OUTLINE OF RESEARCH AND DEVELOPMENT OF THERMAL-HYDRAULICS AND SAFETY OF JAPANESE SUPERCRITICAL WATER COOLED REACTOR (JSCWR) PROJECT

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Abstract

In the thermal-hydraulic area of Japanese Supercritical Water Cooled Reactor project (JSCWR), the main objective is to provide high-precision heat transfer and hydraulics resistance correlations of supercritical water which are necessary for the conceptual design of the core and fuel. For this purpose, a database was constructed from literature survey and previous research results. The most suitable correlation applied for circular tubes was selected based on the database and the range of application and predictive accuracy were defined. A thermal-hydraulics analysis code has started to be developed based on large eddy simulation, which is selected for simulation of the heat transfer deterioration, to give detailed information of thermal-hydraulics phenomena in a fuel bundle.

1. Introduction

Two R&D projects on the pressure-vessel type Supercritical Water Cooled Reactor (SCWR) with fast/thermal options are ongoing in Japan joined by universities, research institutes and industries. The present paper introduces the summary of R&D project on thermal option, entitled “Development of SCWR in GIF Collaboration (Phase-I) “, which was granted to Toshiba Corporation and The Institute of Applied Energy in August 2008 and will complete in March 2011.

The objective is to establish database and correlations necessary to evaluate rod surface temperatures and pressure drop for pre-conceptual and conceptual core/fuel designs of SCWR. Major R&D items are as follows:

1) Construction of database for heat transfer and pressure drop for SCWR,

2) Validation of best-estimate heat transfer and hydraulic resistance correlations, and

3) Thermal-hydraulics analysis of fuel channel with computational fluid dynamics (CFD) code.

Japan has been conducted supercritical Freon tests for more than 10 years and are conducting supercritical-pressure water tests for 5 years. Those test data and other data from literatures and through GIF collaboration have been utilized to establish the database and correlations. A thermal-hydraulics analysis code based on large eddy simulation (LES) has also started to be developed.

2. Construction of database for heat transfer and pressure drop for SCWR

Heat transfer and pressure drop database was made to evaluate accuracy of correlations.

2.1 Basic concept of database

Supercritical pressure heat transfer tests and pressure loss experiments have been carried out a lot for supercritical pressure boiler development, and there are a lot of papers. However, database has not been made from a point of view to evaluate correlations. Therefore we made a database of numerical value table to evaluate correlations.

We discussed framework of the database, and decided as follows.

(1) For making a general-purpose database, we select experimental data using water, freon and carbon dioxide as working fluid.

(2) Information of experimental apparatus and test section are included in database.

(3) The database specifies important parameters (pressure, flow rate, entrance temperature, enthalpy, rod temperature, heat transfer rate, pressure drop) that are necessary to evaluate correlation.

2.2 Database Construction

Tables 1 and 2 show the heat transfer coefficient and pressure drop database specification. Both tables specify main parameter range. The database covers the following fluid and test section.

(1) Fluid : Freon (Hydrochlorofluorocarbon ; HCFC22), Water, CO_2

(2) Test section : Tube, Single rod (Annulus), 3 rod bundle, 7 rod bundle

Table 1 Heat transfer rate database specification

Data	Fluid	Test section type	Test section size	Pressure MPa	Mass flux $kg/m^2/s$	Heat flux kW/m^2	Enthalpy kJ/kg
Kyushu Univ. data [1, 2]	Freon	Tube	4.4 mm ID 2000 mm L	5.5	194 - 2031	2.5 - 90	215 - 440
		Annulus	8.0 mm Rod OD 10.0 mm Housing ID 1800 mm L	5.5	400, 1000	15 - 90	219 - 405
		3 rod bundle	8.0 mm Rod OD x 3 Rods 1.5 mm Rod Gap 1450 mm L	5.5	397 - 1005	5.0 - 100	226 - 442
Kyushu Univ. data [3]	Freon	Tube	4.4 mm ID 2000 mm L	5.5	400,1000	10 - 80	222 - 452
		7 rod bundle	8.0 mm Rod OD x 7 Rods 1.0 mm Rod	5.5	400,1000	10 - 80	249 - 399

