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Prediction of minimum departure from nucleate boiling ratio in VVER-1200 reactor core using heat balance and direct substitution methods

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Abstract. *Based on the direct substitution and heat balance methods and using the Levitan-Lantsman correlation, a prediction of the minimum departure from nucleate boiling ratio (MDNBR) was made. The equilibrium quality at the exit of the VVER-1200 channel was directly substituted into the correlation to predict the critical heat flux (CHF) while keeping other parameters constant. This was done for 100 %, 105 %, 110 %, until the CHF and the maximum local heat flux intersected each other. The ratio of the CHF and the maximum local heat flux was also recorded for each power level. The point at which the MDNBR intersected the local heat flux was regarded as the operational limit of VVER-1200 with an MDNBR value of 1.445 at thermal power of 160 %. While the point at which the local heat flux intersects the CHF was regarded as the point of CHF occurrence with an MDNBR equaling to a critical power ratio (CPR) value of 1.195 and a CHF value of 1.83 MW m*$^{-2}$*. A statistical analysis was carried out to ascertain the accuracy of the predicted MDNBR. Furthermore, a comparison of the result was done with VVER-1200 PCTRAN Simulator, and a good result comparison was achieved.*

Key words: *MDNBR, CHF, correlation, thermal, power*

Introduction

Traditionally, the Departure from Nucleate Boiling Ratio (DNBR), which is the ratio of the predicted CHF to the actual local heat flux, has been used to express the CHF margin for low quality regions that are characteristic of PWR operating conditions. This method usually predicts the CHF based on an empirical correlation, where the CHF is a function of local flow conditions [1]. The minimum DNBR computed against different operating conditions is often compared to a DNBR limit spanning the correlation's uncertainty with the experimental data in order to determine the DNBR margin. Numerous authors have noted that the DNBR margin and the power margin-to-CHF can differ greatly [2, 3], and that the CHF correlation that is employed determines the DNBR's numerical value. In this work, we used a DNBR correlation with successive increase of power until reaching the CHF condition. This approach is more commonly used in the Pressurized Water Reactor (PWR) community since it can handle cross-flow and thermal mixing in open multiple channels, while requiring an iterative calculation of the CHF power against DNBR.

Research methods

Regardless of their form, CHF predictors for low and sub-cooled conditions fall into one of three types [3]: local, non-local, and semilocal predictors.

Local conditions dependent predictors (type 1 correlation) usually have the form of

$$q''_{CHF} = f\left(G, x_{eq}, p, D_h\right) \text{ or } q''_{CHF} = f\left(G, x_{eq}, p, D_h, L\right), \quad (1)$$

When the heated length is taken into account. Examples include the 2006 Groeneveld LUT [4], the 2011 Bobkov LUT [5], and the Biasi correlation [6], OKB Gidropress correlation and Levitan-Lantsman correlation. Nonlocal predictors include the Bowring correlation [7] and the EPRI generalized correlation, while the semilocal predictors include the W-3 correlation [8] and the PI-I correlation (Perniea and Cizck, 1991).

We employed the Levitan-Lantsman correlation which is a type 1 correlation with local conditions suitable for VVER-1200 under anticipated operational occurrence with increasing thermal power.

$$q''_{CHF}\left(8mm, G, p, x_{eq}\right)=\left[10.3-7.8\left(\frac{p}{98}\right)+1.6\left(\frac{p}{98}\right)^2\right]\left(\frac{G}{1000}\right)^{1.2\left\{\left[0.25\left(p-98\right)/98\right]-x_{eq}\right\}}\cdot e^{-1.5\cdot x_{eq}} \quad (2)$$

The correlation is valid within the range of $29.4 \le P \le 196$ [*bar*] and $750 \le G \le 5000$ with an accuracy of ±15 %.

Result

By increasing the thermal power of the reactor at 5 % interval, we obtained an iterative table of MDNBR, CHF and maximum local heat flux. We plotted the MDNBR, CHF and maximum local heat flux against the thermal power (which translates to local equilibrium quality equivalent) as seen in Fig 1(a). It was observed that at about 160 % nominal thermal power, the MDNBR intersected the maximum local heat flux, with a value of 1.445.

