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Mixing Vane Effect on the Critical Heat Flux

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Abstract

The mixing vane effect on the Critical Heat Flux (CHF) is discussed with focus on the vortex flow effect. In the subchannel approach, this effect is not quantified by the calculation model, but directly taken into account by the CHF correlation itself through data analysis. The vortex flow effect is identified for the two Westinghouse correlations, and then the CHF margin issue given rise to by the Vantage-5H design change is evaluated and discussed. It is noted that deficiency of information about CHF dependency on the vortex flow effect could induce an error in the Departure from Nucleate Boiling Ratio (DNBR) sensitivity calculation.

I. Introduction

A recent design change in the Vantage-5H fuel where successive grid rotation led to the 16.5 % of Departure from Nucleate Boiling Ratio (DNBR) penalty has drawn a special attention[1]. This DNBR penalty means that the minimum DNBR calculated in the reference safety analysis should be multiplied by a factor of 0.835, resulting in a significant margin decrease to the DNBR safety limit. Such margin degradation is seen to be attributed to interruption of vortex development in the rotated grids with shorter grid span.

However, some questions remain unresolved. One of the questions is whether the change of the vortex flow effect could be resolved just by introducing a single multiplication factor to the Critical Heat Flux (CHF) correlation. In the subchannel approach the vortex flow effect is known to be implicitly included in the CHF correlation itself. If the vortex flow effect on CHF is decoupled from other local parameter effect, the change of vortex flow effect can be modeled by changing only the CHF correlation terms of the vortex-related parameters. Another question arises from the previously reported observation that the DNBR sensitivity factors are generally lower in magnitude at the higher values of CHF associated with Vantage-5 than for 17x17 OFA[2,3]. Introduction of a DNBR penalty factor does not support this observation because the sensitivity factor does not change between the higher and the decreased values of CHF.

In this study these questions are discussed through a close examination of two Westinghouse correlations, WRB-1[4] and WRB-2[2]. The basic assumption is that in each correlation the intrinsic mixing vane effect (here, the terminology, "intrinsic", means "unquantifiable through subchannel modelling") can be distinguished from the effect of other local parameters on the CHF. Another useful assumption by intuitive reasoning is that the vortex flow effect on CHF becomes zero as the sum of two values, grid spacing and distance-to-CHF location, goes to the infinity. These two parameters in each correlation are the main factors for describing the intrinsic effect of the mixing vane on the CHF.

II. Mixing Vane Effects

It is generally accepted that two main effects of the mixing vane can be considered in the subchannel approach[5]: 1) mixing effect between adjacent flow channels causing fluid mixing, and 2) intrinsic effect based on microscopic phenomena on CHF, such as internal thermal mixing within the subchannel. The former is quantified by a mixing coefficient, for example, defined as Thermal Diffusion Coefficient (TDC) or inverse Pe number in the subchannel codes, while the latter is taken into account by the CHF correlation itself. Large interchannel thermal mixing will decrease the local quality in the subchannel, resultantly enhancing the CHF performance. The intrinsic effect to the CHF, however, becomes more important than the interchannel thermal mixing effect, in the flow geometries where the vortex flow plays an important role in enhancing the CHF performance. In this case some physical parameters are often introduced into the CHF correlation to explain the intrinsic effect on the CHF more directly. These parameters will be called the intrinsic mixing vane parameters for convenience.

Carefully looking into two Westinghouse correlations, WRB-1 and WRB-2, it seems that each correlation is composed of two parts: one by the intrinsic mixing vane parameters and another by the calculated local parameters. Therefore, it is assumed that the CHF is predicted by the sum of the terms for the intrinsic mixing vane effect and for other local parameter effect in each correlation: i.e.,