			Gap 1950 mm L				
JAEA data [4, 5]	Water	Annulus	8.0 mm Rod OD 10.0 mm Housing ID 1800 mm L	25.5	1892 - 2633	0.8 - 1.10	1430 - 2128
		7 rod bundle	8.0 mm Rod OD x 7 Rods 1.0 mm Rod Gap 1950 mm L	25	925 - 2333	0.53 - 1.07	450 - 1965
Kyushu Univ. data [1, 6]	Freon	Tube	9.0,13.0 mm ID	5.5	400 - 2000	10 - 70	206 – 453
	Water	Tube	7.5,10 mm ID	24.5	410 - 1260	115 - 698	1444 - 3015
A. P. Ornatskii et al [7]	Water	Tube	3 mm ID	25.5	850 - 1500	395 - 1810	120 - 2044
M. E. Shitsman [8]	Water	Tube	16 mm ID 1600 mm L	24.5	55 - 389	238 - 372	522 - 2598
Yu. V. Vikhrev et al. [9]	Water	Tube	7.85 mm ID	26.5	493 - 1400	570 - 1160	278 - 2564
H. Herkenrath et al. [10]	Water	Tube	10 mm ID	24	700 - 3500	500 - 2000	1506 - 2992
J. W. Ackerman [11]	Water	Tube	14 mm ID 2743 mm L	22	1000 - 2500	450 - 600	1601 - 2386
H. Griem [12]	Water	Tube	14 mm ID	25	500 - 2500	300 - 600	1625 - 2766
H. S. Swenson et al. [13]	Water	Tube	9.42 mm ID	25.75	2144	788	680 - 3024
A. P. Ornatsky [14]	Water	Tube	3 mm ID	25.5	1000	1210	767 - 1687
H. Kim, Y. Y. Bae et al. [15]	CO_2	Tube	4.4 mm ID 2000 mm L	8.12	1200	30 - 130	289 - 470
H.Y.Kim, H. Kim et al. [16, 17, 18]	CO_2	Tube	4.4 mm ID 2000 mm L	8.12~~,~~	400 - 1200	30 - 50	270 - 496
H.Y.Kim, H. Kim et al. [16, 17, 18]	CO_2	Tube (Vertical)	9.0 mm ID 2000 mm L	8.12	400 - 1200	30 - 50	215 - 390
H.Y.Kim, H. Kim et al. [16, 17, 18]	CO_2	Annulus	8 mm OD 10 mm ID 1800 mm L	8.12	400 - 1200	30 - 50	219 - 373

Table 2 Pressure drop database specification

Data	Fluid	Test section type	Test section size	Pressure MPa	Mass flux kg/m^2/s	Heat flux kW/m^2	Enthalpy kJ/kg
Kyushu Univ. data [1,2]	Freon	Tube	4.4 mm ID 2000 mm L	5.5	690	0 - 30	222 - 417
		Annulus	8.0 mm Rod 10.0 mm Housing ID 1800 mm L	5.5	700	0 - 50	219 - 408
		3 rod bundle	8.0 mm Rod OD x 3 Rods 1.5 mm Rod Gap 1450 mm L	5.5	1000	0 - 80	227 - 376
Kyushu Univ. data [3]	Freon	Tube	4.4 mm ID 2000 mm L	5.5	1000	0 - 80	222 - 424
		7 rod bundle	8.0 mm Rod OD x 7 Rods 1.0 mm Rod Gap 1950 mm L	5.5	400,1000	0 - 80	216 - 430
JAEA data [4,5]	Water	Annulus	8.0 mm Rod OD 10.0 mm Housing ID 1800 mm L	25.5	1892 - 2633	0.8 - 1.10	1430 - 2128
		7 rod bundle	8.0 mm Rod OD x 7 Rods 1.0 mm Rod Gap 1950 mm L	25	925 - 2333	0.53 - 1.07	450 - 1965
S. Ishigai et al. [19]	Water	Tube	3.92 mm ID	25.3	1000	291 - 1372 -	1018 - 2851
V. G. Razumovskiy [20]	Water	Tube	6.28 mm ID	23.5	2190	0 - 1748	1800 - 2043
B. S. Petukhov [21]	CO_2	Tube	8 mm ID	7	3250	0 - 1036	582 - 865

