DEVELOPMENT AND VALIDATION OF A SCALING METHOD FOR SUPERCRITICAL FLUID HEAT TRANSFER

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ABSTRACT

In the recent years, the heat transfer behavior in supercritical water arouses lots of attention in the nuclear R&D filed due to its application to the SuperCritical Water Cooled Reactor (SCWR). However, experimental studies using supercritical water require high pressure, high temperature and high power, which bring out expensive cost. Therefore, model fluid technique has been widely applied in the thermal-hydraulic studies of supercritical fluid. In spite of growing activities of heat transfer at supercritical conditions using model fluids, there does still not exist any reliable fluid-to-fluid scaling methods, to transfer the test data in model fluids directly to the conditions of prototype fluid. This paper presents a fluid-to-fluid scaling method for heat transfer in circular tubes cooled with supercritical fluids. Based on conservation equations and boundary conditions, on set of dimensionless numbers and the requirements of a complete scaling are determined. Scaling of pressure and temperature ensures the similarity of thermo-physical properties of various fluids. A new dimensionless number, presenting the product of the so-called pseudo Boiling number, Reynolds number and Prandtl number, is applied to scale heat flux. The distortion approach is used to scale mass flux. These contribute a scaling method for the supercritical fluid.

The experimental data from water and Freon are selected to validate the scaling method. Some amendment technique to the data is developed to meet the scaling requirement from the method. The preliminary validation results show good feasibility and reasonable accuracy of the proposed scaling method.

KEYWORDS
Supercritical fluid, fluid-to-fluid scaling, heat transfer, validation

1. INTRODUCTION

One of the most challenging tasks in the SCWR fuel assembly design of supercritical water-cooled reactors (SCWR) is to keep the maximum cladding temperature well below the design upper limit, to guarantee the integrity of the fuel rods. Thus, an accurate prediction of heat transfer behavior plays an important role and attracts extensive investigations. Due to the strong variation of thermal-physical properties in the vicinity of the pseudo-critical point, heat transfer of supercritical fluids shows abnormal behavior compared to that of conventional fluids [1]. One of the main features of heat transfer of supercritical fluids is its strong dependence on heat flux, especially as bulk temperature close to the pseudo-critical value.

In spite of extensive studies in the past five decades and a large number of prediction models, prediction of heat transfer of supercritical (SC) fluids uses mainly empirical approaches. In the open literature there exist a large number of empirical correlations, which were derived based on experimental data with limited parameter ranges, as reviewed and summarized by Pioro and Duffey [2], and Cheng and Yang [3]. In the frame of the development of SCWR, heat transfer in SC fluids becomes a focusing topic in the research of nuclear thermal-hydraulics. A literature survey emphasizes big deficiency in experimental data in the SCWR typical parameter range, and consequently, big deficiency in an accurate description and prediction of heat transfer behavior at SCWR conditions [1].

Experimental studies using supercritical water require high pressure, high temperature and high heat power. To reduce both technical difficulties and economic expense, heat transfer experiments have often been performed in a scaled model system. Two different modeling techniques are available, i.e. geometric modeling and fluid modeling. By the geometric modeling simplified flow channels, e.g. circular tubes or small rod bundles, instead of prototypical rod bundles are used. By using such simple flow channels it is possible to study systematically the effect of different parameters on heat transfer and to gain detailed knowledge of heat transfer for a wide range of test parameters. By the fluid modeling a substitute fluid is used instead of the original fluid (water). By a proper selection of model fluids, the operating pressure, operating temperature, and the heat power required would be reduced significantly. As it was successfully exercised in the nuclear thermal-hydraulics, experimental technique using model fluids is a feasible and effective measure to achieve scientific and engineering purposes and at the same time to overcome technical and economic problems associated with the experiments using the prototypical fluid.

The key issue concerning the fluid modeling is the transfer of the test data obtained in the model fluid to the prototypical fluid (water), the so called fluid-to-fluid modeling. The success in the application of model fluids depends on the reliability of the scaling methods, which transfer the experimental data from the model fluids directly to conditions of prototypical fluid. Unfortunately, there are still very limited studies on fluid-to-fluid modeling of heat transfer at supercritical conditions. Pioro & Duffey [2] gave a brief review on fluid-to-fluid modeling of heat transfer at supercritical conditions. To transfer the test data to supercritical water conditions, the following three dimensionless parameters are applied to scale pressure, bulk temperature and mass flux, i.e.:

Pressure ratio: $$\left(\frac{P}{P_c}\right)_{CO_2} = \left(\frac{P}{P_c}\right)_{water} \tag{1}$$