$$q''_{CHF} = f_v + f_l \qquad (1)$$

where f_v is a function of the intrinsic mixing vane parameters and f_l is a function of the calculated local parameters. In other words, mixing vane effect caused by the upstream grid becomes negligible when grid spacing becomes large. In this way f_v is defined as the negative contribution to the CHF caused by the mixing vane. f_v for the WRB-1 correlation is related only to the intrinsic mixing vane parameters, while f_v for the WRB-2 correlation is dependent on two calculated local parameters, pressure and mass flux, as well as the intrinsic mixing vane parameters. Based on the previous intuitive reasoning, we can also make f_v approach zero as grid spacing goes to the infinity. As the sum of grid spacing (gsp) and distance-to-CHF location (dg) decreases, the value of f_v scatters over a wider range and the pressure and the mass flux begin to couple to the intrinsic mixing vane effect. Considering the physical fact that vortex intensity increases as mass flux and decrease as pressure, it seems that pressure and mass flux in f_v for the WRB-2 correlation represent the vortex intensity effect of the two parameters, rather than they are directly related to CHF. This is well explained in Fig.1, where f_v for WRB-2 is plotted with the mean values of pressure and mass flux along with the minimum and maximum in their applicable ranges. It is notable that a good agreement between WRB-1 and WRB-2 is observed for the range of the sum of dg and gsp greater than 40". Considering f_l's for WRB-1 and WRB-2 are the same, the direct effect on CHF of the two local parameters is represented only with the local parameter effect term, fl, while they affect the vortex intensity in shorter grid span, fv and resultantly CHF. In this figure, the applicable range of gsp in x-axis is 10" to 26" for WRB-2 and 13" to 32" for WRB-1 and dg becomes equal to the grid spacing, gsp, at the grid location.

III. Rotated Grid Effect Evaluation

When the WRB-2 correlation was used to analyze the CHF test data for rotated grid configuration with 10" grid spacing in the Vantage-5H fuel assembly, the mean of the measured-to-predicted CHF was about 0.835. This means that the mean of the measured CHF data set for rotated grid is shifted by a factor of 0.835 against that for aligned grid. We evaluated the rotated grid effect by considering the following cases of approaches.

Case (a): the WRB-2 correlation is applicable by multipling a single factor, 0.835, and then, f_v and f_l in Eq.(1) are changed to (0.835*f_v) and (0.835*f_l) respectively.

Case (b): the WRB-2 CHF correlation is modified by adjusting the coefficients included in f_v in Eq. (1) without change of f_l. The adjustment is made in the correlation to give the exact prediction for both rotated data sets for 10" and 20" grid spacing.

The case (b) approach represents the physical phenomena more realistically because grid rotation does not affect the local parameters calculated by the subchannel code.

It was reported that the CHF performance for 20" grid spacing does not change before and after grid rotation while the grid rotation effect for 10" grid spacing is notable, i.e.,

$$q''_{r,CHF} = 0.835q''_{a,CHF}, \quad \text{for 10" grid spacing,}$$
$$= q''_{a,CHF}, \quad \text{for 20" grid spacing.} \qquad (2)$$

Here, subscripts, r and a indicate the association with rotated and aligned grid respectively. For 10" grid spacings cases (a) and (b) can be expressed as follows.

$$q''_{r,CHF} = 0.835f_{v,a} + 0.835f_{l,a}, \text{ for case (a), and} \qquad (3)$$

$$q''_{r,CHF} = f_{v,r} + f_{l,a} = (0.835f_{v,a} - \delta f) + f_{l,a}, \text{ for case (b).} \qquad (4)$$

δf is $0.165f_{l,a}$ if Eq.(3) is really correct. Considering only the intrinsic mixing vane effect term of Eq.(4), the functional form of $f_{v,r}$ is the same as $f_{v,a}$ but with different coefficients adjusted by using the CHF data base.

<u>**Rotated Grid Effect Estimation**</u>

By case (b) approach, the rotated grid effect can be roughly estimated from the existing WRB-2 data base. Considering the distribution of the measured CHF's for 10" grid spacing in the WRB-2 data base, if we can obtain the means of $f_{v,a}$ and $f_{l,a}$ from the distribution, the mean of $f_{v,r}$ can be estimated for 10" grid spacing by use of Eq.(4). The mean of $f_{v,r}$ for 20" grid spacing is estimated to be the same as that of $f_{v,a}$, because there was no degradation of CHF performance for 20" grid spacing. Given the two estimated $f_{v,r}$ values for the different grid spacings, we can obtain two equations which relate the unknown coefficients. If we take the mean values of pressure and local mass flux and fix the associated coefficients, we can obtain the adjusted two new coefficients for $f_{v,r}$. This simplification used for the new $f_{v,r}$ is better acceptable if considering that in each CHF test the operating conditions such as pressure, inlet mass flux, and inlet coolant temperature are randomly determined regardless of grid spacings, or grid rotation.