3. Validation of best-estimate heat transfer and hydraulic resistance correlations

In this section, the predicting performance of empirical generalized correlations for heat transfer and hydraulic resistance of supercritical pressure fluid tube flow will be examined with the database created in the previous session. In addition, the applicability of tube flow correlations to a bundle system will be discussed.

3.1 Heat transfer correlation

Heat transfer to supercritical pressure fluids has two characteristics; 'normal' heat transfer at low heat fluxes and 'deteriorated' heat transfer at high heat fluxes. For the normal heat transfer, several generalized correlations have been developed so far based on experimental data. Here, the predicting accuracy of these correlations was examined using 'normal' heat transfer data of supercritical pressure water and HCFC22 cited in the database. Assessment was made for the following 13 correlations; correlations of Petukhov et al. [22], Swenson et al. [13], Krasnoshchekov and Protopopov [23], Miropolsky and Shitsman [24], Bishop et al. [25], Miropolsky and Pikus [26], Yamagata et al. [6], Jackson and Hall (the modified correlation of Krasnoshchekov and Protopopov by Jackson and Hall) [27], Jackson and Fewster [27], Watts and Chou [28], Kurganov [29, 30] and Bae et al. (two modified correlations of Watts and Chou by Bae et al.) [31, 32]. For comparison, the well-known Dittus and Boelter correlation [33] for constant property fluids was also examined. According to the dependence of fluid physical properties on temperature, predicting performance was evaluated for three different fluid enthalpy regions; liquid-like low enthalpy region, near-pseudocritical moderate enthalpy region and vapor-like high enthalpy region.

Experimental conditions and number of water and HCFC22 data used for the examination are listed in Table 3. High enthalpy data were very few compared with low or moderate enthalpy data for both fluids. The uncertainty of each correlation was evaluated by the arithmetic mean value AD of the deviation of calculated heat transfer coefficients from experimental data, shown by the ratio $(\alpha_{cal}-\alpha_{exp})/\alpha_{exp}$, and the standard deviation SD of the ratio $(\alpha_{cal}-\alpha_{exp})/\alpha_{exp}$

from the value of AD, as follows.

$$AD=\frac{1}{N}\sum_{n=1}^{N}\left(\frac{\alpha_{cal}-\alpha_{exp}}{\alpha_{exp}}\right)\times 100=\overline{\left(\frac{\alpha_{cal}-\alpha_{exp}}{\alpha_{exp}}\right)}\times 100 \qquad \% \tag{1}$$

$$SD=\sqrt{\frac{1}{N}\sum_{n=1}^{N}\left\{\left(\frac{\alpha_{cal}-\alpha_{exp}}{\alpha_{exp}}\right)-\overline{\left(\frac{\alpha_{cal}-\alpha_{exp}}{\alpha_{exp}}\right)}\right\}^{2}}\times 100 \qquad \% \tag{2}$$

