ANALYSIS OF THERMAL RADIATION HEAT TRANSFER ON A VERY HIGH TEMPERATURE GAS-COOLED REACTOR

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ABSTRACT. Thermal radiation plays an important role in a heat transfer analysis for a *Very High Temperature gas-cooled Reactor* (VHTR). Due to its high operating temperature of 950°C, thermal radiation heat transfer becomes an important heat transfer mechanism. Radiation is fundamentally different from flow. Flow takes place in a continuum but in contrast, radiation travels from every emitting boundary face passing the whole domain to other boundaries. It is a difficult phenomenon to calculate in full detail due to its geometrical complexity with physical effects of radiation: emissivity, reflection, absorption, and scattering. We discussed the importance of thermal radiation on the VHTR design and analysis work including experimental measurements and thermal radiation damage criteria quantitatively.

THERMAL RADIATION TRANSFER EQUATION

Thermal radiation is that electromagnetic radiation emitted by a body as a result of its temperature. The propagation of thermal radiation takes place in the form of discrete quanta. By considering the radiation as a gas, the principles of quantum statistical thermodynamics can be applied to derive an expression for the energy density of radiation. When the energy density is integrated over all wave lengths, the total energy emitted is proportional to the absolute temperature to the fourth power;

$$E_R = \sigma T^4, \qquad (1)$$

Equation (1) is called *the Stefan-Boltzmann law* representing the ideal radiation energy, E_R is the energy radiated by the ideal radiator, and σ is a Stefan-Boltzmann constant ($5.669 \times 10^{-8}\ W/m^2 \cdot K^4$). Passing through a medium, thermal radiation and fluid may interact in a number of ways. Radiation intensity is attenuated by the absorption and out-scattering, while being augmented by emission and in-scattering of the fluid on the way. For incremental step *ds* along a ray, all relevant effects are described by the *Radiation Transfer Equation (RTE),* as can be written as follows [1],

$$\frac{dI(s,\omega)}{ds} = -(K_a + K_s) \cdot I(s,\omega) + K_a \frac{\sigma T^4}{\pi} + \frac{K_s}{4\pi} \int_0^{4\pi} I^{in}(s,\omega) \varphi d\omega \qquad (2)$$

In this equation K_a is the absorption coefficient, K_s is the scattering coefficient and φ is the scattering phase function.

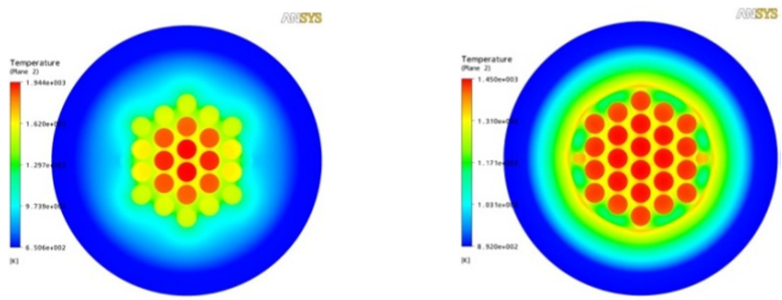
APPLICATION OF THERMAL RADIATION FOR VHTR

VHTR Core Simulated Heater Analysis

A medium-scale helium loop has a high-temperature electric heater of the test helium loop for simulating a VHTR core up to 950°C. To optimize the design specifications of the heater, the conjugate heat transfer in a high-temperature helium heater was analyzed using a "*computational* *fluid dynamics*" simulation with P1 radiation model [2]. The P1 model is a four-term truncation of the general Pn model expanding the RTE equation into an orthogonal series of spherical harmonics [3]. In this design analysis, we found that the buoyancy effects on the helium flows of the heater is suppressed by the radiation inside the heating channel. When we apply gravitation without a P1 radiation model, the heater maximum temperature increases 500°C higher than with the P1 radiation model case, as shown in Table 1 and Figure1.