Intrinsic mixing vane effect for case (a) is quantified by (0.835^*f_v) in Fig.1 and applicable only for 10" grid spacing. Mixing vane effects for case (b) are quantified by using the WRB-2 data base. Using Eq.(4), these values at the means of pressure and local mass flux are calculated as 0.2823 and 0.1250 for 10" and 20" grid spacing respectively, with which the two coefficients stated above were adjusted. Fig.2 shows the intrinsic mixing vane effect as function of (dg+gsp). In this figure $f_{v,r}$ of case (a) is represented by ($0.835^* f_{v,a}$) and $f_{v,r}$ of case (b) with the adjusted new coefficients are shown. The intrinsic mixing vane effect of case (a) approach is larger than that of case (b) approach. Here, we note that introduction of DNBR penalty could overestimate the intrinsic mixing vane effect. In Fig.2, ($0.835^* f_{v,a}$) is shown to be valid only for dg+gsp $\leq$20", because the grid rotation effect is observed only in 10" grid spacing data base. When case (a) approach is extended over up to 20" grid spacing, Fig.2 still shows the grid rotation effect by the deviation of $0.165 f_{l,a}$ in Eq.(4), which is contradictory to the fact that there is no grid rotation effect for 20" grid spacing. Therefore, the discontinuity at (dg+gsp) of 20" implies that case (b) approach is preferred if we analyze the CHF data set over the extended applicable range of the WRB-2 correlation, 10" to 26" grid spacing.

<u>**Exemplary Sensitivity Calculation**</u>

The DNBR sensitivity factor to the mass flux used for determining the DNBR safety limit is defined as:

$$S_i = \frac{\partial \ln DNBR}{\partial \ln G_{in}} = \frac{\partial \ln \left(q''_{p,CHF}/q''_{loc}\right)}{\partial \ln (G_{loc} \times FD)}, \qquad (5)$$

where G_{in} is the inlet mass flux, G_{loc}, the local mass flux at the minimum DNBR location and FD is a flow deviation factor. In one-dimensional context, FD is unity and the variation of q''_{loc} is negligible for small change of G_{in}. Reducing of three- to one-dimensional problem can be justified for a small change and then the minimum DNBR location is not changed. Now, the DNBR sensitivity is approximated as:

$$S_i = \frac{G_{loc}}{q''_{p,CHF}} \times \frac{\partial q''_{p,CHF}}{\partial G_{loc}}. \qquad (6)$$

The sensitivity in case (a) approach can be calculated by substituting Eq.(3) with WRB-2 into Eq.(6), giving the same sensitive value for both aligned and rotated grid. However the sensitivity in case (b) approach it is affected by grid rotation.

When additional simplified assumptions for CHF position and local conditions are given, we can determine the sensitivity by Eq. (6) as shown in Table 1. Considering that the case (b) approach explains well the rotated data sets both for 10" and 20" grid spacing and is more consistent with the previous observation that the DNBR sensitivity factors are generally lower in magnitude at the higher values of CHF[2].

IV. Conclusion

In this study one of two main effects of the mixing vane, the intrinsic effect on CHF in a subchannel approach was reviewed. In fact, the vortex flow effect was loosely used for the intrinsic mixing vane effect because the intrinsic effect is majorly attributed to existence of the vortex flow. For discussion, the vortex flow effect was decoupled from other calculational parameter effects in two Westinghouse correlations, WRB-1 and WRB-2, and then rotated grid effect in the Vantage-5H fuel was evaluated on the basis of the WRB-2 correlation. Here, it was noted that introduction of DNBR penalty could overestimate the intrinsic mixing vane effect, inducing an error in calculating the DNBR sensitivity factor.

Considering these potential problems pointed out in this study, the current subchannel approach tends to lose the credibility when the mixing vane design becomes more important to enhance CHF performance. A more detailed computational hydrodynamics study will be needed to answer these questions.

References

[1] Nuclear Fuel, Vol.19, No.15, July 18, 1994

[2] WCAP-10444-P-A, "Reference Core Report - Vantage 5 Fuel Assembly," Westinghouse, Sep. 1985.

[3] WCAP-9500-A, "17x17 Optimized Fuel Assembly," Westinghouse, May 1982.

