Study RELAP5 Helium Properties for HTGR Thermal Hydraulic Analysis

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Abstract. The system codes non-specific for HTGR such as RELAP5 has been utilized for HTGR thermal hydraulic analysis even helium gas property is not based on KTA 3102.1. However, those RELAP5 applications for HTGR above are merely based on the assumption that RELAP5 helium properties are comparable to the helium properties in the KTA 3102.1. Therefore, the study for comparing the helium properties used in RELAP5 and the helium properties in KTA 3102.1 is required. The objective of this paper is to study the appropriateness’ helium properties in RELAP5 code for high temperature gas reactor (HTGR) thermal hydraulic analysis. There has been an inclined interest in the scientific community in the study of the application RELAP5 for HTGR thermal hydraulic analysis. The KTA 3102.1 provides the helium properties that are the most commonly use for the HTGR thermal hydraulic analysis. For this study, the RELAP5 helium properties are compared with the helium properties in KTA 3102.1. The comparison results showed that the RELAP5 helium properties are satisfactory for the HTGR thermal hydraulic analysis.

Keywords: Helium, KTA 3102.1, RELAP5, HTGR Thermal Hydraulic.

1. Introduction

Thermal-hydraulics plays a very important role in the design, operation, performance and safety of nuclear power plants. The thermal hydraulic analysis of nuclear reactors is commonly accomplished by what are known as “System Codes”[1]. These codes calculate the flows in the complex network of piping systems, pumps and vessels that together form the thermal hydraulic systems of a nuclear reactor. Thermo-physical properties of reactor coolant are required by the system codes to calculate the thermal-hydraulic behaviour of the nuclear reactor.

The Helium gas is used as coolant in the high temperature gas reactor (HTGR) technology for both prismatic [2] and pebble [3] core arrangements. For the HTGR thermal hydraulic analyses purpose, helium properties in the KTA 3102.1 [4] should be use in the calculation as suggested by IAEA [5]. Specific computer codes for HTGR thermal hydraulic analyses have been developed and used[6–9]. Those codes use helium properties that provided in KTA 3102.1.

In the mean time, the system codes non-specific for HTGR such as and RELAP5[10–14]has been utilized for HTGR thermal hydraulic analysis even the helium gas property is not based on KTA 3102.1. The RELAP5 has been proposed as part for HTGR pebble bed design analysis [15]. A simulation of helical steam generator for HTGR has been performed by using RELAP5-3D [16],
RELAP5 has been used to perform Intermediate Heat eXchanger [IHX] as well[17]. Moreover, steady state and transient thermal simulations of HTR-10 has been carried out using RELAP5-3D[18].

However, those RELAP5 applications for HTGR above are merely based on the assumption that RELAP5 helium properties are comparable to the helium properties in the KTA 3102.1. There have been no controlled studies that compare the helium properties used in the RELAP5 and the helium properties in the KTA 3102.1. The objectives of this study are to determine whether or not the RELAP5 is appropriate for HTGR thermal hydraulic analyses regarding on the helium properties. In this study, the helium properties that are concerned include the mass density, specific heat, dynamic viscosity and thermal conductivity. For this study, the helium properties data were collected by executing the RELAP5 for helium pressure ranges between 1 and 100 bar and temperature ranges between 25 and 1500 °C. Those helium properties data were compared with the associate values in the KTA 3102.1 based on the pressure and temperature. The findings should make an important contribution to justify the application RELAP5 for HTGR thermal hydraulic analyses. It is beyond the scope of this study to examine the HTGR modeling system.

2. Theory
The helium properties in the KTA 3102.1 are shown in Table 1. The values are depending on the pressure and temperature or only in temperature.

| Properties                  | Value                                                                 | Standard deviation (%) |
|-----------------------------|----------------------------------------------------------------------|------------------------|
| Mass Density (kg/m²)        | \( \frac{p}{T}(1 + 0.4446 \times \frac{p}{T^{1.2}}) \times 48.14 \times \sqrt{p} \) | 0.03 \times \sqrt{p}   |
| Specific Heat (J/kg × K)    | 5195 for constant pressure                                          | 0.05 × \( \frac{T_{0}}{T} \) \times (0.6 - 0.1 × \frac{T_{0}}{T}) |
|                             | 3117 for constant volume                                             |                        |
| Dynamic Viscosity (Pa × s)  | \( 3.674 \times 10^{-7} \times T^{0.7} \times 0.0015 \times T \)    | 0.0035 × T             |
| Thermal Conductivity (W/m × K) | \( 2.682 \times 10^{-3}(1 + 1.123 \times 10^{-3} \times p) \times T^{0.71}(1 - 2 \times 10^{-4} \times p) \times 0.0035 \times T \) |                        |

where :
p is a gas pressure in bar, T is a gas temperature in K and \( T_{0} = 273.16 \) K.

The above equations applicable for the following ranges:
1 bar \( < p < 100 \) bar and,
293 K \( < T < 1773 \) K.

In RELAP5, the water (h₂o) is a default coolant, while helium is provided as a non-condensable gas. The non-condensable gas will mix with default coolant. The nearly pure helium can be realized by put 0 (zero) in the initial gas fraction of non-condensable gas [19]. To get the helium properties in RELAP5, the following variables minor edit are used: rhog for vapor density, csubpg for vapor specific heat, visg for vapor viscosity and thcong for vapor thermal conductivity.
3. Methodology

An imaginary Tank was used to simulate the numerical experiment using RELAP5. The model boundary was defined to provide the controlled parameters namely pressure and temperature. Figure 1 shows the RELAP5 nodalization of the imaginary Tank model used in the present study. The nodalization follows the nodalization guideline [19]. The Tank comprised of three parts: inlet, testing part, and outlet. The node in the testing part was modeled using a single volume component of RELAP5. The boundary conditions of temperature and pressure were set at the inlet and outlet of flow path TMDPVOL 110 and TMDPVOL 130 respectively. Table 2 shows the variation of pressure and temperature in this study, therefore there were 81 pairs of pressure and temperature condition. Those pressure and temperature were chosen to vary typical operation of HTGR [20]. The time dependent junction TMDPJUN 115 controls the flow rate. The helium properties were taken from SNGLVOL 120. Those properties then compared with the helium properties on the KTA 3201.1 based on pressure and temperature.

