Development of Molten Salt Reactor related Thermal Hydraulic Properties for Safety Analysis with AMESIM Code

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1. Introduction

In recent years, the pursuit of sustainable energy solutions has significantly increased interest in advanced nuclear reactors such as the Molten Salt Reactor (MSR) [1], Sodium-cooled Fast Reactor (SFR), High Temperature Gas-cooled Reactor (HTGR) and so on [2]. Especially, there has been a growing interest in MSR in recent years due to the significant potential for increasing the inherent passive safety features when compared to other reactors. Based on the inherent safety advantages of MSR, KRISO is currently applying it to ships and floating structures. This necessitates the evaluation of propulsion systems of ships and floating structures linked with not only reactors but also reactor steam systems, considering multi-physics phenomena and external environmental impacts. Therefore, a performance and safety analysis platform based on AMESIM Code [3], which can consider various physical phenomena, is being developed. In this study, we aim to describe the development of thermal-hydraulic properties related to MSR in the AMESIM Code. This study aims to utilize developed MSR properties to model and apply MSR reactors in the future. The research process is detailed in Figure 1.

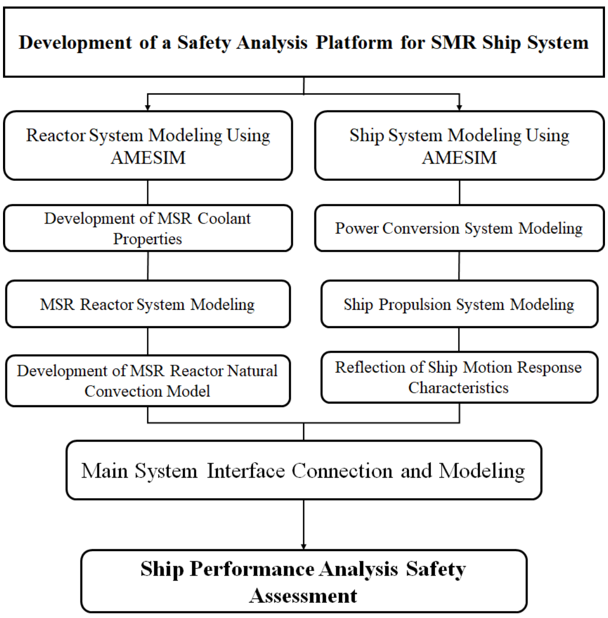

Fig. 1. Research process

2. Methods

This section describes the methodologies for developing properties used in thermal-hydraulic library of AMESIM code.

2.1 AMESIM Thermal-hydraulic Library Property Input

AMESIM code provides many functional libraries to analyze. The most significant library is the thermal-hydraulic library to implement safety analysis for MSR. The library offers comprehensive models for accurately simulating the complex behaviors of thermal-hydraulic systems, ideally addressing the complex dynamics of nuclear reactor components. However, the properties for MSR are not provided from AMESIM code. Thus, the properties are needed to implement safety analysis for MSR. The process of generating liquid properties in AMESIM's thermal-hydraulic library is simplified through four fluid model parameters' values in AMESIM code. These values include "simple: user defined", "advanced: user defined", "simple: database", and "advanced: database". Furthermore, it is necessary to define the coefficient value for determining input file of properties. In this study, the "simple: user defined" model was selected as material property methodology.

2.2 Defining Material Properties

In AMESIM, material properties are defined through specific formulas. Density is calculated based on temperature and pressure variations using Equation (1), reflecting changes in specific volume [3].

$$v_s(p,T) = \frac{1}{\rho(p,T)} \equiv v_{s0} \cdot \left[1 + a_p \cdot \Delta p + a_t \cdot \Delta T + a_{pt} \cdot \Delta T \cdot \Delta p + a_{p2} \cdot (\Delta p)^2 + a_{t2} \cdot (\Delta T)^2\right] \quad (1)$$

Viscosity is determined by Equation (2), influenced by temperature and pressure coefficients.

$$\mu(p,T) \equiv \mu_0 \cdot 10^{x(p,T)}$$
$$\text{with } x(p,T) \equiv b_p \cdot \Delta p + b_t \cdot \Delta T + b_{t2} \cdot (\Delta T)^2 \quad (2)$$

Specific heat capacity follows Equation (3), incorporating temperature and pressure changes through respective coefficients.

$$c_p(p,T) \equiv c_{p0} \cdot \left[1 + c_t \cdot \Delta T + c_{t2} \cdot (\Delta T)^2 + c_p \cdot \Delta p + c_{pt} \cdot \Delta p \cdot \Delta T\right] \quad (3)$$

Thermal conductivity is governed with Equation (4). It is crucial for evaluating material heat conduction capabilities.

$$\lambda(p,T) \equiv \lambda_0 \cdot [1 + d_t \cdot \Delta T + d_{t2} \cdot (\Delta T)^2] \quad (4)$$

These material property equations enable accurate modeling of material properties in AMESIM code, considering the effects of temperature and pressure.