[4] WCAP-8762, "New Westinghouse Correlation WRB-1 for Predicting CHF in Rod Bundles with Mixing Vane Grids," July 1976.

[5] F.de Crecy, "The Effect of Grid Assembly Mixing Vanes on CHF Values and Azimuthal Location in Fuel Assemblies," NURETH-6.

Table 1. Exemplary Sensitivity Calculations

pressure = 2250 psia

heated length =134″=11.16′ at the typical CHF location for cosine power shape

(*) Ratio of the predicted CHF for aligned and for rotated grid is 0.835.

WRB-2		case (a)		case (b)	
$\frac{\partial f_1}{\partial G_{loc}}$	$\frac{\partial f_2}{\partial G_{loc}}$	$\frac{\partial f_1}{\partial G_{loc}}$	$\frac{\partial f_2}{\partial G_{loc}}$	$\frac{\partial f_1}{\partial G_{loc}}$	$\frac{\partial f_2}{\partial G_{loc}}$
0.04254	0.602	0.03552	0.50267	0.03197	0.602
$S_i^2 = 0.41543 \frac{G_{loc}^2}{q''^2_{a,chf}}$		$S_i^2 = 0.28965 \frac{G_{loc}^2}{q''^2_{r,chf}}$ (*) $= 0.41543 \frac{G_{loc}^2}{q''^2_{a,chf}}$		$S_i^2 = 0.40192 \frac{G_{loc}^2}{q''^2_{r,chf}}$ (*) $= 0.57645 \frac{G_{loc}^2}{q''^2_{a,chf}}$	

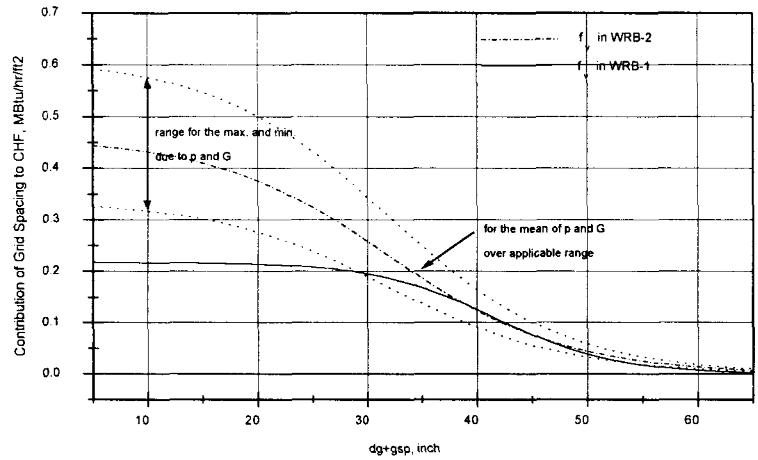

Fig.1 Grid Spacing Effects on CHF in WRB-1 and WRB-2 Correlations

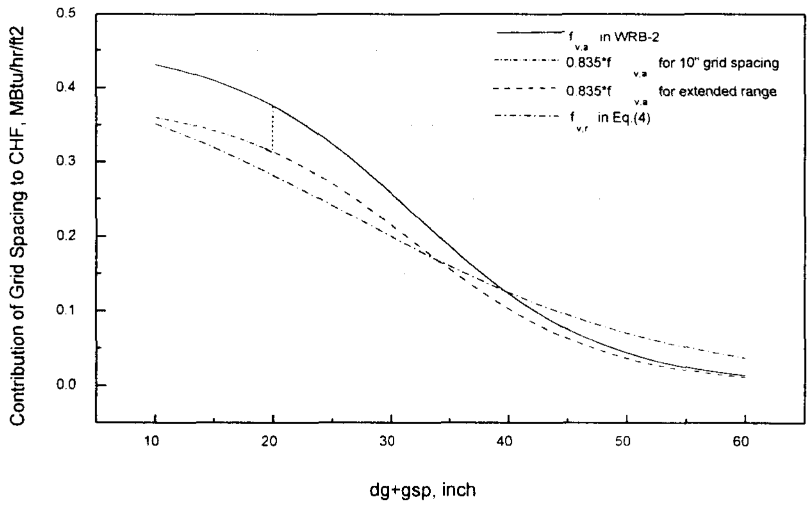

Fig.2 Grid Spacing Effects for Rotated Grid with Adjusted Coefficients