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Developmental Status of TRACE-SFR code for the DBA assessment of SFR

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1. Introduction

Prototype Generation-IV Sodium cooled Fast Reactor (PGSFR) of 150MWe is under development in KOREA. Design base events (DBEs) are assessed using MARS-LMR code to ensure the design safety during system transients by the designer. Korea Institute of Nuclear Safety (KINS) have been preparing licensing review of the reactor including evaluation code and technology development for safety analysis area. SFR version of TRACE (TRACE-SFR) code is under developing to implement audit calculation for PGSFR DBAs since 2012. Due to the design difference of SFR from LWR, TRACE-SFR code development was focused for wire-wrapped fuel bundle pressure drop and sodium heat transfer models.

Initial version of TRACE-SFR code was developed based on the TRACE Version 5 patch 2. Current version of TRACE-SFR code is revised based on TRACE Version 5 Patch 4. To fulfill the validation needs for implemented models in the code, single WW fuel bundle pressure drop correlation and sodium heat transfer model were expanded to multiple models.

In this paper, the recent status of the development of TRACE-SFR code is introduced in terms of for wire-wrapped (WW) fuel bundle pressure drop, sodium heat transfer model etc.

2. WW fuel bundle pressure drop correlations

WW fuel bundle pressure drop correlations were published in the early 50s, CTS correlation is widely used for design and analysis code.

Through the literature survey, WW fuel bundle DP correlations were reviewed including Cheng and Todreas Simplified (CTS 86, CTS 2013), Engel, Rehme, Baxi and Dalle Donne, Kirillov correlations listed below

2.1 Cheng and Todreas [1][2]

(1) Laminar region

$$f_T = \frac{C_T}{Re^{0.18}}$$

$$C_L = \left[-974.6 + 1621\left(\frac{P_t}{D_r}\right) - 598.5\left(\frac{P_t}{D_r}\right)^2\right] \times (H/D_r)^{0.06-0.085(P_t/D_r)}$$

$$When: \ Re < Re_L = 300 \times 10^{1.7(P_t/D_r-1)}$$

(2) Turbulent region

$$f_T = \frac{C_T}{Re^{0.18}}$$

$$C_T = \left[0.8063 - 0.9022 \times Log_{10}\left(\frac{H}{D_r}\right) + 0.3526 \times \left(Log_{10}(\frac{H}{D_r}\right)^2\right]$$

$$\times (P_t/D_r)^{0.97} \times (H/D_r)^{1.78-2(P_t/D_r)}$$

$$When: \ Re > Re_T = 10{,}000 \times 10^{0.7(P_t/D_r-1)}$$

(3) Transition region

- Cheng et al., 1986

$$f_{tr} = (1-\varphi)^{1/3} f_L + \varphi^{1/3} f_T$$

$$\varphi = \frac{Log_{10}(Re/Re_L)}{Log_{10}(Re_T/Re_L)}$$

- Cheng et al., 2013

$$f_{tr} = (1-\varphi)^{1/3}(1-\varphi)^{13} f_L + \varphi^{1/3} f_T$$

$$\varphi = \frac{Log_{10}(Re/Re_L)}{Log_{10}(Re_T/Re_L)}$$

$$When: \ Re_L \le Re \le Re_T$$

2.2 Engle, Markley and Bishop [3]

(1) Laminar region

$$f_L = \frac{110}{Re} \text{ for Re} < 400$$

(2) Turbulent region

$$f_T = \frac{0.55}{Re^{0.25}} \text{ for Re} > 5000$$

(3) Transition region

$$f_{tr} = (1-\varphi)^{0.5} f_L + \varphi^{0.5} f_T$$

$$\varphi = \frac{(Re-400)}{4600}$$

2.3 Rehme correlation [4]

(1) All region

$$f = \left(\frac{64}{Re}F^{0.5} + \frac{0.0816}{Re^{0.133}}F^{0.9335}\right) \cdot \frac{N_r \cdot \pi \cdot (D_r + D_w)}{S_i}$$

$$F = \left(\frac{P_t}{D_r}\right)^{0.5} + \left[7.6 \cdot \frac{(D_r + D_w)}{H} \cdot \left(\frac{P_t}{D_r}\right)^2\right]^{2.16}$$