The results are shown in Table 4 for water and in Table 5 for HCFC22. For the liquid-like low enthalpy and near-pseudocritical moderate enthalpy regions, the Watts and Chou correlation is the most effective best, and the Krasnoshchekov and Protopopov correlation is second to the Watts and Chou correlation. Subsequently the modified correlation of Krasnoshchekov and Protopopov by Jackson and Hall, the Jackson and Fewster correlation and the modified version of the Watts and Chou correlation by Bae et al. are equally good. For all the correlations, the uncertainty was higher for the near-pseudocritical region than for the liquid-like low enthalpy region. The Watts and Chou correlation was originally developed based on water data. It was concluded that the Watts and Chou correlation was the most suitable to predict the normal heat transfer coefficient of supercritical pressure water in the liquid-like low enthalpy and near-pseudocritical moderate enthalpy regions. For the vapor-like high enthalpy region, it was difficult to determine which correlation was superior because of a scarcity of data. It was found that the Dittus and Boelter correlation reproduced well water data. For further examination, more reliable data are required.

Table 3 Experimental data used to test heat transfer correlations

Fluid	Pressure P MPa (P/P_{cr})	Tube Diameter D mm	Mass flux G kg/(m^2·s)	Heat flux q kW/m^2	Bulk enthalpy region	Number of data N
Water	22.6 - 29.5 (1.02 - 1.33)	3 - 14	398 - 3500	116 - 2000	Low h	127
					Near-h_{pc}	306
					High h	47
					All	480
HCFC22	5.5 (1.1)	4.4 - 13	194 - 2031	2.5 - 170	Low h	466
					Near-h_{pc}	698
					High h	53
					All	1217

Table 4 Predicting performance of heat transfer correlations for water data

Fluid		Water			
Region of specific enthalpy		Low h	Near-h_{pc}	High h	All
Number of data		127	306	47	480
Dittus and Boelter correlation	AD %	12.1	12.7	-0.4	11.2
	SD %	10.5	35.9	10.3	35.5
Petukhov et al. correlation	AD %	2.3	15.4	-12.9	9.1
	SD %	9.9	23.9	8.7	26.8
Swenson et al. correlation	AD %	-5.8	19.0	-28.3	7.8
	SD %	7.7	42.0	5.9	46.3
Krasnoshchekov and Protopopov correlation	AD %	0.9	6.6	-17.1	2.8
	SD %	9.5	23.6	8.5	24.3
Miropolsky and Shitsman correlation	AD %	5.3	38.7	-2.2	25.8
	SD %	9.5	42.2	10.9	41.1
Bishop et al. correlation	AD %	3.7	42.9	-13.6	27.0
	SD %	7.9	44.3	7.4	48.8
Miropolsky and Pikus correlation	AD %	-0.2	2.4	-10.2	0.4
	SD %	11.9	33.7	10.2	29.5
Yamagata et al. correlation	AD %	7.9	97.6	35.4	67.8
	SD %	9.2	122.8	15.1	118.6
Jackson-modified Krasnoshchekov and Protopopov correlation	AD %	10.3	7.9	-11.7	6.6
	SD %	9.2	23.4	8.9	24.0
Jackson and Fewster correlation	AD %	11.2	11.3	-14.2	8.8
	SD %	9.5	24.9	8.7	26.3
Watts and Chou correlation	AD %	2.0	-2.3	-25.0	-3.4
	SD %	8.7	23.4	8.1	24.1
Kurganov correlation	AD %	6.4	21.6	-11.3	14.4
	SD %	9.8	28.1	9.3	30.5
Bae et al. correlation	AD %	7.5	2.3	-23.5	1.1
	SD %	9.0	27.6	9.5	27.8
Modified Bae et al. correlation	AD %	-15.5	-17.6	-29.2	-18.2
	SD %	10.6	22.3	6.4	20.6

