Annals of Nuclear Energy 123 (2019) 86–96

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Numerical study of thermal hydraulics behavior on the integral test facility for passive containment cooling system using GASFLOW-MPI

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ARTICLE INFO

Article history:
Received 2 July 2018
Received in revised form 4 September 2018
Accepted 9 September 2018

Keywords:
Passive containment cooling system
Dynamic film model
Containment thermal hydraulics
CFD

ABSTRACT

A dynamic film model is developed in GASFLOW-MPI to study the thermal-hydraulic behaviour of the containment with external film cooling, i.e. the passive containment cooling system (PCCS). Former researches on PCCS are mainly conducted with lumped parameter computer codes, hence the CFD study coupling both sides of the containment is necessary. In this study, the dynamic film model of GASFLOW-MPI is validated with both a separate effect test EFFE (Experiments on Falling Film Evaporation) facility and an integral test facility. Firstly, the 2D model of the EFFE facility is built and analyzed in both dry cases and wet cases. The results agree well with the experimental data indicating that the dynamic film model of GASFLOW-MPI can provide reasonable predictions for both heat and mass transfer between the film and gas. Then the 3D model of the scaled down containment test facility is built with the cylindrical coordinate, and a mesh sensitivity analysis is conducted with one section of the 3D model. The 3D model results show that the steady state analysis of GASFLOW-MPI has good agreement with experimental data. Furthermore, GASFLOW-MPI manages to capture the thermal stratification in the containment which is underestimated in former research. The heat transfer analysis on both sides of the containment shell shows that the steam condensation in the dome contributes almost 50% to the total steam condensation, while the film evaporation in the cylinder part contributes about 90% for the heat removal of PCCS. This is the result of heat and mass transfer on both sides of the containment shell coupling with each other. The validation of these two cases indicates that the GASFLOW-MPI can provide reasonable predictions for the thermal hydraulics behavior on both sides of the containment when implementing PCCS. Further research will focus on transient analysis and the model for film coverage.

1. Introduction

A dynamic film model is developed in GASFLOW-MPI for the passive containment cooling system (PCCS) utilized to maintain the containment integrity in nuclear reactors like AP1000 and CAP1400. During a postulated accident induced by loss of coolant (LOCA) or main steam line break (MSLB), the decay heat can be released into the containment through the loss of coolant (Wang et al., 2013). This residual heat will be removed by continuously flowing thin liquid film on the outside surface of a containment shell, as shown in Fig. 1.

The major issues for the thermal hydraulic behavior of PCCS are the condensation inside the containment shell, the evaporation of external film, and the resulting natural convection. There are separate effect experiments focusing on either steam condensation (Ambrosini et al., 2009), film evaporation (Ambrosini et al., 2002; Huang et al., 2015; Kang and Park, 2001) or water distribution of the film (Chang et al., 2017) to provide validation database for integral models as well as CFD codes. There are also integral experiments mainly aiming to evaluate the heat removal capability for a certain design of PCCS (Broxtermann and Allelein, 2013; Zheng et al., 2016). Former numerical researches on PCCS are mainly conducted with lumped parameter computer codes such as COCOSYS, GOTHIC (Broxtermann and Allelein, 2013), MELCOR (Tills et al., 2009), and MAAP (Tong et al., 2015). While CFD simulations are focusing either inner (Wang and Cao, 2017) or outside phenomena (Wang et al., 2016) with assuming temperature or heat flux on the containment shell. However, the fluid behavior near both sides of the containment shell will not be captured in the integral code (Li et al., 2018), leading to overpredict the gas mixing in the containment. Meanwhile, the thermal hydraulics behavior on both sides of the containment shell influenced with each other during external film cooling. Hence the coupling study on both sides of the containment is necessary.

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https://doi.org/10.1016/j.anucene.2018.09.014
0306-4549/

Nomenclature

$\overline{C_{f,x}}$	the averaged friction coefficient;
h	heat mass transfer coefficient;
h_m	mass transfer coefficient;
L	Character length of the film
m''	the mass flux;
Nu	the Nusselt number $\overline{Nu_L} = \frac{\bar{h}L}{k}$;
Pr	the Prandtl number $Pr = \frac{\nu}{\alpha}$;
V	velocity

Special characters

δ	the film thickness;
ρ	the film density;

Subscripts

0	initial or inlet value
bulk	bulk value
center	centerline
conv	convective heat transfer
evap	evaporation
ex	external of the containment
g or gas	gas
f-g	interface of gas and film
in	inside the containment
Q	thermal power;
q''	heat flux between gas and film;
Re	the Reynold number, $Re_{g,L} = u_g L/\nu_g$;
Sc	the Schmidt number;
$\overline{Sh_L}$	the Sherwood number Sh $\overline{Sh_L} = \frac{\overline{h_m}L}{D_{AB}}$;
St	the Stanton number $St = \frac{h}{\rho c_p u_g} = \frac{Nu}{RePr}$;
St_m	mass Stanton number $St_m = \frac{h_m}{u_g} = \frac{Sh}{ReSc}$;
T	temperature
ν	the kinematic viscosity of film, a
φ	mole fraction
lh	latent heat
m	mass
nom	nominal
ref	reference value
s	the meridian value;
sat	saturate value
ω	the azimuthal value;
w or wall	wall or structure.

