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An experimental study of air–steam condensation on the exterior surface of a vertical tube under natural convection conditions

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ABSTRACT

To investigate the heat transfer characteristics of a condenser tube in a Passive Containment Cooling System (PCCS) of an advanced nuclear power plant, an experimental investigation has been conducted on the air–steam condensation over external surfaces of a vertical tube under natural convection conditions. Local temperature data and average heat transfer coefficients were measured on a test condenser of 40 mm in O.D. and 1.0 m in length while axial air concentrations and wall temperatures were kept almost uniform. The experiments covered the pressure ranging from 2 to 5 bar, the air mass fraction from 0.10 to 0.88, the wall subcooling from 19 to 70 K, and the Grashof number of an air-steam mixture varied from $1.36 \cdot 10^{10}$ up to $1.42 \cdot 10^{11}$ accordingly. In particular, the effect of the wall subcooling on the condensation heat transfer coefficient and the total heat removal rate was evaluated. From the comparison to Dehbi's tube data, it was found that the condensation heat transfer coefficients on a vertical tube were significantly influenced by the strength of natural convection of the air-steam mixture, which can be described by the Grashof number. To complement the inadequacy of physical bases in deriving previous correlations, a new empirical correlation for the condensation heat transfer coefficient was proposed by using a consolidated data of this study and Dehbi's test; the Nusselt number is correlated in terms of the Grashof number, Jakob number, and the air mass fraction. The suggested correlation was assessed by experimental data and its deviation was turned out to be less than 26%.

1. Introduction

Steam condensation is an effective heat transfer process which commonly results from the contact with a cold surface in industrial equipment. In the nuclear industry, influenced by the catastrophic consequences of Fukushima Daiichi accident, its importance has been much more emphasized as a heat transfer mode on the passive safety systems to assure the safety of nuclear power plants (NPPs) even in the absence of electricity supply. During a postulated LOCA (Loss-of-coolant accident) or MSLB (Main steam line break), large amount of the steam is released from the RCS (Reactor coolant system) or the main steam line, and then the containment building would be more and more pressurized. If the released energy is not properly removed, the structural integrity of the containment can be threatened since the design pressure of most containment buildings is at most 4 bar. The PCCS (Passive Containment Cooling System) is one of the passive engineered safety features to provide an ultimate heat sink for a light water reactor.

Unlike the AP1000 in which the incorporated PCCS uses the containment wall, made of steel, as heat transfer media [1], a NPP with the concrete containment building is supposed to introduce the condenser tubes for heat exchange. One feasible approach is to employ the heat exchangers composed of tube bundles inside the containment and to connect them with the water storage tank installed outside so that the residual heat can be transported to an external heat sink by a naturally driven flow. The Korean state-run power operator KHNP also plan to deploy the PCCS with internal condensers illustrated in Fig. 1 in an innovative NPP to be developed [2]. This PCCS consists of four trains, each having 8 heat exchanger assemblies composed of multiple vertical tubes. Once the pressure boundary of the nuclear system is broken, the released coolant with high energy flashes to steam and then mixes with the air inside the containment to form a vapor–gas mixture. Furthermore, if the cooling of the core fails, hydrogen is also possibly generated by the chemical reaction between the fuel cladding and steam. Then the gaseous mixture of steam and noncondensable gases is condensed on the cold wall of vertical condenser tubes, and a natural circulation flow of coolant is established inside a heat transport circuit. Inside the containment, strong natural convection of the vapor–gas mixture is formed as steam is released

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Nomenclature

A_s	surface area (m^2)
c_p	specific heat at constant pressure (J kg^{-1} K^{-1})
D	diameter (m) or mass diffusivity (m^2 s^{-1})
g	gravitational acceleration (m s^{-2})
Gr	Grashof number
h	heat transfer coefficient (W m^{-2} K^{-1})
$\bar{h}$	average heat transfer coefficient over length (W m^{-2} K^{-1})
h_{fg}	latent heat (J kg^{-1})
Ja	Jakob number
j_g	diffusive mass flux (kg m^{-2} s^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
L	length (m)
$\dot{m}$	mass flow rate (kg s^{-1})
M	molecular weight (g mol^{-1})
Nu	Nusselt number
P	pressure (Pa)
Pr	Prandtl number
q''	heat flux (W m^{-2})
r	radial position (m)
R	gas constant (J mol^{-1} K^{-1})
Re	Reynolds number
Sc	Schmidt number
T	temperature (K)
$\overline{T}$	average temperature (K)
u	velocity in axial direction (m s^{-1})
U	uncertainties
v	velocity in radial direction (m s^{-1})
V	reference velocity (m s^{-1})
W	mass fraction
x	axial coordinate (m)
X	mole fraction
y	radial coordinate (m)

