R134a Flow Boiling Analysis with Modified Thermodynamic Property File of MARS Code

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1. Introduction

Initially aimed for analyzing two-phase transients of nuclear power plant, various functions of multi-dimensional analysis for reactor safety (MARS) code enabled to simulate other features associated with thermal-hydraulic experiments. MARS requires 3 files for analysis: executable MARS file, input deck, and thermodynamic property file (tpf) for target fluids like light water or heavy water (tpfh2o). As its application became wider, needs for other fluid properties rose since MARS do not have extra function to interpret foreign materials that does not have tpf. One way of solving this problem is generation of external tpf file and implementation. The addition of thermodynamic properties of the fluids in MARS code could extend the application of MARS to various engineering fields related to thermal-hydraulics.

Previous study showed application of RELAP5 code to solar energy facility with molten salt (60% $NaNO_3$ and 40% KNO_3) as working fluid [1]. Based on external experimental correlations, thermodynamic properties of molten salt were evaluated as a function of pressure and temperature and those equations were used to generate tpf. To validate external tpf, experimental values were compared with RELAP5 analysis. In nuclear field, utilization of other fluid is also important since many thermal-hydraulic experiments used various fluids such as FC-72, R123, and R134a. Theses refrigerants have been used to simulate the high pressure environment of nuclear power plants due to their low boiling point, and density ratio between vapor and liquid. Experimental data was converted to water's case by applying dimensionless numbers originated from Pi theorem.

Thus, this study aims for tpf generation of R134a and verification by analyzing real case. R134a is selected as a fluid to be implemented and analyzed because it is currently used in refrigerator and frequently used in flow boiling experiment related with heat transfer coefficient and CHF measurement. The paper overviews methods for generating tpfr134a and analysis of flow boiling experiment with simplified nodalization of test section. In order to minimize error, modified heat transfer correlations for R134a will be added in source code of execution file.

2. Implementation of R134a thermodynamic property in MARS

2.1 Thermodynamic Property File Generation

Original tpf is generated by FORTRAN subroutine that utilizes Gibbs function. The tpf contains information of the fluid's specific volume, internal energy, thermal expansion coefficient, isothermal compressibility, specific heat, and entropy according to its temperature and pressure. The coefficients used to calculate water's Gibbs energy were defined by experimental values, thus another methods were required for generation of tpfr134a. In this case, external data base from NIST were utilized to form fitted equations of pressure and temperature. By this method, all thermodynamic properties could be calculated with temperature and pressure condition. For example, Equation (1) and Fig.1 shows fitted equations of liquid specific volume relative to temperature and pressure. With same method, 4 thermodynamic properties of liquid and vapor were fitted with all coefficient of determination (R^2) value larger than 0.99. Thermal expansion coefficient and isothermal compressibility's original data were unavailable so their equations were formed by partial derivatives of specific volume.

Liquid specific volume [m^3/kg]

$$V(liq) = (2.649\times10^{-10})T^3 - (2.111\times10^{-7})T^2 + (5.763\times10^{-5})T - (3.169\times10^{-12})P + 0.004612 \tag{1}$$

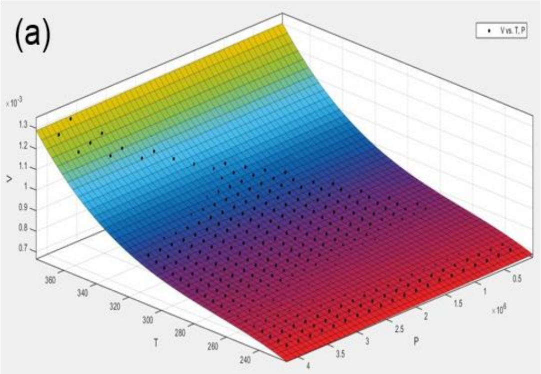

Fig. 1. Specific volume of liquid R134a.

To utilize tpfr134a, additional procedure was required by modifying source code to apply r134a properties. Thermodynamic properties of surface tension, dynamic viscosity, and thermal conductivity was required in extra subroutines. Fitting equations were used again generated with similar methods.