Temperature ratio: $$\left(\frac{T_B}{T_c}\right)_{CO_2} = \left(\frac{T_B}{T_c}\right)_{water} \tag{2}$$

Reynolds number: $$\left(\frac{GD}{\mu_B}\right)_{CO_2} = \left(\frac{GD}{\mu_B}\right)_{water} \tag{3}$$

Jackson & Hall [4] used also the above three dimensionless numbers for scaling pressure, bulk temperature and mass flux. For scaling heat flux and heat transfer coefficient they suggested the following two dimensionless parameters:

$$\left(\frac{qD}{\lambda_B T_B}\right)_M = \left(\frac{qD}{\lambda_B T_B}\right)_P \tag{4}$$

$$\left(\frac{\alpha D}{\lambda_B}\right)_M = \left(\frac{\alpha D}{\lambda_B}\right)_P \tag{5}$$

This paper describes some important requirements on scaling methods for heat transfer of SC fluids. Starting from the governing equations (continuity, momentum, energy, surface heat transfer), which are rearranged in dimensionless form, a set of dimensionless parameters is derived. Based on phenomenological analysis and the distortion approach of Ahmad [5], a fluid-to-fluid scaling law is proposed, which is then validated on existing test data from various fluids combined with existing heat transfer correlations. The experimental data from water and Freon are selected to validate the scaling method. Some amendment technique to the data is developed to meet the scaling requirement from the method. The preliminary validation results show good feasibility and reasonable accuracy of the proposed scaling method.

2. NEW PROPOSED SCALING METHOD

The main objective of a scaling method is to transfer the experimental data from a model fluid to conditions of the prototypical fluid. This requires first of all a clear understanding of general experimental techniques and procedure. In this paper, we concentrate our attention to heat transfer experiments in vertically oriented circular tubes with uniform heat flux distribution. Flow channel geometry is fixed with two parameters, i.e. tube diameter and heated length. The other parameters which can be adjusted during the experiment are pressure, mass flux, bulk temperature and heat flux. Heat transfer coefficient depends on six parameters:

$$\alpha = f\left(L, D, P, T_B, G, q\right) \tag{6}$$

In case the entrance effect is neglected, the dependence on the heated length is omitted. It yields:

$$\alpha = f\left(D, P, T_B, G, q\right) \tag{7}$$

The five parameters in the right side of equation (7) can be adjusted during the experiments. The task of a scaling method is to find expressions for the scaling factors for all six parameters. The detailed procedure to derive the scaling factors is illustrated in reference [6]. It starts with the basic governing equations and boundary conditions, which are then converted into dimensionless structure. Parameters and dimensionless numbers affecting the solution of the dimensionless governing equations are identified. Criteria for a scaling method are summarized as below:

$$f_D = \frac{D_M}{D_P} = 1.0 \tag{8}$$

$$f_P = \frac{P_M}{P_P} = \frac{P_{C,M}}{P_{C,P}} \tag{9}$$

$$f_\theta = \frac{\theta_{B,M}}{\theta_{B,P}} = 1.0 \tag{10}$$

with $\theta = \dfrac{T - T_{PC}}{T_{PC} - T_C}$

$$f_G = \frac{G_M}{G_P} = \frac{\mathrm{Pr}_{B,P}^{5/12}}{\mathrm{Pr}_{B,M}^{5/12}} \cdot \frac{\mu_{B,M}}{\mu_{B,P}} \tag{11}$$

$$f_q = \frac{q_M}{q_P} = \frac{\lambda_{B,M}\left(T_{PC} - T_C\right)_M}{\lambda_{B,P}\left(T_{PC} - T_C\right)_P} \tag{12}$$

$$f_\alpha = \frac{\alpha_M}{\alpha_P} = \frac{\lambda_{B,M}}{\lambda_{B,P}} \tag{13}$$

3. VALIDATION METHOD

Table I summaries the critical parameters of various fluid i.e. water, carbon dioxide and R134a. The parameters and other properties will be used for the scaling analysis of the supercritical fluid using equation (8)-(13).

Table I: Critical parameters of various fluids

Fluid	**P_C, MPa**	**T_C, C**	**ρ_C, kg/m^3**
Water	22.12	374.15	322.0
CO_2	7.384	31.06	466.5
R134a	4.056	101.0	513.3

The direct approach to validate the scaling model is the comparison of test data from various fluids. However, the main difficulty of this approach is the limitation in test data with comparable test parameters. For example, for a test data point obtained in CO_2 at the conditions: D=8.0 mm, P=8.5 MPa, T_B=37.0 C, G=500 kg/m^{2}s and q=70 kW/m^2, we need for comparison a test data in water at the corresponding conditions: D=8.0 mm, P=25.4 MPa, T_B=385.5 C, G=652 kg/m^{2}s and q=593 kW/m^2. It is hardly possible to find test data point with these values. Therefore, interpolation of test parameters is necessary. However, interpolation of five parameters requires a huge number of test data.

