Preliminary Study of the Artificial Neural Networks to replace the constitutive equations in the Reactor Safety Analysis Code

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1. Introduction

Accurate safety analyses of various accident scenarios of the reactor are first dependent on the accuracy of the safety analysis code. Most of existing reactor system safety codes consist of the governing equations and constitutive relation. Two-phase mass, momentum, and energy conservation equations are averaged for describing one dimensional flow for each phase, and results are obtained through numerical analysis. Constitutive equations have to be included in the process of averaging conservation equations, and contribute significantly to the accuracy of the code calculation results. Therefore, since the 1970s and 1980s when the system analysis code was mostly developed, numerous experiments and studies on the two-fluid constitutive equations were carried out. As a result, the accuracy of the accident analysis capability of the system safety analysis code has been steadily improved since then [1]. MARS-KS code which is the safety analysis code used by Korean regulatory body, is also constructed in the same fashion.

However, there are many uncertainties and errors in the modeling of reactor accident phenomena even though many thermal hydraulic experiments and researches have been conducted for five decades. This is because of the complexity and non-linearity of the two-phase flow phenomena and the constitutive relations are based on the empirical correlations. Furthermore, the constitutive relations usually take a limited mathematical form which cannot express all data accurately. This makes the safety analysis code to have a limited capability for prediction.

In order to resolve the abovementioned problem, the ultimate destination of this study is to develop a data-driven modeling that can replace the constitutive relations so that it can have more degree of freedom for mathematical form. Since artificial neural network (ANN) enables non-linear regression analysis of data easily, it has higher degree of freedom than the existing mathematical functions in finding the regularity. Furthermore, since ANN evolves through adding the training data, it can be updated constantly with more experiments.

Therefore, in this paper, as a preliminary study for data-driven modeling of the constitutive relations, the authors will check whether the artificial neural network can replace the constitutive relations successfully. In other words, the performance of the model will be confirmed after it has been trained using the constitutive equation data used in the existing MARS-KS code.

2. Model Description

In this paper, the artificial neural network predicts the wall heat transfer coefficient first. The data sets used for model training and testing is based on the MARS-KS code. In the previous paper [2], Sung Gil Shin developed a heat transfer coefficient calculation code based on MARS-KS code, and it will be utilized in this paper for generating data. For selecting the range of the thermal-hydraulic conditions, several kinds of design basis accidents in Barakah nuclear power plant are selected. LOOP, SGTR, and SLOCA are considered, and their thermal hydraulic ranges during accident simulations are summarized in Table I [2]. The number of total training data is 80,000, and 25% is used for model validation. The number of test data is 20,000, which is different from training data sets. Input data is randomly selected within given range.

Table I. Defined conditions for training

Thermal Hydraulic Conditions	
Pressure	1.35 – 17.8 MPa
Mass Flux	7 – 120 %
ΔT_{wall}	0 – 350 K
Internal Energy	200 – 2700 kJ/kg
Geometry Information	
Hydraulic Diameter	0.012 m
Heated Length	3.66 m
Angle	0
Material Property	
Roughness	0

Table II. The number of training data according to the heat transfer mode

Heat Transfer Mode	
Subcooled Nucleate Boiling	11
Subcooled Transition Boiling	11,059
Subcooled Film Boiling	68,869
Single Phase	61

In the artificial neural network in this paper, multi-layer perceptron with two hidden layers are used. The structure of this neural network is shown in Figure 1. Heat transfer coefficient is calculated from 6 input parameters: pressure, liquid and vapor temperature, wall temperature, void fraction, and mass flux. The specific information of the hyper parameters, data, learning information are summarized in Table III. MSE Losses for each Epoch are plotted in Figure 2. MSE loss of training is 3.20E-4 at Epoch 50 which shows there is no over-fitting issue.

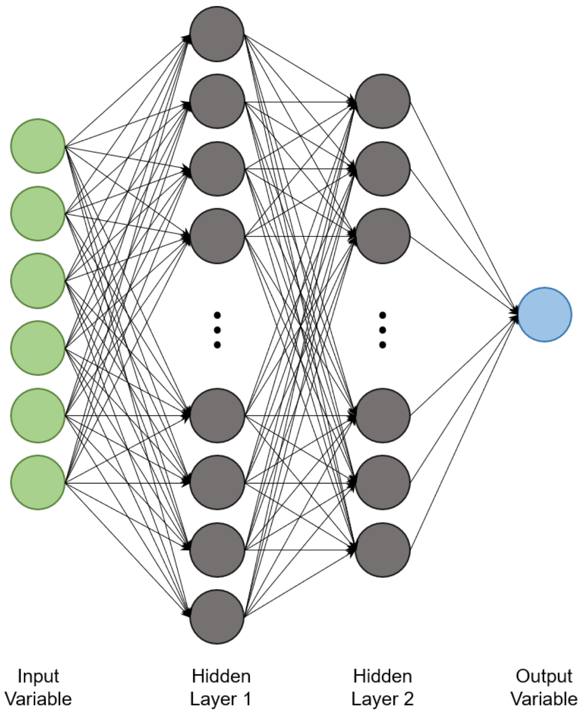

Fig. 1. Structure of the artificial neural network

Table III. Hyper parameters of the ANN model

Hyper parameters	
	Platform : Pytorch (Python)
	Number of hidden layer : 2
	The number of Node : 20 / 10
Data	
	Training and Validation : 75% training / 25% validation
	The number of data : 80,000
	Batch size : 500
Learning	
	Epoch : 50
	Learning Rate : 1E-2
	Loss function : Mean Squared Error (MSE)
	Optimizer : Adam optimizer

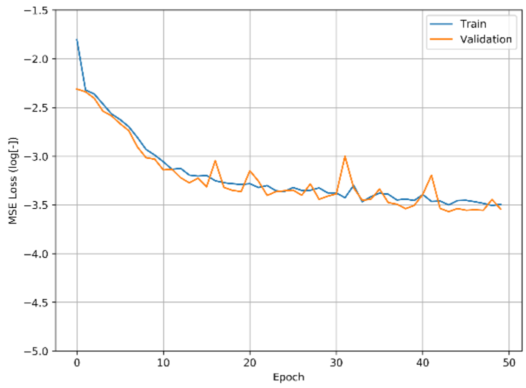

Fig. 2. Mean Squared Error according to the Epoch

3. Results and Discussions

The preliminary results of applying the ANN model to the test data are shown in Table IV. Mean squared error for test data set is 2.9E-3. As the heat transfer coefficient is normalized in log scale, two types of mean absolute percentage error (MAPE) are both calculated. MAPE of heat transfer coefficient is 7.11%. Also, R-square value is 0.970 which is very close to 1.

Table IV. ANN test results

Mean Squared Error	2.899E-3
Mean absolute percentage error	7.11 %
Mean absolute percentage error (log)	3.24 %
R-squared	0.970

4. Conclusions

In this paper, the artificial neural network is developed to observe the potential for replacing the current algebraic constitutive relations in the Reactor Safety Analysis Code. ANN is chosen for data-driven modeling method so that the experimental data can be more readily reflected to the code without limitation on the mathematical form. The data used for training and testing the model is calculated from the constitutive relation of MARS-KS code first. Total 80,000 data are used for training and validation, and 20,000 data are used for testing. When the test data sets are applied to the model, the mean squared error is 2.899E-3. R-square value is 0.970 and MAPE is 7.11%. The preliminary test results are satisfying so far. In the near future, different structure of ANN will be tested as well as integrating newly obtained separate effect test data to the training data will be also investigated.

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