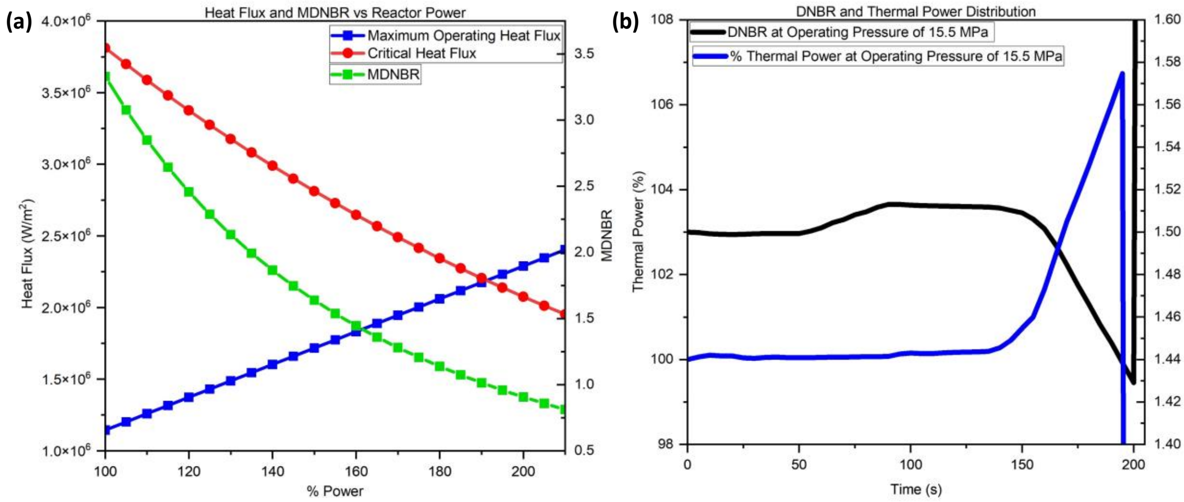

Fig. 1: (a) Heat flux, critical heat flux and MDNBR vs nominal thermal power of reactor; (b) Nominal thermal power of reactor and departure from nucleate boiling ratio (DNBR) vs simulation time (PCTRAN)

This point was predicted to be the operating limit of VVER-1200, which was verified with a PCTran Simulator for VVER-1200. The CHF intersected the maximum local heat flux at about 191.25 % thermal power with an MDNBR value of 1.195, which was equated to the CPR and a CHF value of $1.83 MWm^{-2}$. The point of intersection of the local and critical heat flux was regarded as the CHF occurrence point. The true margin for CHF occurrence was calculated to be 19.5 % overpower (119.5 %), while the margin at MDNBR limit was calculated to be 6.9 % overpower (106.9 %). The PCTRAN simulator was operated at 110, 115 and 120 percent turbine demand power. It was observed that for all cases, the maximum permissible power of the reactor before scram was 106 % power with an approximate MDNBR value of 1.428 as seen in Fig 1(b). This clearly validates our calculation of MDNBR of 1.445 at 106.9 % overpower.

By increasing thermal power, we tend to reduce MDNBR to be equal to DNBR correlation limit (LDNBR). For VVER-1200, we obtained the following values from our correlation analysis:

$$\left(Safety\right)_{margin}=1-\frac{LDNBR}{MDNBR};\ \overline{DNBR}=1.095;\ K=1.686;\ SD=0.209,$$

where SD is standard deviation, $\overline{DNBR}$ is DNBR mean, and K is D.B Owen constant at 95 % probability and 95 % confidence. For the upper limit,

$$MDNBR=\overline{DNBR}+K\cdot SD;\ MDNBR=1.095+\left(1.686\cdot 0.209\right)=1.447.$$

For the lower limit,

$$LDNBR = \frac{1}{DNBR - K \cdot SD}, \quad LDNBR = \frac{1}{1.095 - (1.686 \cdot 0.209)} = \frac{1}{0.742626} = 1.34657,$$

$$(Safety)_{margin} = 1 - \frac{LDNBR}{MDNBR} = 1 - \frac{1.34657}{1.447} = 0.0694.$$

For VVER-1200, according to our Levitan-Lantsman Correlation analysis, the safety margin of 6.094 % is the MDNBR margin.

Conclusion

An attempt was made to predict MDNBR for VVER-1200 using an iterative procedure and validated with a VVER-1200 PCTRAN Simulator. It was observed that the point at which the DNBR intersected the maximum local heat flux is the MDNBR, and it is tied to the occurrence of onset of significant void (OSV) in reactor channel. This point was also regarded as the operational limit for the reactor.

References

1. Ahn, Seung-Hoon, and Gyoo-Dong Jeun. A heuristic application of critical power ratio to pressurized water reactor core design // Nuclear Engineering and Technology. – 2002. – Vol. 34, № 1. – P. 68–79.
2. G.S. Lellouche, The Boiling Transition: Analysis and Data Comparisons // Nucl. Engrg. & Des. – 1989. – Vol. 116. – P. 117–133.
3. Pavel Hejzlar and Neil E. Todreas, Consideration of CHF Margin Prediction by Subcooled or Low-Quality CHF Correlations // Nucl. Engrg. & Des. – 1996. – Vol. 163. – P. 215–223.
4. Groeneveld D.C. et al. The 2006 CHF look-up table // Nuclear engineering and design. – 2007. – Vol. 237, № 15–17. – P. 1909–1922.
5. Bobkov V.P. et al. A modified table for calculating critical heat fluxes in assemblies of triangularly packed fuel rods // Thermal engineering. – 2011. – Vol. 58, № 4. – P. 317–324.
6. Kumamaru H., Koizumi Y., Tasaka K. Critical heat flux for uniformly heated rod bundle under high-pressure, low-flow and mixed inlet conditions // Journal of Nuclear Science and Technology. – 1989. – Vol. 26, № 5. – P. 544–557.
7. Kao S.P., Kazimi M.S. Critical heat flux predictions in rod bundles // Nuclear Technology. – 1983. – Vol. 60, № 1. – P. 7–13.
8. Tondreas Neils, Kazimi M.S. Nuclear systems. Volume 1: Thermal hydraulic fundamentals // Boca Raton, FL : Taylor & Francis, 2012.