2.4 Boxi and Dalle-Donne [5]

(1) Laminar region for Re < 400

$$f_L = \left(\frac{K}{Re}\right) \cdot \left(\frac{T_w}{T}\right)$$

$$K = \frac{80}{Re} \cdot \left(\frac{P_t}{D_r}\right)^{1.5} \ ; where \ H \ in (cm)$$

(2) Turbulent region for Re >5000

$$f_T = \frac{0.316}{Re^{0.25}} \cdot M$$

$$M = \left[\frac{1.034}{\left(\frac{P_t}{D_r}\right)^{0.124}} + \frac{29.6 \cdot \left(\frac{P_t}{D_r}\right)^{6.94} \cdot Re^{0.086}}{\left(H/(D_r + D_w)\right)^{2.239}} \right]^{0.885}$$

(3) Transition region

$$f_{tr} = (1-\varphi)^{0.5} f_L + \varphi^{0.5} f_T$$

$$\varphi = \frac{(Re - 400)}{4600}$$

2.5 Kirillov [6]

(1) Laminar region for Re < 400

$$f_L = \left(\frac{64}{Re}\right) \cdot \left(\begin{array}{c} 0.407 + 2.0\left(\frac{P_t}{D_r} - 1\right)^{0.5} \\ \cdot \left(1 + 17.0\left(\frac{P_t}{D_r} - 1\right) / \left(\frac{H}{D_r}\right)\right) \end{array} \right)$$

(2) Turbulent region for Re > 5000

$$f_T = \left(\frac{0.21}{Re^{0.25}}\right) \cdot \left(1 + \left(\frac{P_t}{D_r} - 1\right)^{0.32}\right) \cdot \left(1 + 600\left(\frac{D_r}{H}\right)^2 \left(\frac{P_t}{D_r} - 1\right)\right)$$

(3) Transition region

$$f_{tr} = (1-\varphi)^{0.5} f_L + \varphi^{0.5} f_T$$

$$\varphi = \frac{(Re - 400)}{4600}$$

2.6 Correlations coded in TRACE-SFR

Among above six correlations above, Rheme, Kirillov, Engel, CTS (1986, 2013), Boxi Dalle-Donne correlations were implemented into the new version of TRACE-SFR codes. WW fuel bundle DP correlations can be selected by "command line argument" option "--wwc*n*", where *n*=1 for CTS(1986), *n*=2 for Kirillov, *n*=3 for Engle, *n*=4 for Rheme, *n*=5 for CTS(2013) and *n*=6 for Boxi Dalle-Donne correlation. These correlations except Boxi Dalle Donne were validated through the assessment of KAERI 19-pin (Test section: B2, P/D: 1.125, H/D: 25.0) pressure drop experiment. Mean error of form loss coefficient in 95% confidence level is listed in Table 1 for 5 correlations. For the case of KAERI 19-pin pressure drop test [7] evaluation, CTS (2013) correlation was the best correlation to evaluate the form loss coefficient of the WW bundle test section B2. [8]

Table I: Mean error of form loss coefficient in 95% confidence level and sample standard deviations [8]

Correlations	Laminar	Transition	Turbulent	All Region
CTS13	**17.44/7.22**	**-5.70/8.54**	**-9.98/2.2**	**-3.62/11.07**
CTS86	17.14/7.22	-6.34/7.22	-9.98/2.23	-3.88/11.44
Kirillov	0.84/7.62	-12.72/8.16	-15.85/4.27	-11.20/9.11
Engel	-1.91/8.84	-35.92/17.82	-47.82/5.45	-32.52/20.16
Rheme	27.42/6.00	12.64/5.53	12.08/2.42	14.36/7.29

3. Sodium heat transfer model

The main reason for the difference of heat transfer between liquid metals and water is that liquid metals have a very low Prandtl number (Pr). In other words, the contribution to the total heat transfer from the thermal conductivity is much higher for liquid metals compared to water. Hence, a proper selection of the correlation for heat transfer to liquid metal flowing is important. Original TRACE code have Lion-martinelli correlation for sodium wall heat transfer.