![Figure 1. The nodalization of imaginary Tank to get helium properties](image)

**Table 2.** Variation of pressure and temperature for boundary conditions

| Controlled parameters | Values |
|-----------------------|--------|
| Pressure (bar):       | 1.1    2    5    10   30   40    60   70    99    |
| Temperature (°C):     | 25    100   250  500  700  900  1000  1200  1500 |

4. Results and Discussion

4.1. Helium mass densities

Fig. 2 shows the comparison of helium mass densities in RELAP5 and in KTA 3102.1 in the range of pressure and temperature of interest 1.1 to 99 bars and 25 to 1500 °C respectively. The low values of helium mass density found in the low pressure and high temperature conditions, whereas the high values of helium mass density found in the high pressure and low temperature conditions. The highest different mass density between RELAP5 and KTA 3102.1 is about 5% and it is occur at high pressure and low temperature (i.e. 99 bar and 25 °C). For typical current and future HTGR [20], the helium working pressure and temperature are 30 ~ 70 bar and 250 ~ 900 °C respectively. In such a conditions, the helium mass densities are around 1.23 to 6.33 kg/m³. From Fig. 2, it can be seen that at mass density 1.23 to 6.33 t/kg/m³ hel RELAP5 has helium mass density that is very close to the helium mass density in KTA 3102.1. Therefore, the helium mass density in RELAP5 can be use to analyses in HTGR.
4.2. Helium specific heat at constant pressure

Fig. 3 shows the helium specific heat at constant pressure in RELAP5 and in KTA 3102.1 as function of helium temperature. For helium temperature under 600 °C, RELAP5 has lower values of specific heat than KTA 3102.1 has. For helium temperature over 600 °C, RELAP5 has higher values of specific heat than KTA 3102.1 has. For typical HTGR operational coolant temperature ranges (i.e. 250 ~ 900 °C), the RELAP5 provides helium specific heat that not only in side the allowable plus-minus a sigma error but also very close to the 5195 J/kg-K. Therefore, the helium specific heat at constant pressure in RELAP5 can be use to analyses in HTGR.

![Figure 2. Helium mass density in RELAP5 Vs. KTA 3102.1](image1)

![Figure 3. Helium specific heat at constant pressure in RELAP5 and KTA 3102.1](image2)
4.3. Helium dynamic viscosity

A Fig. 4 shows the comparison of helium dynamic viscosity in RELAP5 and in KTA 3102.1. The data are based on the helium pressure and temperature in the range 1.1 to 99 bars and 25 to 1500 °C respectively. The low values of helium dynamic viscosity are corresponding with the low temperature and vice verse. The highest different dynamic viscosity between RELAP5 and KTA 3102.1 is about 14% and it is occur at high temperature (i.e. 1500 °C). In the range of HTGR coolant operational temperatures, the RELAP5 has the highest under value about 9% of dynamic viscosity than KTA 3102.1 has and it is occur at 900 °C. In the low temperatures, the helium dynamic viscosity in RELAP5 is closer to the helium dynamic viscosity in KTA 3102.1. Therefore, the helium mass density in RELAP5 can be use to analyses in HTGR with caution at higher temperature.

![Helium dynamic viscosity in RELAP5 Vs. KTA 3102.1](image)

**Figure 4.** Helium dynamic viscosity in RELAP5 Vs. KTA 3102.1

4.4. Helium thermal conductivity

The comparison of helium thermal conductivity in RELAP5 and in KTA 3102.1 can be seen in Fig. 5. The data in this figure are based on the helium pressure and temperature in the range 1.1 to 99 bars and 25 to 1500 °C respectively. The high values of thermal conductivity are corresponding with the high temperature and vice verse. For all temperatures, RELAP5 predicts helium thermal conductivity slightly lower, about 3%, than thermal conductivity in KTA 3102.1. From Fig. 5 it also can be seen that the helium thermal conductivity in RELAP5 are well in side the allowable plus-minus a sigma of KTA 3102.1. Therefore, the helium thermal conductivity in RELAP5 can be use to analyses in HTGR.
In general, the difference of helium properties in RELAP5 and KTA 3102.1 is increasing with the increase of the helium temperature. However, RELAP5 has helium properties that very close to the helium properties in KTA 3102.1. Some values of helium properties in RELAP5 are slightly higher and some values are slightly lower than corresponding values in KTA 3102.1. Therefore, the helium properties in RELAP5 can be use to analyses in HTGR.

5. Conclusion
The study of helium properties for HTGR analysis was performed for RELAP5 code. In the range of HTGR coolant operational pressures and temperatures, it is found that the RELAP5 helium properties such as mass density, specific heat, dynamic viscosity and thermal conductivity are very close to the helium properties in KTA 3102.1. The difference values between helium properties in RELAP5 and in KTA 3102.1 are within standard deviation of the helium properties in KTA 3102.1, except for the helium dynamic viscosity in which the largest error is near 9%. As conclusion of the present study, it was found that the RELAP5 helium properties are appropriate for HTGR thermal hydraulic analyses.

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