3.1. Databank for scaling

At the Shanghai Jiao Tong University, efforts were made to establish a test data bank of heat transfer of supercritical fluids. An extensive open literature survey and experimental work have been performed and a preliminary database of supercritical fluid heat transfer in vertical upward tubes is set up, containing more than 14000 data points for water 5000 data points for carbon dioxide, 6000 data points for R134a. For the present studies, five test data bases are selected according to the following criteria:

- The experimental facility and test data accuracy are well documented.
- Test data points are easily obtained from open literatures with limited additional uncertainties.
- Number of test data points is large.

The experimental data for R134a are carried out on the test facility SMOFTH (***S***upercritical ***MO***del ***F***luids ***T***hermal-***H***ydraulics). This facility was used to generate the modeling experimental data to validate the scaling method. Figure x shows schematically the test facility SMOFTH. The main design parameters are:

Fluid:	Freon 134a
Pressure:	6.0 MPa
Temperature:	200°C
Flow rate:	10 t/h
Heat power:	300 kW

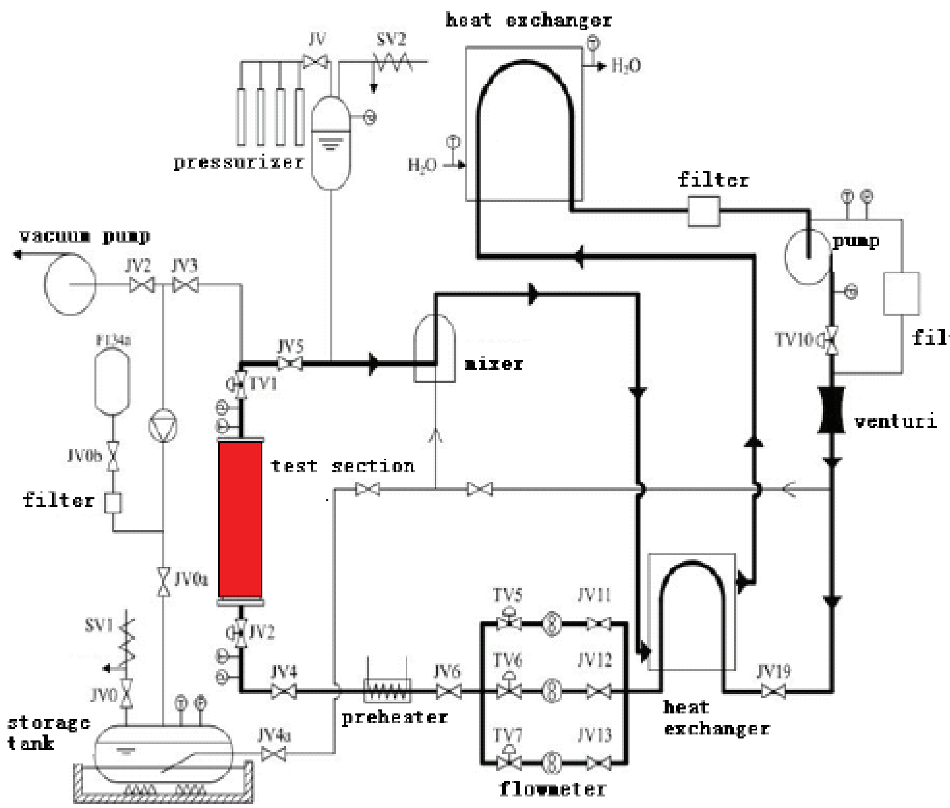

Figure 1. Scheme of the test facility: SMOFTH [7]

The test parameter ranges of the present experiments on SMOFTH are summarized in Table II. About 6000 heat transfer coefficient data in the vertical heating tube are generated on this test facility and can be used for the scaling method assessment in the following section.