Surface tension [N/m]

$$\sigma = 0.0617(1-0.0027T)^{1.262} \quad (2)$$

Dynamic viscosity [kg/m-s]

$$\mu(liq) = 2.352\times10^{-8}T^2 - 1.705\times10^{-5}T + 0.003184 \quad (3)$$

$$\begin{aligned}\mu(vap) &= 1.961\times10^{-14}T^5 - 3.011\times10^{-11}T^4 + 1.841\times10^{-8}T^3 \\ &-5.605\times10^{-8}T^2 + 8.493\times10^{-4}T - 0.05123\end{aligned} \quad (4)$$

Thermal conductivity [W/m-K]

$$k(liq) = -0.0004134T + 0.2086 \quad (5)$$

$$\begin{aligned}k(vap) &= 1.071\times10^{-11}T^5 - 1.641\times10^{-8}T^4 \\ &+1.002\times10^{-5}T^3 - 0.003044T^2 + 0.4605T - 27.74\end{aligned} \quad (6)$$

2.2 Modeling of Flow Boiling Experiment

For validation, experimental case will be compared with MARS analysis. From flow boiling experiment of R134a with single loop, test section and other components were simplified into single channel [3]. Pumps were replaced with inlet composed of time dependent volume and time dependent junction in order to simulate wide range of quality while outlet has single volume and single junction. In order to maintain consistent flow, adequate initial conditions were adjusted with pressure difference with outlet volume having fixed pressure. Test section with 40 volumes (pipe) was heated uniformly, covered with copper tube. Inner diameter represents pipe’s diameter while outer diameter represents diameter of heater.

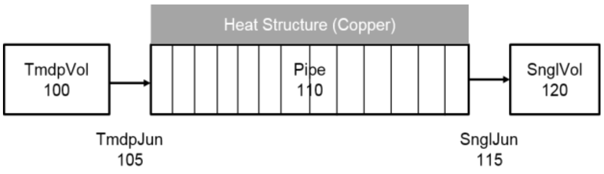

Fig. 2. Simplified node of test section.

3. Results and Discussion

3.1 Single Phase Flow Analysis

In reference, single phase experiments were conducted for inner diameters of 1.002 and 2.168 mm (each case 1 and case 2), by comparing Nusselt number for given Reynolds number condition. For case 1, Re ranges from 3000 to 7000, while MARS code utilizes Dittus-Boelter equation, effective for Re larger than 10000. Thus Gnielinski correlation which has effective range of 3000 < Re were also compared with experimental case and MARS code analysis.

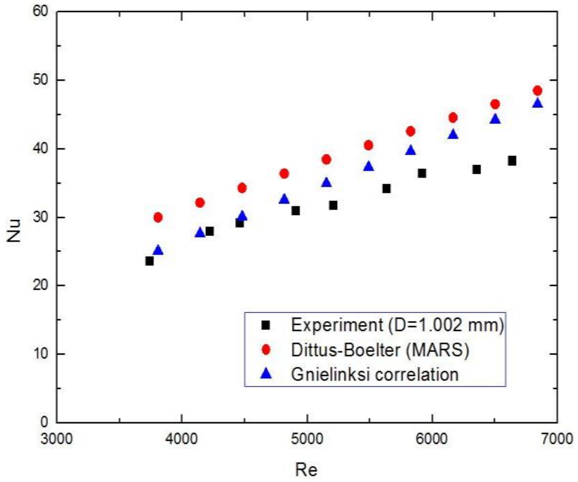

Fig. 3. Comparison for case 1 (ID=1.002 mm)

