Development of beta version of TRACE-SFR code and component test assessments

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1. Introduction

Prototype Generation-IV Sodium cooled Fast Reactor (PGSFR) of 150MWe is on the specific design stge. MARS-LMR code [1] is being used for Design Base Events (DBEs) assessment to analyze the design safety during the system transients by designer. Korea Institute of Nuclear Safety (KINS) have been preparing licensing review of the SFR including evaluation code and technology development for safety analysis area. SFR version of TRACE (TRACE-SFR) code have being developed to implement audit calculation for PGSFR DBAs since 2012. Due to the design difference between SFR and LWR, TRACE-SFR code development was focused on the liquid sodium properties, wire-wrapped fuel bundle pressure drop and sodium heat transfer models. [2]

Initial alpha version of TRACE-SFR code was developed based on the TRACE Version 5 patch 2. 5 additional wire-wrapped (WW) SFR fuel bundle pressure drop correlations and 6 more sodium heat transfer correlations were expanded as optional models for their effect analysis on the developmental version of TRACE-SFR based on TRACE Version 5 Patch 4 in 2017. [2] Due to the release of TRACE version 4 Patch 5 in November 2017, TRACE-SFR code was also updated along the reference code enhancement.

In this paper, re-assessment result of the beta version of TRACE-SFR code is addressed about version comparison between the developmental version and the beta version of the code on pre-assessed tests for verification of successful SFR package migration into new reference code. In addition to the basic verification of the beta version of the code, Sodium heat exchanger tests were assessed as verification of the code for the modeling and assessment of future plant applications.

2. Re-assessment of wire-wrapped bundle pressure drop test and sodium heat transfer

2.1 KAERI 19-pin wire-wrapped pressure drop test

Rheme, Kirillov, Engel, CTS (1986, 2013), Boxi Dalle-Donne correlations was also migrated into beta version of TRACE-SFR codes. These correlations except Boxi Dalle Donne were validated through the assessment of KAERI 19-pin (Test section: B2, Pitch to diameter ration: 1.125, Wire pitch to diameter ratio : 25.0) pressure drop experiment.[4] Mean error of form loss coefficient in 95% confidence level is listed in Table 1 for 5 correlations. These result is same for both of developmental [3] and beta version of TRACE-SFR code. Beta version of TRACE-SFR code also showed that CTS13 wire-wrapped pressure drop correlation calculated most accurate pressure drop of wire-wrapped SFR fuel bundle with 3.62% for the form loss coefficient estimation. Therefore, the beta version of the code have identical pressure drop predictability for wire-wrapped bundle with the pre-validated code version.

Table I: Mean error of form loss coefficient in 95% confidence level and sample standard deviations for the beta version of TRACE-SFR code

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

2.1 Heat transfer correlation effect on Steady-State

When different sodium HT correlations is used for fuel rod steady-state calculation that system power and flow is maintained unchanged, one of major differences of the calculation result is the temperature difference between bulk coolant and clad outer surface.

TRACE-SFR code have 6 additional sodium heat transfer optional correlations including Mikityuk, Ushakov, Graver, Modified schad, Borishanskii and Westinghouse as well as original Lion-martinelli correlation.[2] 7 sodium HT correlation can be used for bundle and shell side heat transfer calculation and Lion-martinelli correlation is used for tube side heat transfer calculation.

The fuel driver of EBR-II experimental reactor is composed of 4.4mm diameter 19 fuel pins surrounded by the hex-can. Pitch to diameter ratio of the fuel pin bundle is 1.28 and wire-spacer pitch to diameter is 34.48. Calculated maximum temperature difference between clad outer surface and bulk coolant for the hottest fuel driver channel of EBR-II SHRT-17 test is showed in Fig. 1. Beta version of TRACE-SFR code calculated identical temperature difference with the developmental version.

The maximum temperature difference was calculated for the WH correlation and minimum difference was calculated for Ushakov correlation. Temperature difference of two correlations was 8.8K. These heat transfer correlation effect analysis result is maintained valid also for the beta version of the code.