Table II: Ranges of test parameters [7]

Parameters	values	Unites
Pressure	4.3, 4.5, 4.7	MPa
Mass flux	400-2500	kg/m^2s
Heat flux	10-180	kW/m^2
Fluid temperature	71-115	°C

3.2. Scaling validation method

According to the scaling methodology summarized in chapter 2, five experiment parameter, i.e. tube diameter, pressure, mas flux, bulk temperature, heat flux, are the scaled parameters, and the heat transfer coefficient is the value which should to be compared for the assessment purpose. As discussed before, it is very difficult to find test data point with 5 parameters perfect corresponding to the scaled values. Sometimes two or three parameters (e.g. diameter, pressure and mass flux) are satisfied with the scaled value, but the other parameters (heat flux and bulk temperature) are deviated from the scaled value. Therefore, it is necessary to perform correction for the parameters which are deviated from the scaled values. Figure 2 demonstrates the methodology for the validation. Firstly, the heat transfer data for fluid 1 is selected; secondly, the scaling method is applied to this data and 5 scaled parameters as well as scaled heat transfer coefficient are derived for fluid 2; thirdly, considering the scaled parameter, the test data for fluid 2 are chosen, to make sure at least 3 parameters are close to scaled parameter; fourthly, the effect of other 2 parameters are taken into consideration by a selected heat transfer correlation, a correction factor is calculated; the amended heat transfer coefficient is calculated as scaled heat transfer coefficient for fluid 2 multiplied by this correction factor; finally, the comparison between the corrected heat transfer coefficient and experimental heat transfer coefficient for fluid 2 are performed to demonstrate the applicability of the current scaling method. It should be pointed out that due to the challenge to meet all the 5 parameters between scaled and experimental data, the effect of the diverted parameters are considered by one supercritical heat transfer correlation.

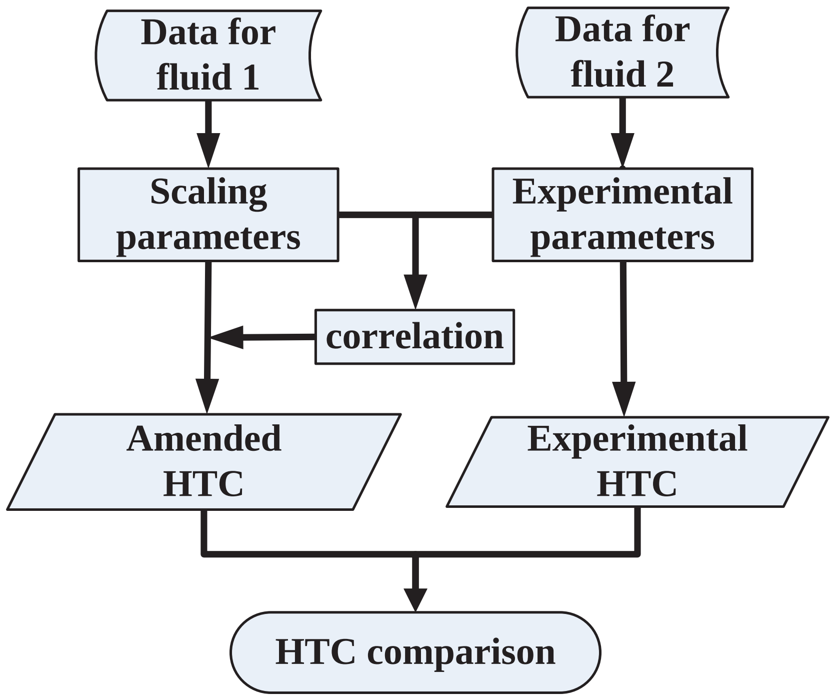

Figure 2. Scheme of validation for scaling

4. RESULTS AND DISCUSSION

Following is one example to show how to assess the scaling method from two supercritical fluid using the methodology described in Figure 2. The heat transfer experimental data point for supercritical water is tube diameter 7.6mm, pressure 23.1MPa, bulk temperature 352°C, mass flux 618kg/m^{2}s, heat flux 278.0kW/m^2, heat transfer coefficient 9.26kW/m^{2}K. Using equation (8)-(13), it can be deduced the corresponding heat transfer point for R134a: diameter 7.6mm, pressure 4.23MPa, bulk temperature 88.3°C, mass flux 502kg/m^{2}s, heat flux 20.05kW/m^2, heat transfer coefficient 1.13kW/m^{2}K. This data point is close to one data in the R134a database, i.e. diameter 7.6mm, pressure 4.31MPa, bulk temperature 88.0°C, mass flux 606kg/m^{2}s, heat flux 21.6kW/m^2. It is clear to see that except the mass flux, the other parameters are closed to the scaled parameter. Therefore the deviation between the scaled parameter and experimental data are considered by the Cheng correlation [3]:

$$Nu_b = 0.023 \cdot \mathrm{Re}_b^{0.8} \cdot \mathrm{Pr}_b^{0.33} \cdot F \tag{14}$$

$$F = \min\left(F_1, F_2\right),$$

$$F_1 = 0.85 + 0.776(\pi_a)^{2.4}$$

$$F_2 = \frac{0.48}{(10^3 \cdot \pi_{a,pc})^{1.55}} + 1.21 \cdot \left| \left(1 - \frac{\pi_a}{\pi_{a,pc}} \right) \right|$$

$$\pi_a = \frac{\beta}{C_p} \cdot \frac{q''}{G}$$

The corrected heat transfer coefficient are calculated by following equation:

$$\alpha_{amend} = \alpha_{scaled} \times \frac{f(D,P,T,G,q)_{exp}}{f(D,P,T,G,q)_{scaled}} \tag{15}$$