Table 5 Predicting performance of heat transfer correlations for HCFC22 data

Fluid		HCFC22			
Region of specific enthalpy		Low *h*	Near-h_{pc}	High *h*	All
Number of data		466	698	53	1217
Dittus and Boelter correlation	*AD* %	5.4	13.6	6.3	10.2
	SD %	9.7	38.7	10.8	32.7
Petukhov et al. correlation	*AD* %	13.2	18.7	-1.7	16.2
	SD %	10.3	18.4	9.0	19.7
Swenson et al. correlation	*AD* %	-1.4	13.5	-7.6	7.3
	SD %	10.0	24.1	5.0	22.4
Krasnoshchekov and Protopopov correlation	*AD* %	11.7	6.0	-6.1	8.0
	SD %	10.3	16.9	8.4	17.7
Miropolsky and Shitsman correlation	*AD* %	47.8	21.6	3.3	31.5
	SD %	13.7	29.7	10.4	30.8
Bishop et al. correlation	*AD* %	15.2	28.5	6.1	22.9
	SD %	8.9	16.5	6.1	17.6
Miropolsky and Pikus correlation	*AD* %	40.9	-4.6	-2.8	13.2
	SD %	24.2	39.4	9.9	41.7
Yamagata et al. correlation	*AD* %	47.9	107.6	40.4	83.0
	SD %	11.6	123.0	14.8	100.5
Jackson-modified Krasnoshchekov and Protopopov correlation	*AD* %	12.7	8.1	0.8	9.8
	SD %	9.4	17.2	8.8	18.0
Jackson and Fewster correlation	*AD* %	13.6	7.0	-0.7	9.5
	SD %	9.4	14.4	8.6	16.8
Watts and Chou correlation	*AD* %	9.6	-0.6	-12.8	3.2
	SD %	9.4	14.5	8.4	17.5
Kurganov correlation	*AD* %	11.3	4.7	-1.6	7.2
	SD %	11.0	16.8	8.7	17.9
Bae et al. correlation	*AD* %	12.3	4.0	-9.3	7.0
	SD %	10.3	16.5	11.8	19.0
Modified Bae et al. correlation	*AD* %	-19.4	-26.6	-24.7	-23.7
	SD %	11.3	14.5	5.7	16.3

3.2 Hydraulic resistance correlation

Evaluation of the predicting performance of hydraulic resistance, or friction factor, at heating for supercritical pressure fluid tube flow was made for the following 5 correlations; correlations of Popov [34], Tarasova and Leont'ev [35], Kirillov [36], Ishigai et al. [37], and Yamashita et al. [1]. These correlations consider the modification of a constant property friction factor equation due to physical properties change under heating condition.

Water data by Ishigai et al. [37] and HCFC22 data by Yamashita et al. [1] were used for the evaluation. Experimental conditions and number of their data are listed in Table 6. In these data, information of heating wall surface temperature necessary to estimate the physical property effect was available coupled with pressure drop data.

Results of the comparison of calculated frictional pressure drop and experimental data are shown in Table 7. The Ishigai et al. correlation with around 12% of SD was found superior to other correlations, and is the most suitable to predict the pressure drop of supercritical pressure water tube flow at heating.

Table 6 Experimental data used to test friction factor correlations

Fluid	Pressure P MPa (P/P_{cr})	Mass flux G kg/(m^2·s)	Heat flux q kW/m^2	Mean bulk enthalpy h_m kJ/kg	Number of data N
Water	24.5 (1.1)	1000	290 - 825	1018 - 2851	18
HCFC22	5.5 (1.1)	700	10 - 40	296 - 417	12

Table 7 Predicting performance of friction factor correlations

Fluid		Water	HCFC22
Number of data		18	12
Popov correlation	*AD* %	-3.9	7.3
	SD %	12.7	13.2
Tarasova and Leont'ev correlation	*AD* %	9.2	11.8
	SD %	13.5	14.8
Kirillov correlation	*AD* %	3.7	12.7
	SD %	11.3	15.3
Ishigai et al. correlation	*AD* %	0.1	4.5
	SD %	12.5	11.5
Yamashita et al. correlation	*AD* %	-0.6	-8.3
	SD %	19.0	6.9

4. Thermal-hydraulics analysis of fuel channel with CFD code

In order to develop a numerical analysis method for predicting the deteriorated turbulent heat transfer, adequacy and validity of four kinds of turbulence models (standard k-ε model (SKE), modified k-ε model (MKE), Reynolds stress model (RSM) and large eddy simulation (LES)) have been evaluated.