2.3 Material Properties Development process

Each coefficient can be determined using the equations provided in the aforementioned AMESIM. For example, the coefficient for volumetric expansion, denoted as 'a_t' can be derived from equation (1) where, during an isobaric process, the pressure change becomes zero, leaving only

$$v_1 = v_0(1 + a_t \Delta T) \quad (5)$$

Simplifying this expression as shown in equation (6) defines the coefficient.

$$a_t = \frac{1}{v}(\frac{\partial v}{\partial T})_P \quad (6)$$

In a similar manner, each coefficient can be obtained, and by substituting experimental values for volumetric change due to temperature variation, the coefficients can be determined accordingly. By calculating coefficients based on temperature changes and selecting the coefficients with the least error at MSR's operating temperature, the properties for each AMESIM component can be defined. Table 2 presents the properties chart for the respective AMESIM components.

2.4 Verification through a simple heat exchange model

The verification of MSR properties was conducted using a simplified heat exchanger model. The modeling of the heat exchanger is illustrated in Figure 2. Upon comparing the heat transfer rate 'Q,' it can be observed from Table 2 that there is a close alignment between the values. Information regarding mass flow rate and temperature was referenced from [4].

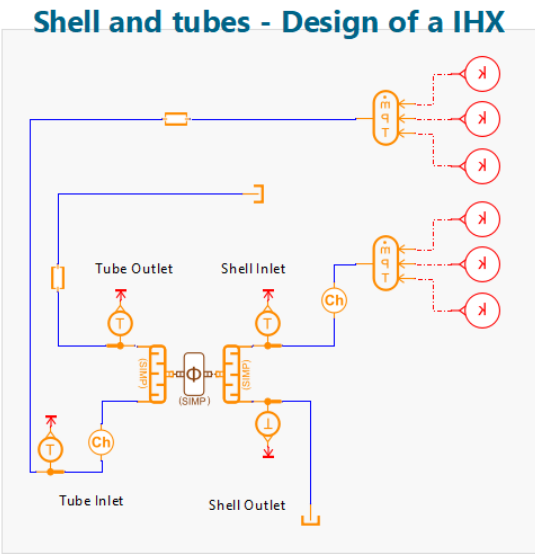

Fig. 2. Modeling of the Heat Exchanger

Table 2: Comparison of Heat Flow Rates

	c_p [J/kg·k]	$\dot{m}$ [kg/s]	ΔT [K]	Q [W] heat transfer rate
Analysis Result	2386.5	120	41.173	1.17933×10^7
AMESIM Result	2386.5	120	41.173	1.17835×10^7

3. Results

3.1 Simple User Defined Fluid Model

AMESIM code properties such as density, viscosity, heat capacity, and thermal conductivity at specific temperatures and pressures can be defined, with their variations due to changes in temperature or pressure calculated through respective coefficients. These coefficients are calculated using the equations mentioned above. The values for these characteristic properties are based on open experimental data from MSRE [4][5] studies. The proper functioning for the safety analysis was verified through a simple demonstration problem. We are currently in the process of modeling MSR. We plan to apply the developed MSR properties in the future.

Table 2: Simple User Defined Fluid Model for MSR Properties

Variable	Definition	Value
definition pressure [PaA]	P	$1.0xx \times 10^5$
definition temperature [degC]	T	$6.4xx \times 10^2$
definition density [kg/m^3	ρ	$2.2xx \times 10^3$

definition absolute viscosity [kg/m*s]	μ	$7.1xx \times 10^{-6}$
definition specific heat [J/kg/K]	c_p	$2.4xx \times 10^{3}$
definition thermal conductivity [W/m/K]	λ	$1.0xx$
Minimum pressure allowed	T	0
Maximum pressure allowed	T	$5.0xx \times 10^{7}$
Minimum temperature allowed	P	0
Maximum temperature allowed	P	$1.0xx \times 10^{3}$
Temperature coefficient for specific volume	a_t	$2.3xx \times 10^{-4}$
Temperature squared coefficient for specific volume	a_{t2}	$1.1xx \times 10^{-7}$
Pressure coefficient for specific volume	a_p	$-4.6xx \times 10^{-10}$
Squared pressure coefficient for specific volume	a_{p2}	$1.0xx \times 10^{-19}$
Temperature coefficient for absolute viscosity	b_t	$-1.9xx \times 10^{-3}$
Temperature squared coefficient for absolute viscosity	b_{t2}	$4.1xx \times 10^{-6}$
Pressure coefficient for absolute viscosity	b_p	$4.6xx \times 10^{-10}$
Pressure coefficient for specific heat	c_p	$-5.4xx \times 10^{-10}$

4. Conclusions

In this study, MSR properties were developed using equations defined in the AMESIM code. The properties of MSR define density, viscosity, specific heat capacity, and thermal conductivity as functions of specific temperature and pressure. Coefficients for density, viscosity, specific heat capacity, and thermal conductivity as functions of temperature or pressure were determined using experimental values from MSRE. The properties were validated using a simple heat exchange model, and MSR modeling will be incorporated in the future. KRISO is currently applying MSR technology to ships and floating structures, which requires evaluation of propulsion systems considering multi-physics phenomena and external environmental impacts. We plan to apply these properties to ships and floating structures to assess propulsion systems, considering multi-physics phenomena and external environmental impacts within the vessels. Currently, we are in the process of modeling propulsion ships with MSR applied and developing natural convection model.

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