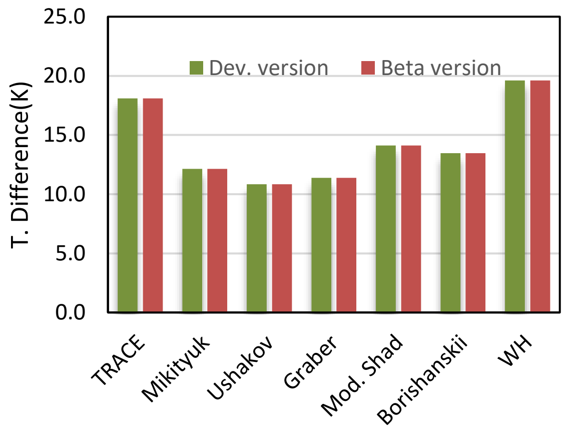

Fig. 1. The Maximum temperature difference between clad outer surface and bulk coolant for the hottest channel of EBR-II with various heat transfer correlations.

3. Heat exchanger test assessments

Major SFR components are Intermediate Heat Exchanger (IHX), Steam generator (SG), Decay Heat Exchanger (DHX) and AHX (Air Heat exchanger). IHX and DHX are sodium-to-sodium exchangers and SG and AHX are sodium-water and sodium-air heat exchanger each.

In this section, IHX and AHX test was assessed with TRACE-SFR code with optional sodium heat transfer correlation.

3.1 IGCAR 3MW IHX test

IGCAR (Indira Gandhi Centre for Atomic Research) 3 MW IHX (Intermediate Heat Exchanger) test facility is a typical IHX performance test facility.[5] Shell side heat is transferred through 180 tubes (D : 12.7mm, Thickness : 0.91mm, Tube pitch(azimuthal/radial : 19.3mm/18.4mm) to the tube side. Fig. 2 shows the schematic diagram of the test facility.

IHX heat tube length is 4.8m and IHX shell diameter is 600mm.

IGCAR IHX test loop is configured that sodium coolant heated up to 811K in heater vessel injected into the shell side inlet of IHX by sodium pump then shell side outlet 644K sodium is cooled to 616K by air heat exchanger, this cooled sodium entered into tube side inlet and heated up to 783K then return to the heater vessel.

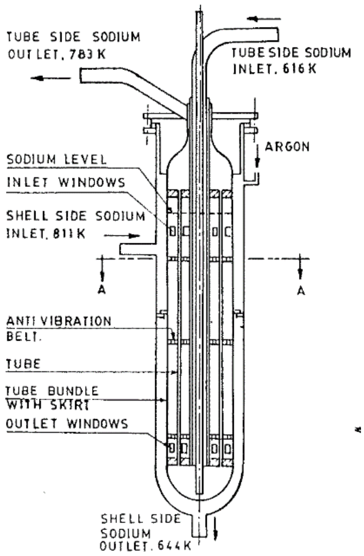

Fig. 2.IGCAR 3MW IHX test facility diagram.[5]

The test have implemented to measure IHX out temperatures with 7 sets from 3.61kg/s to 10.86kg/s for shell and tube side sodium flow. IHX heat transfer capacity was calculated using temperature difference between inlet and outlet, sodium flow and sodium heat capacity.

Assessment result of IHX performance test for 7 tests showed that the estimation error of original TRACE code HT correlation (Lion-martinelli) was 1.58% and 6.41% for each IHX outlet temperature and heat capacity.

Heat transfer capacity estimation errors for other heat transfer correlations were 5.09, 4.79, 4.79% and 5.95% for each Graber, Mod. Shad, Mikityuk, Ushakov correlation. Mod. Shad and Mikityuk correlation showed more improved predictability than Lion-Martinelli correlation.

To compensate these heat capacity estimation error in the heat exchanger modeling, heat transfer coefficient adjustment is needed. When this adjustment method is applied for IGCAR IHX test assessment with a highest heat capacity data set, both estimation errors of Lion-martinelli and Mikityuk correlation decreased to 0.93%. as shown in Fig. 3.

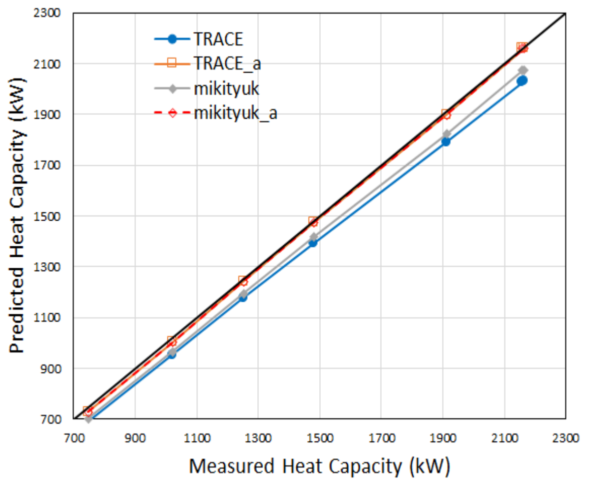

Fig. 3. IGCAR 3MW IHX heat capacity estimation for TRACE code and Mikityuk sodium heat transfer correlations (_a: HTC adjusted)