The experimental geometry is a three-dimensional vertical circular tube with a diameter of 4.4 mm and the axial heating length is 2 m. The computational domain simulates the experimental geometry partially, and the size is 4.4 mm in diameter and 5 mm in axial length as can be seen in Fig. 1. The periodic boundary conditions are given to the inlet and outlet of the computational domain in the axial direction. The number of calculation grids is 3340 in the radial direction and 1250 in the axial direction for the three-dimensional simulation using LES, and also is 550 in the radial direction and 200 in the axial direction for the two-dimensional simulations using SKE, MKE and RSM. The grid division is not uniform and the minimum grid size is 1 μm. The exit pressure is fixed at 5.5 MPa.

The supercritical pressure freon that is a working fluid flows upward in the vertical circular tube. The mass flow rate and fluid temperature at the inlet of the computational domain are 400 kg/m^{2}s and 320 K. Furthermore, the uniform heat flux was given to the wall. The present calculations were performed for two heat flux conditions of 20 and 25 kW/m^2. The wall function near the wall surface is used for SKE and MKE. The SIMPLE algorithm is used to the pressure-velocity coupling calculation, and every variable such as velocity and turbulent quantities is discretized by a second-order upwind scheme. When residuals of all variables become smaller than 10^{-4}, the calculation is judged to be converged.

Figure 2 shows the wall temperature distributions against the bulk enthalpy at 25 kW/ m^2. Here, the solid circle shows the experimental result and the open circle shows the predicted result of SKE, and the colored circles indicate the predicted results of the other turbulence models; red is MKE, green is RSM, and purple is LES. As for the predicted turbulent heat transfer deterioration, the result of LES showed the nearest value to the experiment results. It was difficult for other models to predict the deterioration of the turbulent heat transfer. As a reason of this, the following consideration will be derived. The LES can predict the turbulent heat transfer for the time-dependence condition. On the other hand, since SKE, MKE and RSM are the time-averaging model, it is difficult for these models to predict accurately the turbulence phenomenon that changes substantially over time.

From this study, it is considered that the design analysis by LES is most promising for simulation of the heat transfer deterioration.

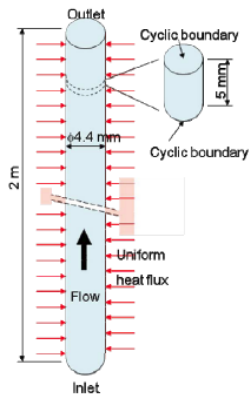

Figure 1 Computational geometry of a vertical circular tube

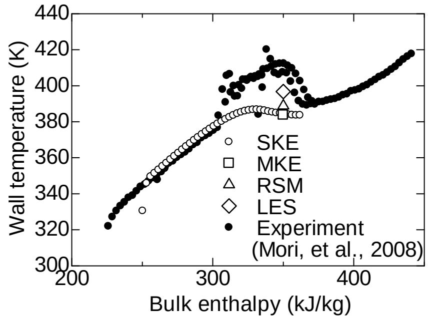

Figure 2 Wall temperature predicted under the condition of surface heat flux of 25 kW/m^2

5. Conclusion

To provide high-precision heat transfer and hydraulics resistance correlations of supercritical water which are necessary for the conceptual design of the SCWR core and fuel, the database was constructed from literature survey and previous research results. The most suitable correlation applied for circular tubes was selected based on the database and the range of application and predictive accuracy were defined.

A thermal-hydraulics analysis code to predict turbulence heat transfer coefficient had been developed, which will give detailed information of thermal-hydraulics phenomena of supercritical water in a fuel bundle and contribute to the development of the correlations.

6. References

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