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Heat Transfer Experiments on an Internally Insulated Hot-Gas-Duct

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1. Introduction

A Hot Gas Duct (HGD) is a unique component of a gas cooled reactor (GCR).It links the outlet of a GCR vessel to the inlet or outlet of an intermediate heat exchanger. The coolant temperature at the internal of an HGD can go up to 950°C in the case of a Very-High Temperature gas-cooled Reactor (VHTR) as shown in Figure 1[1]. The internal of an HGD is insulated using a ceramic fiber insulator (Kaowool) to prevent a mechanical failure itself from high-temperature and high-pressure VHTR operating conditions.

The temperature distribution on a surface of horizontal HGD is important information in designing the HGD because it can set or confirm the maximum allowable temperature of the HGD surface. The surface temperature distribution will be affected by both free convection and radiation on the HGD outer surface. Free convection is formed by a volume expansion (buoyance or body force) of air heated by the hot surface of an HGD.

The experimental research of heat transfer on the free convection from cylinders is set well with many empirical correlations. However, there are no experimental investigations found for the geometry of an internally insulated cylinder (or a porous media cylinder) such as an HGD form. We measure the temperature distribution across the external surface of a horizontal HGD and compare it to predictions from CFD simulations.

2. Heat transfer at the HGD

2.1. Heat transfer characteristics at the HGD

The once-through type HGD is composed of a flow channel, a liner tube, an internal insulation and an outer vessel (pipe) as shown in Figure 2. Each element has obvious or dominant heat transfer characteristics among the conduction, convection or radiation (Table I). The heat transfer of the metal structures (liner and HGD vessel) is governed by the heat conduction only. Flow channel in the HGD has the convection dominant heat transfer regime where ignored the gas radiation from the hot gas to the relatively cold liner. Meanwhile, the radiation heat transfer is dominant at the HGD outer surface where the surface temperature approaches to 300°C. As a matter of course, there is the natural convection at HGD outer surface, but the portion of heat transfer less than radiation in case of the HGD analysis.

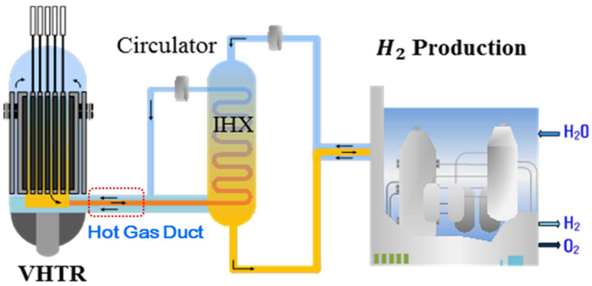

Fig. 1 Conceptual layout of a very-high temperature gas-cooled reactor

The internal insulation has rather complex heat transfer characteristics with both conduction and radiation. An ideal insulator traps the gas in the micro pore (porous media) produced by the thin fibers of the few micrometers and limits the convection of gas in the internal. The conduction in the insulator (porous media) is defined an effective conductivity that is combined to both solid (fiber) and gas conductivity under the assumption of a local thermal equilibrium at the unit volume of a pore and fiber mixture [2].

2.2. Free convection heat transfer

Average free-convection heat-transfer coefficients can be represented in the following functional form fora variety of circumstances:

$$\overline{Nu}_f = C(GrPr)^m \quad (1)$$

where the subscript indicates that the properties in the dimensionless groups are evaluated at the film temperature.

$$T_f = \frac{T_\infty + T_w}{2} \quad (2)$$

And the constants *C* and *m* depend upon whether the flow regime is laminar or turbulent. The Rayleight number (Ra = Gr Pr) is used to produce the criteria of the flow regime.

