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Thermal hydrodynamic modeling and simulation of hot-gas duct for next-generation nuclear reactor

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HIGHLIGHTS

- Thermal hydrodynamic nonlinear model is presented to examine a hot gas duct (HGD) used in a fourth-generation nuclear power reactor.
- Experiments and simulation were compared to validate the nonlinear porous model.
- Natural convection and radiation are considered to study the effect on the surface temperature of the HGD.
- Local Nusselt number is obtained for the optimum design of a possible next-generation HGD.

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ABSTRACT

A very high-temperature gas-cooled reactor (VHTR) is a fourth-generation nuclear power reactor that requires an intermediate loop that consists of a hot-gas duct (HGD), an intermediate heat exchanger (IHX), and a process heat exchanger for massive hydrogen production. In this study, a mathematical model and simulation were developed for the HGD in a small-scale nitrogen gas loop that was designed and manufactured by the Korea Atomic Energy Research Institute. These were used to investigate the effect of various important factors on the surface of the HGD. In the modeling, a porous model was considered for a Kaowool insulator inside the HGD. The natural convection and radiation are included in the model. For validation, the modeled external surface temperatures are compared with experimental results obtained while changing the inlet temperatures of the nitrogen working fluid. The simulation results show very good agreement with the experiments. The external surface temperatures of the HGD are obtained with respect to the porosity of insulator, emissivity of radiation, and pressure of the working fluid. The local Nusselt number is also obtained for the optimum design of a possible next-generation HGD.

1. Introduction

A very high-temperature gas-cooled reactor (VHTR) is a fourth-generation nuclear power reactor that has been developed in a few countries recently. The VHTR requires an intermediate loop that is composed of a hot-gas duct (HGD), an intermediate heat exchanger (IHX), and a process heat exchanger (Chang et al., 2007). The HGD is a key part of a gas-cooled reactor (GCR), connecting GCR vessel and an intermediate heat exchanger (Song and Kim, 2009), as shown in Fig. 1.

Since the flowing temperature inside the HGD can reach up to 950 °C, the internal insulator (Kaowool) inside HGD plays an important role for deciding the maximum temperature on the surface of the HGD. The surface temperature of the HGD is also influenced by free (natural) convection due to air density difference, and radiation on the both inside and outside of the HGD. The external surface temperature distribution along a surface of the HGD provides the convective heat transfer coefficient, so it is very important to examine the exact temperature distribution on a surface to design optimized internal insulation for an HGD.

Recently, a series of HGD tests was carried out for the small-scale nitrogen gas loop of the Korea Atomic Energy Research Institute (Hong et al., 2015; Lee et al., 2015). A variety of factors in the temperature behavior inside and outside of ducts or pipes are studied for various applications, such as the duct diameter, insulation thickness, emissivity, and thermal conductivity. Kang et al. (2011) estimated the insulation thickness for a horizontal pipe under thermal radiation conditions. The required insulation thickness for surface temperature control increased with increasing

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Nomenclature

A	heat transfer area, (m^2)
D	pipe diameter, (m)
C_p	specific heat, (J/kg K)
E	energy, (J)
Gr	Grashof number
g	gravitational acceleration, (9.81 m/s^2)
h	heat transfer coefficient, (W/m^2K)
k	thermal conductivity, (W/m K)
k_{eff}	effective thermal conduction coefficient, (W/m K)
L	length, (m)
Nu	Nusselt number
Pr	Prandtl number
Q	heat loss, (W)
R	thermal resistance, (K/W)
Ra	Rayleigh number
T	temperature, (K)
u	fluid velocity, (m/s)

Subscripts

P	porous
conv	convection
rad, R	radiation
s	vessel surface
∞	ambient

Greek letters

ε_p	porosity
κ	permeability tensor of the porous medium
ε	emissivity
β_F	Forchheimer drag coefficient
μ	dynamic viscosity, (kg/m s)
ρ	density, (kg/m^3)
σ	Stefan–Boltzmann constant, (5.669×10^{-8} W/m^2 K^4)
θ	volume fraction