In this paper, we conduct a numerical study on a scaled-down containment test facility using parallel CFD code GASFLOW-MPI in order to validate the dynamic film model of GAFLOW-MPI. Firstly, the film evaporation model, part of the dynamic film model, is validated with experimental data of EFFE facility (Ambrosini et al., 2002), since the evaporation contributes most to the heat removal capability of PCCS. Then, a simplified model of the integral test facility for PCCS is built and analyzed with GASFLOW-MPI. The steady state result of GASFLOW-MPI is compared with experimental data to further validate the dynamic film model. Moreover, the thermal hydraulics behavior for both inner and outside the containment is analyzed.

2. Physical model and validation

The GASFLOW-MPI is a well validated and widely used parallel CFD code (Xiao et al., 2017a, 2017b; Yu et al, 2018; Zhang et al, 2017, 2018). The relevant thermal hydraulics phenomenon as shown in Fig. 1, have been widely validated with both separate effect experiment (Li et al., 2018) as well as large-scale integral tests, for instinct, International Standard Problems on containment thermal hydraulics (Malet et al., 2010), full-scale containment HDR (Royl et al., 2006). Therefore, these issues will not be discussed repeatedly in this study. Only the validation of dynamic film model is presented in this section. Meanwhile, the flow characteristics of the film have already been validated with a code-to-code validation including local solutions (Xiao et al., 2017b). Since this study focuses on the heat removal capability of external film cooling, only the validation of film evaporation model is presented in this paper.

2.1. Dynamic film model

The dynamic film model in GASFLOW-MPI solves the mass, momentum, and energy transport equations of laminar water film, with heat and mass transfers between structure – film – gas. The main assumptions for the film model are listed below:

- Pressure and physical properties are constant across the film thickness;
- The film flow is in laminar regime, based on which further assumptions can be made.
- The liquid flow in the thin film can be considered parallel to the wall;
- The velocity profile is assumed to be parabolic across the film thickness;
- Normal velocity component is negligible compared to tangential one.

Eqs. (1)–(4) give the time-dependent conservation equations of mass, momentum, and energy in cylindrical coordinates. The transport equations for the film and the gas are calculated separately. The two phases free surface is not modeled, and the mass, momentum and energy transfers on the interface are treated as the boundary condition for both equations.

$$\frac{\partial \delta}{\partial t} + \frac{1}{r\partial s}(r\delta U_s) + \frac{1}{r\partial \omega}(\delta U_\omega) = \frac{-|m''_{evap}|}{\rho} \quad (1)$$

$$\frac{\partial \delta U_s}{\partial t} + \frac{1}{r\partial s}(r\delta U_s U_s) + \frac{1}{r\partial \omega}(\delta U_s U_\omega) = g\delta sin\varphi - \nu(T)\frac{3}{\delta}U_s \quad (2)$$

$$\frac{\partial \delta U_\omega}{\partial t} + \frac{1}{r\partial s}(r\delta U_\omega U_s) + \frac{1}{r\partial \omega}(\delta U_\omega U_\omega) = -\nu(T)\frac{3}{\delta}U_\omega \quad (3)$$

$$\frac{\partial \delta T}{\partial t} + \frac{1}{r\partial s}(r\delta U_s T) + \frac{1}{r\partial \omega}(\delta U_\omega T) = \frac{1}{\rho C_v}\left[h_w(T - T_w) + h_{gas}(T_g - T) - |m''_{evap}|h_{lh}(T)\right] \quad (4)$$

The heat transfer coefficient between film and structure, h_w is calculated with Eq. (5) (Al-Khalil et al., 1991).

$$h_w = \frac{k}{\delta}[3.2 + 2.37e(-4) \cdot Re] \quad (5)$$

The Chilton–Colburn analogy model is adopted to consider the heat and mass transfer between film and gas. According to Chilton–Colburn analogy, the correlation between heat and mass transfer is given in Eq. (6) (Incropera et al., 2007).

$$\frac{C_{f,x}}{2} = StPr^{\frac{2}{3}} = St_m Sc^{\frac{2}{3}}, 0.6 < Pr < 60; 0.6 < Sc < 3000 \quad (6)$$