3.2 STELLA-1 AHX test

STELLA-1 AHX test facility have scaled AHX (Air heat exchanger) of PGSFR as below figure. [6] It have 36-helical coil type tube. (OD : 34.0mm, Thickness : 1.65, Shroud ID/Length : 1.53m/5.66m)

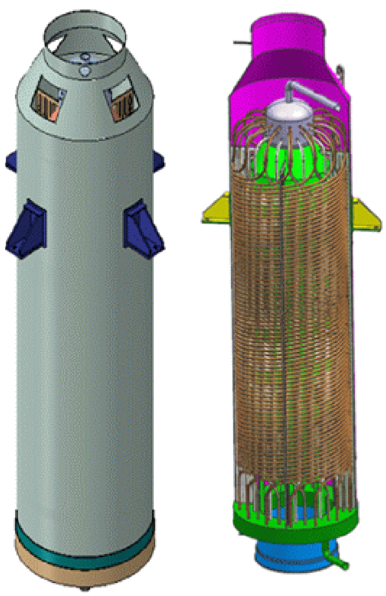

Fig. 4. STELLA-1 AHX geometry

STELLA-1 AHX test was implemented with 13 test sets with various air inlet mass flow and temperature. MARS-LMR code assessment result showed that the heat capacity estimation error was below 10.0% [6]

Assessment result of beta version of TRACE-SFR code with Lion-martinelli correlation for tube side and each of Gnielinski and Zukauskas correlations for air side heat transfer were compared in Fig. 5

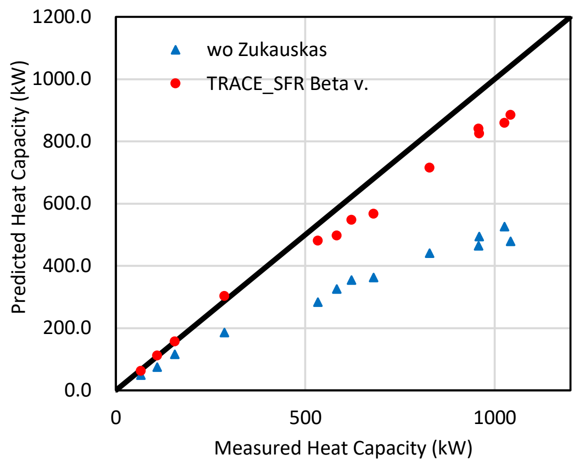

Fig. 5. STELLA-1 AHX test assessment result

Normal air heat transfer correlation (Gnielinski) case (wo Zukauskas) estimated 42% lower than the test. Applying Zukauskas tube bank heat transfer correlation for the air side, heat capacity estimation mean error of the TRACE-SFR code was reduced to 9.14% that is similar to the MARS-LMR code assessment result. Air side correlation effect was dominant in the assessment.

5. Conclusions

Five additional wire-wrapped (WW) SFR fuel bundle pressure drop correlations and six more sodium heat transfer correlations expanded in the developmental version of TRACE-SFR code was successfully migrated to beta version of TRACE-SFR code based on TRACE version 5 patch 5 with identical wire-wrapped bundle pressure drop estimations for the KAERI-16 pressure drop test and temperature difference estimation between sodium and fuel surface of EBR-II driver.

TRACE-SFR code assessment of the sodium to sodium heat exchanger test of IGCAR IHX showed that Mikityuk correlation estimated more accurate IHX out temperature and heat transfer capacities than Lion-martinelli correlation. Adjustment of sodium heat transfer coefficient based on the test data enhanced the overall heat transfer capacity prediction.

For the sodium to air heat transfer capacity estimation for STELLA-1 AHX tests, the beta version of TRACE-SFR code have predictability with mean error of 9.15 %.

On the basis of component test assessment result of the TRACE-SFR code, it could be used for SFR component models with estimation uncertainty identified with component test assessment.

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