1.135	96.33	1.000	96.33	1.162	101.88
Semi-statistical horizontal	1.528	59.33	1.687	95.56	1.089	96.22	1.000	96.22	1.094	101.44

RESULTS AND DISCUSSION

A computer program is developed and verified against the TRR thermal-hydraulic design values. The program calculates local temperatures of coolant bulk, outer clad surface, inner clad surface, and central fuel for 616 points, every 1 mm, along the fuel plate. Also, it calculates local generated heat as well as pressure that could subsequently be used to determine the local critical heat flux (CHF), onset of nucleate boiling (ONB), and departure from nucleate boiling (DNB). In the present work, merely the hot channel factors for the different physical variables that were influenced by temperature changes were focused.

The hot channel factors have a large influence on the thermal-hydraulic performance and affect the design and safety margins of the reactor. Hot channel factors are applied to the heat flux, the temperature 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.

Table 1 shows physical uncertainties that influence the heat flux, the temperature rise or enthalpy change of coolant, and heat transfer coefficient. Factors for coolant channel thickness and coolant flow rate are treated statistically. However, the factor for the heat transfer coefficient is multiplicative. As seen from the table, the uncertainty in the heat transfer coefficient is the largest one. Should the uncertainty be reduced from the largest contributor, safety margins will increase.

Table 2 shows different factors that caused temperature rise of coolant, film, clad, gap, and fuel, respectively. The hot channel factors were calculated by different statistical methods. It is evident from the table that semi-statistical method produced results that are more accurate than the rest. Upon comparison with the original designed values, the direct method produced results that are conservative whilst the combined statistical method provided results that are too optimistic.

CONCLUSIONS

The intent of present work is to demonstrate the application of statistical methods to determine the hot channel factors arising from temperature variations in the reactor core. It is hoped that either these or similar methods of more exact interpretation and calculations than these factors, in conjunction with related design procedures, will result in a reactor plant of increased capability and decreased uncertainties.

1. The sample results from the TRR show that 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.

2. For two groups of statistical variables, process as well as physical characteristic, the semi-statistical method shown to be a more efficient and far less conservative and particularly useful when the physical characteristic variable affects the process variable directly. It is also shown that the semi-statistical method is more accurate than the other methods available.
3. Taking into account the uncertainties in the parameters that determine the temperature distributions as well as safety margins in the design process is to be taken into consideration.
4. The obtained results could be used in the TRR Safety Analysis Report (SAR) in order to license the TRR for future safe operation.

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REFERENCES

- [1] Le Tourneau, B. W. and Grimble, R. E., "Engineering Hot-Channel Factors for Nuclear Reactor Design", *Nucl. Sci. Eng.* **1**, 359(1956).
- [2] Abernathy, Frederick H., "The Statistical Aspects of Nuclear Reactor Fuel Element Temperature", *Nucl. Sci. Eng.* **11**, 290-297(1961).
- [3] Rude, P. A. and Nelson, A. C., *Nuclear Sci. and Eng.* Vol. **7**, 156-161(1960).
- [4] Tingey, F. H., *Nuclear Sci. and Eng.* Vol. **9**, 127-131(1961).
- [5] Todreas, N. E. and Kazimi, M. S., "*Nuclear Systems: Vol. II, Elements of Thermal Hydraulic Design*", Hemisphere, NY, 1990.
- [6] Safety Analysis Report, AEOI, Tehran, Iran.
- [7] Fabrega, S., "Le Calcul Thermique Des Reacteurs De Recherche Refroidis Par Eau", *Repport CEA-R-4114*, Centre d'Etudes Nucleaires de Grenoble, 1971.

الحسابات الإحصائية لمعاملات القناة الحارة

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إنه من المتعارف عليه في تصميم المفاعلات النووية أن يجري إدخال معاملات قناة حارة للسماح بالتراوحدات المكانية لتوليد القدرة وتوزيع السريان. وبالتالي فإنه لا يكفي لحساب توزيعات درجات الحرارة الإعتيادية لعناصر الوقود والتغليف والتبريد والوقود المركزي. وفي الواقع يجب أن تكون هناك القدرة لحساب احتمالات ألا تتعدى درجات الحرارة المفروضة أو طيف الحرارة الحدود المقدره لقلب المفاعل. وفي هذا البحث استخدمت الطرق الإحصائية لحساب معاملات القناة الحارة لحالة خاصة لمفاعل غير متجانس لأغراض إختبارات المواد. ومقارنة النتائج التي تم الحصول عليها باستخدام طرق إحصائية مختلفة. وقد أظهرت الدراسة أنه من بين الطرق الإحصائية المتاحة فإن الطريقة شبه الإحصائية هي الأكثر وثوقية.