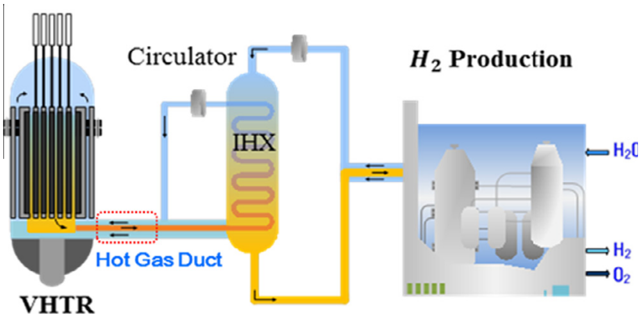

Fig. 1. Schematic of a very high-temperature gas-cooled reactor (VHTR).

pipe diameter and decreasing emissivity. The surface radiation played a crucial role in the insulation design, especially for high-temperature applications.

Heo and Chung (2010) conducted an experiment to visualize the local heat transfer rate on a horizontal cylinder using a copper electroplating system under natural convective conditions. Copper ions produced at the anode of the electroplating system are transferred to the cathode by convection and diffusion, which is the same as the heat transfer. The experiment showed good agreement with the conventional heat transfer correlation. Demir (2010) studied natural convection heat transfer for horizontal concrete and bare cylinders both experimentally and numerically. Heat transfer was obviously enhanced for concrete cylinders compared to the bare cylinder. The average Nusselt number and surface temperature were compared between the experiment and numerical simulation.

Atayilmaz and Teke (2009) also conducted a similar experimental and numerical study on natural convection for a heated horizontal cylinder. The correlation introduced by Churchill and Chu (1975) showed good agreement with the numerical simulations for pure solid materials used to study the effect of natural convection on the surface temperature of the cylinder. However, many studies show a discrepancy in surface temperature between experiments and simulations when fibrous or porous materials are used inside the cylinder as insulation (Spinnler et al., 2004; Karamanos et al., 2004). When fiber materials are used as insulation, the air movement in voids between the fibers is practically negligible due to the very small dimensions of the cavities, and the effective thermal conductivity is only considered for papers in the initial studies.

Porous materials are also very commonly used as insulation. Alkam and Al-Nimr (1998) present a numerical simulation for transient forced convection in a cylindrical channel partially filled with a porous material. The porous substrate improves the Nusselt number in the fully developed region by up to eight times. Parvazinia et al. (2006) studied the flow of a Newtonian fluid in porous materials between two parallel plates using the Brinkman equation. They successfully show no-slip boundary conditions in the model using the Brinkman model, but not when using the Darcy equation.

Guo et al. (1997) studied heat transfer in a pipe partially filled with a porous medium under pulsating flow. They found the maximum effective thermal diffusivity at a critical thickness of the porous layer. Aldoss et al. (2004) investigated natural convection in a horizontal annulus partially filled with a porous medium. They examined the effect of physical parameters such as the Grashof number, Darcy number, and porous layer thickness on the local and average Nusselt number. Oro et al. (2013) describe an energy equation model and Brinkman equation model to analyze the fluid flow in porous media and gravitational force. At lower Reynolds number, the Brinkman equation model is useful for showing the effect of free convection inside a cylindrical tank. Bourantas et al. (2014) investigated the natural convection of a nanofluid in a porous matrix and studied the nanofluid properties in the cooling performance using the extended Darcy-Brinkman equation. Saber et al. (2011) studied the effect of a wide range of foil emissivity on the effective thermal resistance in porous material layers using the Darcy-Brinkman equation in COMSOL Multiphysics (2015).

Experimental or theoretical studies on the effect of thermal hydraulic dynamics have not been reported for extremely severe conditions of very high temperature and pressure.

In this study, we investigated the external surface temperature and local Nusselt number of an HGD using experiments and numerical simulations. The conditions included various internal flow temperatures ranging from 331.7 to 592.4 °C for the working fluid and a pressure of 20 bar. The experiment uses an HGD and small gas loop designed and manufactured by the Korea Atomic Energy Research Institute (KAERI). As far as we know, no research has numerically modeled and simulated an HGD in a fourth-generation nuclear power reactor under an extreme pressure of 20 bar and high temperatures. The effects of natural convection