Table I. Heat transfer at the HGD elements

Flow ch.	Liner	Insulator	Vessel	Atmosphere
CD	**CD**	**CD** (Gas+Solid)	**CD**	CD
CV (Turbulent)		CV		**CV** (Laminar)
RAD		**RAD**		**RAD**

Note: CD (Conduction), CV (Convection), RAD (Radiation), Atm. (Atmosphere)

A more complicated expression is available from Churchill and Chu [3] for use over a laminar range of $10^{-6} < Ra < 10^{9}$:

$$Nu_f = 0.36 + \frac{0.518\,(GrPr)^{1/4}}{[1+(0.559\,/Pr)^{9/16}]^{4/9}} \qquad (3)$$

A simplified equation at atmospheric pressure and moderate temperature is given over a laminar range of $10^{4} < Ra < 10^{9}$ (Holman [4]):

$$Nu_f = 1.32\left(\frac{d}{k}\right)\left(\frac{\Delta T}{d}\right)^{1/4} \qquad (4)$$

The characteristic dimension of a horizontal cylinder is diameter D used in the Nusselt and Grash of numbers.

2.3. Thermal radiation heat transfer

Thermal radiation is the electromagnetic radiation emitted by a body as a result of its temperature. When the energy density of radiation is integrated over all wave lengths, the total energy emitted is proportional to the absolute temperature to the fourth power [4],

$$E_R = \sigma T^4. \qquad (5)$$

Equation (5) 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. The radiation heat loss at the surface of a HGD is expressed as

$$q_R = \sigma A \varepsilon\left(T_{wal}^4 - T_{\infty}^4\right). \qquad (6)$$

3. Experiments

3.1. Experimental loop

A series of HGD tests is carried out at a small-scale nitrogen gas loop at the Korea Atomic Energy Research Institute. The gas loop simulates the VHTR intermediate loop operating conditions and has an oil-less gas circulator, a pre-heater, a main heater for raising the nitrogen temperature to 1000°C, a heat exchanger (or evaporator), a water cooler, and a nitrogen supply system. The nitrogen supply system also has the function of a system pressure control using a pressure regulator connected between the pressurizer and nitrogen supply system[6]. The design conditions of the primary loop are as follows:

o	Working fluid	Nitrogen
o	Design temperature	1000 °C
o	Design pressure	6.0 MPa
o	Design flow	2.0 kg/min

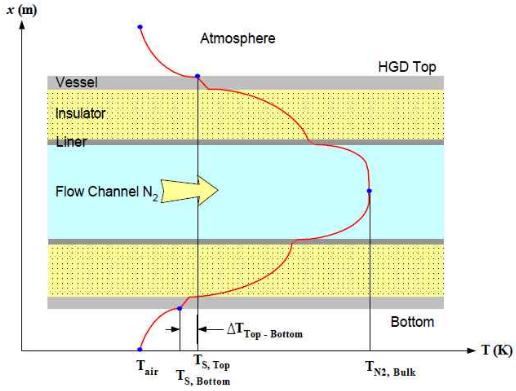

Fig. 2.Conceptual sketch of radial temperature profile in a horizontal HGD

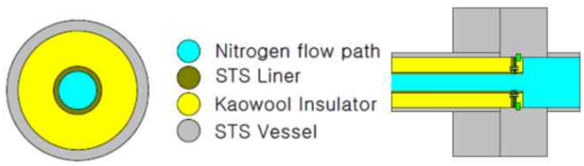

Fig. 3.Internal details of the HGD test section

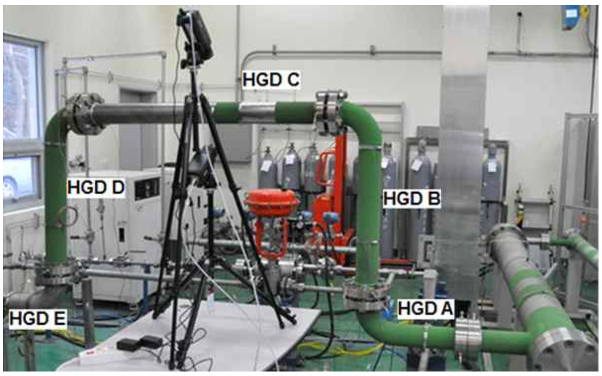

Fig.4.HGD test section with IR cameras

3.2. Test section

The test section of the HGD is provided with an internal thermal insulator to protect the pressure pipe from the high-temperature gas. The internal insulation composed of a stainless-steel liner tube and ceramic fibrous insulator (Kaowool), as shown in Figure 3. Its geometry is fitted to the outlet nozzle of a high-temperature heater of small-scale gas loop. The geometric data of HGD are as follows:

o	Pipe outer diameter	101.6 mm
o	Thickness of pipe	5.7 mm
o	Diameter of flow channel	21.4 mm
o	Thickness of insulator	32.4 mm

As shown in Figure 4, the test section has five HGDs. This paper presents measurements on the HGD-C section using two infra-red cameras and four surface thermocouples.

