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Condensation heat transfer with noncondensable gas for passive containment cooling of nuclear reactors

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Abstract

Noncondensable gases that come from the containment and the interaction of cladding and steam during a severe accident deteriorate a passive containment cooling system's performance by degrading the heat transfer capabilities of the condensers in passive containment cooling systems. This work contributes to the area of modeling condensation heat transfer with noncondensable gases in integral facilities. Previously existing correlations and models are for the through-flow of the mixture of steam and the noncondensable gases and this may not be applicable to passive containment cooling systems where there is no clear passage for the steam to escape. This work presents a condensation heat transfer model for the downward cocurrent flow of a steam/air mixture through a condenser tube, taking into account the atypical characteristics of the passive containment cooling system. An empirical model is developed that depends on the inlet conditions, including the mixture Reynolds number and noncondensable gas concentration.

1. Introduction

This study focuses on the PCCS of the Simplified Boiling Water Reactor (SBWR) that was developed by General Electric (GE). The GE SBWR was designed to employ a passive containment cooling system (PCCS) and was constructed using isolation condensers that provide a passive heat exchange for the removal of the core decay heat.

The SBWR PCCS components are shown in Fig. 1. Noncondensable gases are separated in the PCCS condenser and are returned to the drywell through the vent pipe. There are no valves in the PCCS so that it is completely passive. The design of the PCCS condenser consists of a unit that has two modules with a single inlet pipe. Each module has cylindrical horizontal inlet and outlet headers that are connected by rows of vertical tubes. The inlet steam/gas mixture enters at the top of the upper header and the condensate and noncondensable gases are discharged from the bottom of the lower header (Masoni et al., 1993).

During normal operation the reactor containment is filled with an inert atmosphere of nitrogen. In the event of a loss of coolant accident (LOCA) the drywell becomes pressurized relative to the suppression chamber. This differential pressure is the driving force that produces the flow of the steam and nitrogen into the PCCS condenser. In the case of a severe accident, hydrogen (a noncondensable gas) may be generated due to the chemical reaction between the fuel cladding metal and steam. The steam condenses in a downward flow through the condenser and the condensate drains back to the GDCS and then to the reactor pressure vessel. The noncondensable gas causes a decrease in the condensation process since it acts as a resistance to the steam motion to the tube walls (Upton et al., 1993).

The heat transfer coefficients vary greatly along the length of the condenser tubes. This decrease in the rates of heat and mass transfer with distance down the tubes is mainly caused by the progressively increasing air mass fraction and the decreasing flow velocity. Since the rate of heat transfer is strongly coupled to

Abbreviations: DW, drywell; GDCS, gravity driven cooling system; GE, General Electric; GIRAFFE, Gravity Driven Integral Full-Height Test for Passive Heat Removal; GIST, GDCS Integrated Systems Test; HTC, heat transfer coefficient; ICS, isolation condenser system; LOCA, loss of coolant accident; NRC, Nuclear Regulatory Commission; PANTHERS, Performance Analysis and Testing of Heat Removal Systems; PCCS, passive containment cooling system; PUMA, Purdue University Multi-dimensional integral test Assembly; RPV, reactor pressure vessel; SBWR, Simplified Boiling Water Reactor; SP, suppression pool; UCB, University of California Berkeley

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Nomenclature

a, b, c	constants
A	cross sectional area (m^2)
c_p	specific heat at constant pressure (J/kg K)
D	diameter (m)
e, E	total energy (W)
$f(z)$	shape function for local axial HTC analysis
$g(z/L(t))$	shape function for local axial HTC analysis
h	heat transfer coefficient (W/m^2 K)
i_{fg}	latent heat (J/kg)
k	thermal conductivity (W/m K)
$\dot{m}$	mass flow rate (kg/s)
M	molecular mass (kg/kmol)
Nu	Nusselt number = hL/k
p	pressure (Pa)
q''	heat flux (W/m^2)
$\dot{Q}$	heat transfer rate (W)
Re	Reynolds number = $\rho Lu/\mu$
t	time (s)
T	temperature (°C)
U	overall heat transfer coefficient (W/m^2 K)
x, y, z	spatial coordinates (m)

Greek symbols

Δ	difference
μ	dynamic viscosity (kg/m s)
ρ	mass density (kg/m^3)
χ	noncondensable gas concentration

Subscripts

b	bulk
c	condensate
f	fluid
g	gas
i	species
in	quantity in
NC	noncondensable
out	quantity out
p	pool
s	system
v	vapor

the PCCS hydrodynamic characteristics, the detailed knowledge of the variation of the local heat transfer coefficient is necessary in order to predict the overall performance of the PCCS.

The PUMA facility, shown in Fig. 2, contains all the major thermal-hydraulic components of the SBWR. It can be applied over the range of conditions required for the assessment of the response of the passive safety systems. It also addresses the integral system response by simulating the interactions between the different components. The PUMA facility was constructed as a distributed system, meaning that the internal tanks of the system were removed from the containment and were then connected to the containment using artificial lines. To assure the scaled system has frictional resistance similarity, additional calculations were performed for the connecting lines (Ishii et al., 1998).

The PCCS system for PUMA differs slightly from the GE SBWR PCCS due to the scaling. Geometrically, the PUMA PCCS is scaled in height to 1/4 full scale of the SBWR PCCS height, there are 13 condensing tubes per condenser unit rather than the 248 tubes in the SBWR and 10 of these tubes are active while three are insulated and effectively non-functional. This scaling distortion was addressed in detail in Leonardi (2000). The upper and lower headers of the PUMA PCCS are cylindrical along the vertical axis whereas the SBWR headers are cylindrical along the horizontal axis. The PUMA inlet of the PCCS is from the upper drywell whereas the outlet is connected via the drain lines to the GDCS. The steam/noncondensable mixture enters the upper header of the PCCS and is distributed to the condensing tubes where the steam is condensed along the length of the tubes. The lower header acts to inhibit the flow of steam since there is no clear passage for the steam to escape. This allows for total condensing of the steam that enters the system. In addition, the noncondensable gases that are collected in the tubes are purged periodically. The purging occurs when the pressure in the drywell exceeds that of the suppression pool gas space. The three condensing units of PUMA are submerged in a pool of water that, as it boils off, is replenished by feed water, as controlled by the operator, to maintain the level above the upper header of the PCCS units.

This study is motivated by the need for research on condensation heat transfer in the presence of noncondensable gases. There has been some work reported but little research has been done to apply the work to integral test facilities such as PUMA. This integral system was discussed in detail in Ishii et al. (1996) and only summarized here.

The integrity of the containment system should be maintained during any postulated accident. This is accomplished by suppressing the pressure and temperature of the containment atmosphere below the design limits. It is important to fully understand the condensation heat transfer capabilities of the PCCS so that a detailed assessment of the long-term cooling capabilities can be performed. The existing correlations and models for the condensation process in the presence of noncondensable gases were determined using experiments that allow the through-flow of the mixture of steam and noncondensable gases. This type of analysis may not be applicable in the case of the PCCS where the condensate tubes are closed at the bottom by the system lower header.

The current models used in the system analysis codes, such as those used in RELAP5, tend to under-predict (as a conservative estimate) the heat transfer capabilities of the PCCS, thus causing the containment pressure to differ from the experimental results. This could mean that the containment pressure boundary is compromised and gives a strong indication that a new method of determining the heat transfer capabilities of the PCCS is needed.

Several authors have studied the heat transfer aspects of condensation and are noted in the analysis that follows. A few have also incorporated the effect of noncondensable gases in the condensation heat transfer analysis. The complexity of the