- TRACE code correlation

$$\mathrm{Nu} = 4.8 + 0.025\mathrm{Pe}^{0.8}$$

For the fuel bundle and heat exchangers, other heat transfer models could be used by designer. Due to these reason, shell side heat transfer model was surveyed and implemented as optional model for future model effect analysis.

3.1. Mikityuk correlations

In Mikityuk's thesis, he reviewed various heat transfer correlation for liquid metal and proposed new correlation derived as a best fit to the data analyzed. The correlations is a function of Peclet number (Pe), pitch to diameter ratio(x)

- Correlation by Mikityuk [9]

$$\mathrm{Nu} = 0.047(1 - \mathrm{e}^{-3.8(x-1)})(\mathrm{Pe}^{0.77} + 250)$$

For Pe: 30-5000, x: 1.1-1.95

During Mikityuk's review and comparison on other correlations, Ushakov and Graver and Reiger correlations showed similar clad-to-coolant temperature drop and lowest error. [9] So above two correlations were also implemented in the TRACE-SFR code.

- Correlation by Ushakov et al. [10]

$$\mathrm{Nu} = 7.55x - \left(\frac{20}{x^{13}}\right) + \left(\frac{0.041}{x^2}\right)\mathrm{Pe}^{(0.56+0.19x)}$$

- Correlation by Graber and Rieger [11]

$$\mathrm{Nu} = 0.25 + 6.2x + (0.032x - 0.007)\,\mathrm{Pe}^{(0.8-0.024x)}$$

3.2. MARS-LMR code correlations [12]

KAERI developed MARS-LMR code for DBE assessment of SFRs. Subbotin and modified Schad correlations are used for MARS-LMR code. For model sensitivity study, PGSFR designer's correlation also included in the TRACE-SAR code.

- Subbotin correlation (Laminar region)

$$\mathrm{Nu} = 5.0 + 0.025\mathrm{Pe}^{0.8}$$

- Modified Schad correlation (Turbulent region)

$$\mathrm{Nu} = [-16.15 + 24.96x - 8.55x^2]\mathrm{Pe}^{0.3}$$

3.3. RELAP5-3D code correlations[13]

INL reviewed the default heat transfer correlations of RELAP5-3D code. Bird correlation is identical to the Subbotin correlation.

RELAP5-3D code also have Westinghouse heat transfer correlation as an option. But Todreas and Kazimi who developed Westinghouse (WH) correlation showed that it agreed well with experimental data at P/D=1.15, but underestimated at P/D=1.30. Also they showed that the correlation of Borishanskii is more accurately reflected the experimental data, particularly at larger values of P/D. On the base of these review findings, Borishanskii and WH correlations are also included as optional models for TRACE-SFR code.

- Correlation by Borishanskii

$$\mathrm{Nu} = 24.15\log\{-8.12 + 12.76x - 3.67x^2\}$$

For 1.1<P/D<1.5 and Pe<200

$$\mathrm{Nu} = 24.15\log\{-8.12 + 12.76x - 3.67x^2\} + 0.0174\left(1 - e^{6(1-x)}\right)(Pe - 200)^{0.9}$$

For 200≤ Pe ≤ 2000

- Westinghouse (WH) correlation

$$\mathrm{Nu} = 4.0 + 0.33(x)^{3.8}\left(\frac{\mathrm{Pe}}{100}\right)^{0.86} + 0.16(x)^{5.0}$$

For 1.1<P/D<1.4 and 10≤Pe≤5000

3.4. Coded heat transfer correlations for TRACE-SFR

Among above correlations, shell side additional 6 heat transfer correlations were implemented into the new TRACE-SFR code.

Optional Sodium heat transfer correlations also can be selected by "command line argument" option "--na_htn", where *n*=1 for Mikityuk, *n*=2 for Ushakov, *n*=3 for Graber, *n*=4 for Modified Schad , *n*=5 for Borishanskii and *n*=6 for WH correlation.