Table 1: Maximum Temperature of 270kW Helium Heater w and w/o Radiation Model

Locations max. temp.	No radiation model [°C]	P1 radiation model [°C]
Heater element	1671.2	1171.0
Vessel inner surface	851.3	1074.8
Vessel outer surface	387.0	287.9



$T_{max.heater}$=1671.2 °C (a) No radiation model

$T_{max.heater}$=1171.0 °C (b) P1 radiation model

Figure 1. Temperature distributions of 270kW Helium heater w and w/o radiation model

Radiation-Corrective Gas Temperature Measurement

Thermocouples normally measure the gas temperature lower than its true temperature. This bias is because of the thermal radiation effect on the measured surface; the convective heat transfer coefficient on the thermocouple surface is not large enough to neglect the thermal radiation effect from the sheath tube. Kim's et al. [4] developed a methodology to correct the thermal radiation effect for the gas temperature measurement. The methodology is the usage of a couple of thermocouples with unequal diameters called the Reduced Radiation Error (RRE) method. The RRE value is defined as the ratio of the temperature difference between the true gas temperature and the measured temperature from a large diameter thermocouple over the measured temperature difference between the thermocouples with small and large diameters. The experimental results (Nitrogen gas loop in KAERI) with the RRE calculation showed that the thermal radiation lead to bias the measurement temperature (1/8" T/C) up to 78.5°C at RRE gas temperature of 810.2°C, as shown in Figure 2.

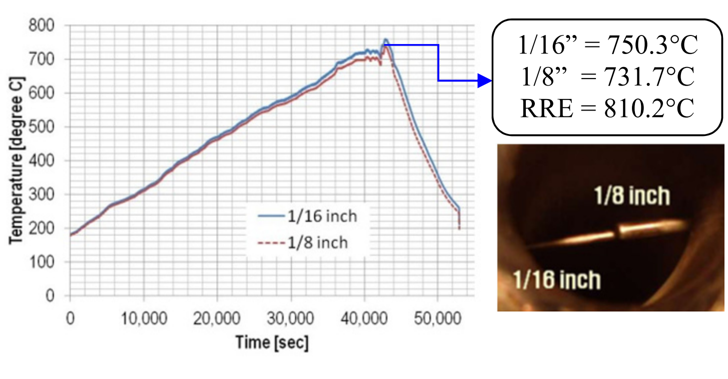


Figure 2. Experiment for radiation corrective gas temperature measurement

Reactor Cavity Cooling System

The Reactor Cavity Cooling System (RCCS) is a system for the removal of the decay and residual heat. Kim & Sim [5] modeled the RCCS of GT-MHR design using CFX with the Monte Carlo method for the radiation heat transfer. They verified their calculation method with the work of Takada et al. [6], who performed experimental and numerical studies on the RCCS of a HTGR. They obtained that the portion of the radiation heat transfer in the total heat transfer from the reactor vessel of 74.6% by the reference method while that in Takada et al.'s work was 74.4%.

Damage Criteria for Thermal Radiation

Strong thermal radiation induced from a Pressure Vessel (PV) will lead to personnel injuries or fatalities. The World Bank reported the radiant heat flux (or intensity) harm criteria for people as shown in Table 2. The radiation intensity of a PV will dependent upon the resulting reactor accident scenario. From the criteria, the maintenance or repair activity in the RCCS cavity should wait until the thermal radiation intensity of the PV is reduced below $1.6\,\mathrm{kW/m^2}$. This intensity is easily converted to the PV surface temperature of 137°C using equation (1) with an assumption; the PV is an ideal radiator.

Table 2: Radiant Heat Flux Harm Criteria for People [7]

Thermal rad. intensity ($\mathrm{kW/m^2}$)	Surface temp. of source* (°C)	Type of damage
1.6	137	No harm for long exposures
4~5	242~272	Pain for 20sec exposure; first degree burn
9.5	367	Second degree burn after 20sec
12.5~15	412~444	First degree burn after 10sec; 1% lethality in 1 min
25	613	Significant injury in 10sec; 100% lethality in 1 min
35~37.5	629	1% lethality in 10sec

*Note: the source assumed ideal radiator in calculation

CONCLUSIONS

Very high temperature VHTR components to enhance the importance of the thermal radiation heat transfer one order larger than convective heat transfer because it is governed by the fourth power of the temperature. Adequate application of the radiation models is a major concern to succeed a design analysis of VHTR components. Proper radiation compensation has a critical effect on the true gas temperature measurement, which is proved through nitrogen gas loop experiments.

ACKNOWLEDGEMENTS

This work was supported by Nuclear Research & Development Program of the Korea Science and Engineering Foundation (KOSEF) grant funded by the Korean government (MEST)

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