Where *f*() is a function to calculate the heat transfer coefficient such as Cheng correlation. Finally, the α_{amend} is calculated as 1.3 kW/m^{2}K, and the real experimental α is 1.5 kW/m^{2}K, so the error is about 14%.

This method is applied to 76 heat transfer point for R134a, the average deviation between the scaled heat transfer coefficient and experimental data is 11%, as shown in Figure 3. This demonstrates the applicability of the new developed scaling method for supercritical fluid.

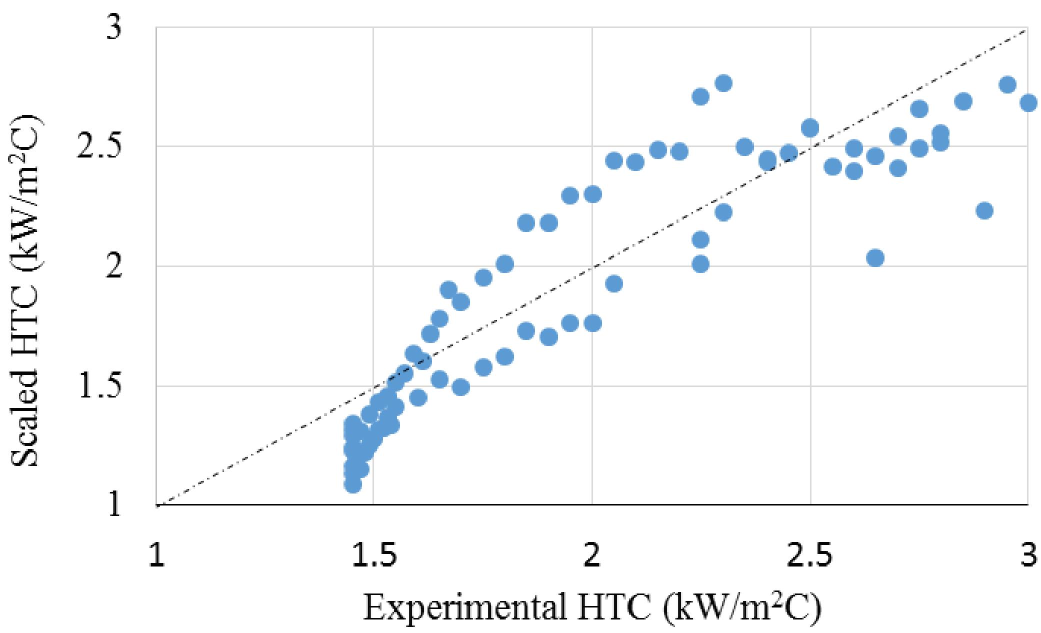

Figure 3. The comparison with experimental data

5. CONCLUSIONS

This paper presents a fluid-to-fluid scaling method and its assessment methodology for heat transfer in circular tubes cooled with supercritical fluids. For evaluation of the new fluid-to-fluid scaling model, this paper utilized a new approach, which requires a set of reliable test data in one fluid and correction by one heat transfer correlation in another fluid in similar parameter range. The correlation of Cheng is applied to correct the scaled heat transfer data in R134a. The validation results show reasonable accuracy of the proposed scaling method.

Further experimental data are required to improve and validate the fluid-to-fluid scaling method. Some further improvements for the scaling method will be performed based on the assessment results.

NOMENCLATURE

D	diameter	[m]
F	correction factor	[-]
G	mass flux	[kg/m²s]
Nu	Nusselt-number	[-]
P	pressure	[MPa]
Pr	Prandtl-number	[-]
q	heat flux	[W/m²]
Re	Reynolds-number	[-]
T	temperature	[°C]
α	heat transfer coefficient	[W/m²K]
λ	thermal conductivity	[W/m K]
μ	dynamic viscosity	[kg/m s]
ν	kinetic viscosity	[m²/s]
θ	pseudo steam quality	[-]
π_A	acceleration number, defined in equation (14)	[-]
ρ	density	[kg/m³]

subscripts

B	bulk
C	critical point
M	model fluid
P	prototype
PC	pseudo-critical
W	wall

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