Greek letters

Γ	mass flow rate per unit width (kg m^{-1} s^{-1})
μ	viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})

Subscript

a	air
b	bulk conditions
c	cooling water or critical state in Eq. (33)
$cond$	condensate
f	liquid film
g	noncondensable gas
i	inner side or inlet
o	outer side or outlet
s	steam
sat	saturated state
w	wall
v	vapor
∞	bulk

Superscripts

sat	saturated state

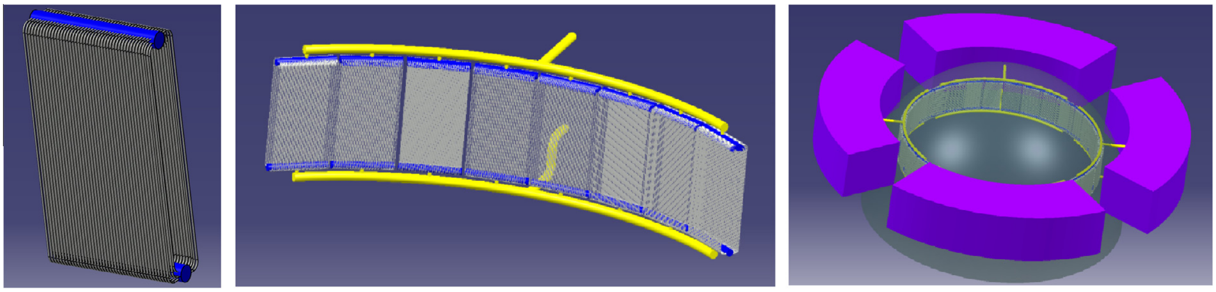

Fig. 1. Passive containment cooling system to be deployed in Korean innovative PWR by KHNP [2]; condenser tube assembly (left), a train (middle), and overall PCCS (right).

from the lower region and condensed on the PCCS at the upper region.

For thermal design and performance evaluation of the PCCS condensers, one needs experimental data and a heat transfer model for condensation heat transfer in the presence of a noncondensable gas on a vertical tube. The safety analysis of the containment has been dependent upon the conservative prediction by empirical correlations by Uchida [3] and Tagami [4]. In order to conduct the best-estimate simulation of the PCCS, however, it is required to have heat transfer data obtained from well-controlled experiments and a realistic empirical correlation derived from them. It is well known that the noncondensable gas degrades significantly the rate of heat transfer by condensation. A number of experimental and theoretical works have been conducted on the effect of a noncondensable gas for various geometries: on flat surface, inside and outside of vertical tubes, on horizontal tubes and so on [3–22,27].

In particular, to support the PCCS design of the SBWR (simplified boiling water reactor) or similar ones, many research efforts have focused on the steam condensation inside a tube, which is experimentally investigated in most cases under forced convection conditions [5–12]. Compared to the condensation phenomena on an external surface of a tube, the in-tube condensation suffers continuous variation in the local composition of a gaseous mixture along the tube, and the buildup of a noncondensable gas at the interface is less accentuated since the bulk motion of the core sweeps away the gases [6]. The effect of an interfacial shear stress is also more pronounced at high velocities. On the contrary, the condensation on a tube outer surface is governed by a complicated multi-dimensional natural convection flow of the vapor–gas mixture, and the rate of heat and mass transfer varies little in the axial direction as long as the bulk conditions are kept almost uniform. Under the free convection conditions, the impact of a noncondensable gas is relatively large, and generally the heat transfer coefficients (HTCs) are lower than those of a forced convection in-tube condensation.

Previous experimental studies of the condensation heat transfer on external surfaces of a vertical tube are summarized in Table 1,