3.3. Measurement of surface temperature distribution

The geometric data of HGD are as follows:

- o Surface temp. (HGD) 250 °C
- o Max. operation temp. 850 °C
- o Nitrogen pressure 2.0 MPa
- o Nitrogen flow 2.0 kg/min

The distribution of temperature on the HGD outer surface is the main measurement parameter in the experiments. Two micro-bolometer type infrared (IR)-camera systems are installed to measure the surface temperature distributions (thermal images) with ten pieces of 0.5 mm ungrounded-type thermocouples, as shown in Figure 4.To capture the thermal images well, one IR-camera is focused on a quarter surface of the HGD-C top side, and another is focused on the quarter surface of the HGD-C bottom side. The specification of FLIR A615 IR-camera gives a (0.111 x 0.086) m^2 surface measurement area with the accuracy of ± 2℃ (or $\pm 2\%$ of reading) at the distance of the close focus limit of 0.25m. The view factor drops as the surface curves away from the camera resulting in an underestimation of temperature. The curvature is the source of an incomplete reflection that leads to an additional distortion of temperature sensing at the camera.

4. Results and discussion

Temperature profiles from bottom to top of the HGD are extracted from the center of thermal images captured by an IR-camera (Figure 5). A tiny pin seen in the thermal image (top of right-hand side) is attached on a T/C-band as a mark of the top peak of the HGD-C. At the bottom peak, a 0.5mm T/C wire is used as an indicator. The temperature profile is adjusted with the help of these indicators. The temperature distortions at the curved surface are realized on the thermal image which is captured by the IR-camera system as shown in Figure 6. The measured temperatures (thermal image) at the down-stream part of the nitrogen flow are slightly higher than those of up-stream part. In addition, this distortion worsens when the horizontal lines move toward the direction of the top or bottom sides, where the curvature deepens. Two sets of the T/C band are set on both ends of the green colored CrO2 painting area of HGD-C to cross check the surface temperature with the IR-cameras. A couple of 0.5mm T/Cs is fastened on the top and bottom measurement points of the HGD using a stainless steel band.

The graph in Figure 7 represents the temperature profiles combined with both bottom and top thermal images (temperatures at the line marked on the images, left in the Figure). The slope of the temperature profiles in the Figure is deepening in the middle of the graphs. This trend is an inherent distortion coming from the curvature of the HGD in which the IR-camera cannot receive all radiation emitted from the HGD surface (incomplete reflection at the curved surface) discussed previous section 3.3. This distortion shall be mitigated if we install more IR-cameras at the test section. However, the more interesting parameter is the temperature difference between the top and bottom peaks. We obtained a very large temperature difference in the experiments against our expectation from a two-dimensional (2D) Computational Fluid Dynamics (CFD) analysis using a COMSOL multi-physics software [7]. A surface temperature difference of 59℃ is measured at the 200C experiments, as shown in Figure 5, while the difference of 4.5℃ is calculated from the 2D CFD analysis considering heat conduction only at the internal insulation as listed in Table II. If we consider a drift phenomenon of the hot gases in the insulator toward the top side, we can expect large temperature difference between the top and bottom parts of horizontal HGD. When we modified the “2D conduction model” to the “2D porous model” considering convection in the insulator, we obtained very large temperature difference of 83°C as shown in Figure 8.

