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The Role of the Thermal Radiation for the Very High Temperature Gas-Cooled Reactor

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1. Introduction

Thermal radiation plays an important role in heat transfer analysis for the *very high temperature gas-cooled reactor* (VHTR). Due to its high operating temperature of 950°C, thermal radiation heat transfer becomes significant heat transfer mechanism. Radiation is fundamentally different from normal fluid flow. While the flow takes place in a continuum, radiation travels from every emitting boundary face passing the whole domain to other boundaries. It is a complicate phenomenon to calculate in full detail due to its geometrical complexity with physical effects of radiation; emissivity, reflection, absorption and the scattering. We have discussed in this paper about the quantitative importance of thermal radiation on the VHTR design and analysis work, including experimental measurements and the criteria of thermal radiation damage.

2. Thermal Radiation

Thermal radiation is electromagnetic radiation emitted from a body caused by its temperature. The electromagnetic wave length lies in the range from about 0.1 to 100 μm. The propagation of thermal radiation takes place in the form of discrete quanta. The radiation propagation might be obtained by considering each quantum as a particle having energy, mass, and momentum, just as we considered the molecules of gas. By considering the radiation such as the 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 absolute temperature to the fourth power;

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

Equation (1) is called the Stefan-Boltzmann law representing ideal radiation energy, E_R is the energy radiated by the ideal radiator, and σ is Stefan-Boltzmann constant ($5.669 \times 10^{-8}\ \mathrm{W/m^2 \cdot K^4}$).

Passing through a medium, thermal radiation and fluid may interact in a number of ways. Radiation intensity is attenuated by absorption and out-scattering while being augmented by emission and in-scattering of fluid on the way. For an incremental step *ds* along a ray all relevant effects are described by the *radiation transfer equation (RTE)* as can be written as follows [1],

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

In this equation $\mathrm{K_a}$ is the absorption coefficient, $\mathrm{K_s}$ is the scattering coefficient and φ is the scattering phase function.

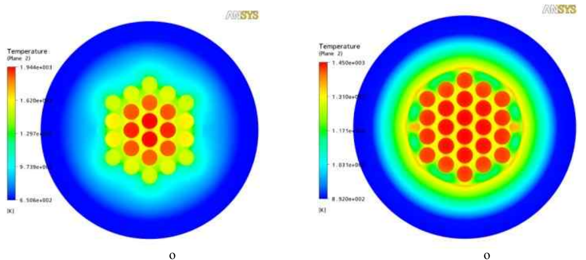
3. Application of Thermal Radiation for VHTR

3.1 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, conjugate heat transfer in the high-temperature helium heater was analyzed by using "*computational fluid dynamics*" simulation with P1 radiation model [2]. The P1 model is the 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 P1 radiation model, the heater maximum temperature increases in 500°C higher than with the P1 radiation model case as shown in Table I and Fig.1.

Table I: Maximum temperature of 270kW helium heater w and w/o radiation model

Locations Max. Temp. obtained	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



$\mathrm{T_{m\,axheater}}$ =1671.2 °C
(a) No radiation model

$\mathrm{T_{m\,axheater}}$ =1171.0 °C
(b) P1 radiation model

Fig. 1. Temperature distributions of 270kW helium heater w and w/o radiation model

3.2 Radiation-Corrective Gas Temperature Measurement

Thermocouples normally measure gas temperature much lower than its true temperature. This bias is due to the thermal radiation effect on the measured surface; the coefficient of convective heat transfer on the thermocouple surface is not large enough to neglect the thermal radiation effect from the sheath tube. Kim's et al.[4] have developed a methodology to correct the thermal radiation effect such as self heat loss to the surroundings, for the gas temperature measurement. The methodology is the usage of thermocouples with two different 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. The RRE can be calculated by cancelling surrounding temperature term from two simultaneous equations - energy balance of each thermocouple. The experimental data have corrected by RRE to obtain the true temperature. The result of calculation showed that the thermal radiation induces bias in the temperature measurement (1/8" T/C) up to 78.5°C compared to the true temperature of 810.2°C which is derived from RRE compensation (Fig. 2).

3.3 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 there calculation method with the work of Takada et al [6] whose 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 was 74.6% by the reference method while that in Takada et al's work was 74.4%.

3.4 Damage Criteria for Thermal Radiation

Strong thermal radiation induced from a pressure vessel (PV) will lead to personnel injuries or fatalities. World Bank reported the radiant heat flux (or intensity) harm criteria for people as shown in Table II [7]. The radiation intensity of a PV will dependent upon the resulting reactor accident scenario. From the criteria, maintenance or repair activity in RCCS cavity should be 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 by using the equation (1) with an assumption; the PV is ideal radiator.

4. Conclusions

Very high temperature of VHTR components enhances the thermal radiation heat transfer very significantly. The effectiveness of the thermal radiation heat transfer is one order larger than convective heat transfer since it is governed by fourth power of the temperature. However, adequate application of the existing radiation models is a major concern to achieve a design analysis of VHTR components. Furthermore, appropriate radiation compensation is a critical problem on measuring true gas (coolant) temperature which has been proved through the nitrogen gas loop experiments.

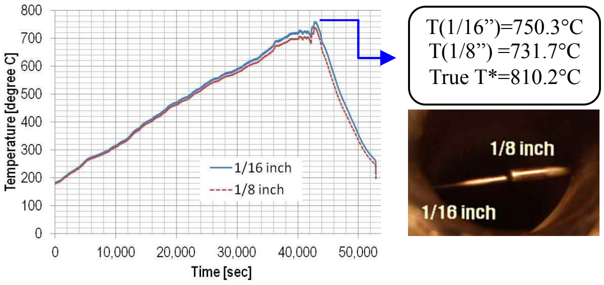


Fig. 2. Experiment for radiation corrective gas temperature measurement at nitrogen gas loop in KAERI (True T* = true temperature, which is corrected by RRE value).

Table II: Radiant heat flux harm criteria for people

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 20 s exposure; first degree burn
9.5	367	Second degree burn after 20 s
12.5~15	412~444	First degree burn after 10 s; 1% lethality in 1 min
25	613	Significant injury in 10 s; 100% lethality in 1 min
35~37.5	629	1% lethality in 10 s

Note: the source assumed ideal radiator in calculation

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