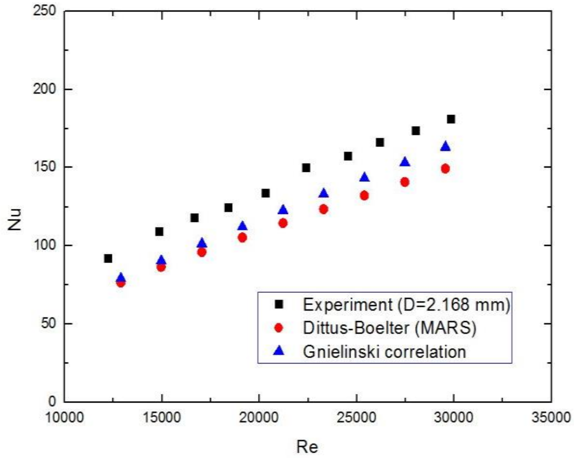

Fig. 4. Comparison for case 2 (ID=2.168 mm)

MARS code predicts Nusselt number with approximate error of 16.10 % for case 1 and 16.66 % for case 2. It should be noted that Gnielinski correlation had better prediction in both case compared to MARS code using Dittus-Boelter equation. Especially it had highest prediction accuracy at low Re region.

3.2 Two Phase Flow Analysis

Case 1 and 2 were considered relatively inaccurate since their diameters are much smaller than normal test conditions. Thus case 3 with inner diameter of 4.065 mm were selected as two phase analysis comparison. To examine the change of heat transfer coefficient with mass flux, heat flux, and saturation pressure, case 3 were compared with more specified case.

Table I: Input Conditions of Case 3 (ID = 4.065 mm)

	3-1	3-2	3-3	3-4	3-5
Mass flux (kg/m^2s)	185	295	410	185	185
Heat flux (kW/ m^2)	28.0	28.0	28.0	28.0	18.5
Pressure (MPa)	0.676	0.676	0.676	0.578	0.676

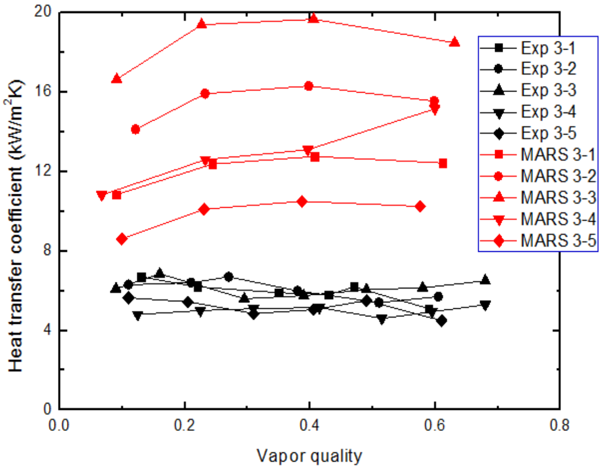

Fig. 5.Comparison of HTC data with experiment and mars code analysis with case 3-1 to 3-5.

For increasing mass flux (case 3-1, 3-2, and 3-3), experimental data shows little difference while code analysis indicates clear increase of HTC. As for increasing heat flux (case 3-1 and 3-5), both analysis and experimental data indicates increasing trend. Although the code distinguishes effects of mass flux and heat flux, it failed to simulate effect of increasing saturation pressure (case 3-1 and 3-4) while experimental data indicates increase of HTC.

There are mainly 3 possible reasons for inaccuracy of code analysis. One is fitting inaccuracy of thermodynamic properties. However, considering original tpfh2o also has fitted factors of Gibbs function and all equation’s R^2 values are over 0.99, it is unlikely that this difference caused large error. Another possible reason is code’s correlation, especially two phase heat transfer equation utilizes factors of S and F from Chen correlation. Thus many refrigerant flow boiling study modifies correlations with their fluid type, geometry, or unusual experiment conditions. Lastly, the most critical cause of error could be related to input file, nodalization and unclear experimental conditions of reference. This resulted to approximated initial conditions of inlet and outlet volumes, which could be crucial for code analysis.

4. Conclusions

R134a property file were generated with fitted equation using temperature and pressure as variables, originated from external data source. For validation, flow boiling experiment case were made into simplified input. Analysis with tpfr134a showed that application of Gnielinksi correlation could enhance single phase flow accuracy. Large error of HTC from two phase analysis requires parameter study. Future work aims for more specified experimental case comparison and correlation enhancement for two phase analysis.

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