3.5. Preliminary analysis

Sodium heat transfer correlations were compared for the EBR-II XX09 driver geometry (x= 1.28) in Fig. 1.

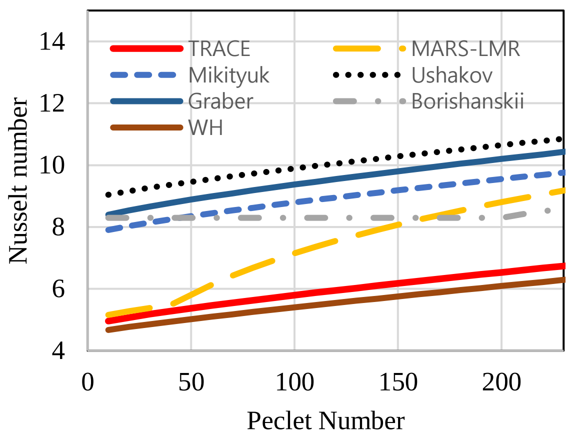

Fig. 1. Sodium heat transfer correlations comparison for the EBR-II XX09 fuel assembly geometry

Comparisons showed that WH correlation estimates lowest Nusselt number, Ushakov estimates highest heat transfer. TRACE default model estimates second lowest Nusselt number. Order of Nusselt number estimated by 7 correlations is different at Peclet number.

TRACE-SFR code simulation result for EBR-II XX09 subassembly in normal condition showed in Fig. 2. Order of estimated temperature difference between the clad surface and the bulk coolant temperature is consistent with the correlation comparison in Fig. 1. Maximum fuel clad surface temperature estimation difference was 10.2K by correlations used in normal condition.

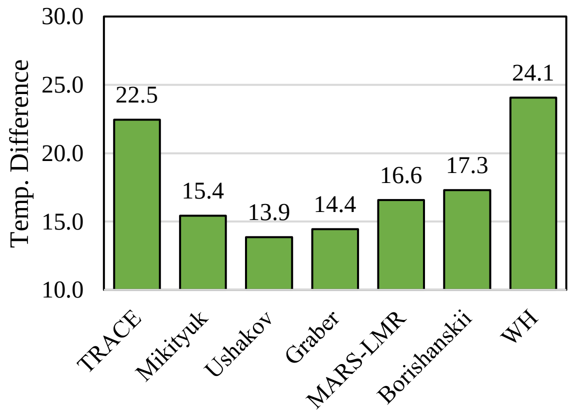

Fig. 2. Temperature difference between clad surface and bulk coolant for EBR-II XX09 subassembly at normal condition

5. Conclusions

SFR version of TRACE (TRACE-SFR) code is under developing to implement audit calculation for PGSFR DBAs since 2012. Earlier version of TRACE-SFR code have single correlation for wire-wrapped fuel bundle pressure drop and sodium heat transfer model.

TRACE-SFR code was upgraded based on the TRACE Version 5 Patch 4 and 5 additional wire-wrapped fuel bundle pressure drop correlation options were implemented and verified with KAERI 19-pin pressure drop test.

In addition to the pressure drop correlations, sodium heat transfer correlation was also expanded with additional 6 correlation options for fuel bundle and shell side heat transfer of heat exchanger. Preliminary analysis of clad temperature of EBR-II XX09 assembly geometry shows clad temperature estimation is different by the heat transfer correlation and flow condition. For normal condition, the clad temperature estimation difference by 7 correlations ranged around 10K.

The goal of TRACE-SFR code development is expanding sodium coolant related functionality keeping up with enhancement of the original version of TRACE code include sodium properties, hydraulics and thermal perspective. So far, TRACE-SFR code development is focused on the major different area from light water reactors and it is ready to use for SFR related validation and applications.

Future activities using TRACE-SFR code is expected to be an area of common interest between LWR and SFR such as natural circulation phenomena and related hydraulics due to the importance of natural circulation flow for SFRs.

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