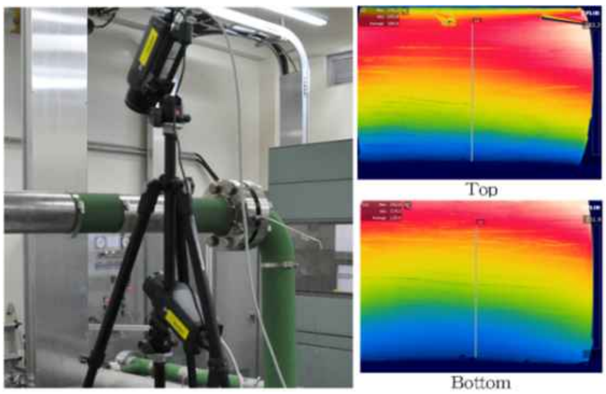

Fig. 5.Thermal images at the HGD surface (135~194℃)
(N2 channel condition: 1.4kg/min, 2.0MPa, 592℃)

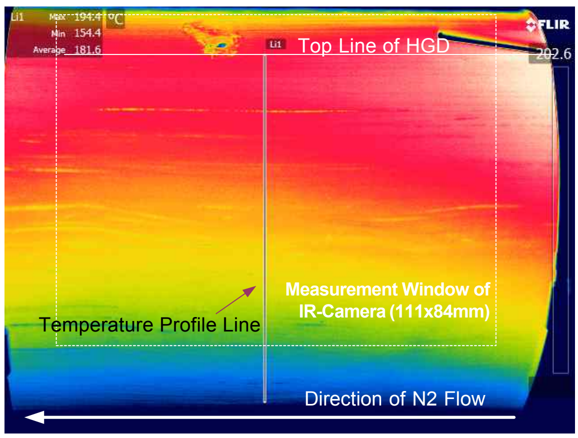

Fig. 6.Thermal image captured by the top side IR-camera at the HGD-C experiment (200C case)

Table II. COMSOL models at the HGD elements

COMSOL Model	Flow ch.	Liner + Vessel	Insulator	Atm.	ΔT (°C)
CD Model	CV	CD	CD	CV + RAD	4.5
Porous model	CV	CD	CD + CV	CV + RAD	83

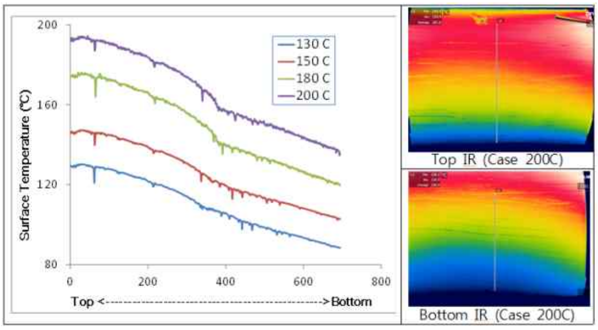

Fig. 7.Measured surface temperature profiles from the top to bottom of the horizontal HGD

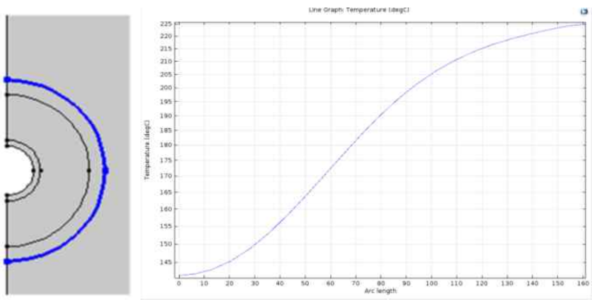

Fig. 8.Prediction of surface temperature profile using a porous media COMSOL model

5. Conclusions

A Hot Gas Duct (HGD) is a unique component of a gas cooled reactor. The internal of an HGD is insulated using a ceramic fiber insulator to prevent a mechanical failure itself from high-temperature VHTR operating conditions. This insulation causes a unique heat transfer characteristics of the HGD. We carried out a heat transfer experiments on the once-through type HGD at the small-scale nitrogen gas loop. We measure the temperature distribution across the external surface of a horizontal HGD using two IR-cameras and compare it to predictions from CFD simulations. From this study, we obtained the following conclusions.

- We obtained a very large temperature difference between top and bottom peak of horizontal HGD in the experiments against our expectation from a 2D CFD model
- Surface temperature distribution of a horizontal HGD is affected very large by the internal insulation where has rather complex heat transfer characteristics with conduction with effective thermal conductivity, radiation at opaque condition, and possible convection presumed a hot gas drift phenomenon.

NOMENCLATURE

A = surface area
C = constant
d = diameter
f = film
m = constant
T = temperature
w = wall
ε= emissivity
∞ = ambient

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