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Prediction of falling film evaporation on the AP1000 passive containment cooling system using ANSYS FLUENT code

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ABSTRACT

AP1000 nuclear plant is an advanced pressurized reactor developed by Westinghouse Electric Company (WEC), with several passive systems applied to the plant to increase its safety. One of the main passive systems is the passive containment cooling system (PCCS), which aims to ensure the integrity of the containment and remove decay heat from the containment during postulated accidents. Film evaporation outside the steel vessel wall plays an important role for the heat removal process in the PCCS. In this study, the Eulerian Wall Film model in ANSYS FLUENT is applied to study falling film evaporation and natural convection outside the PCCS of AP1000. The thermal–hydraulic phenomena of both liquid film and gas mixture in the outside air flow path of the PCCS are analyzed. The Eulerian Wall Film model shows promising performance in modeling falling film behavior and mass transfer between liquid film and gas phase.

1. Introduction

Passive containment cooling system (PCCS) is an important safety system for the AP1000 nuclear plant. The containment of AP1000 includes two layers of containment walls: a concrete structure outside and a steel shell inside. During postulated accidents, a large amount of hot steam is released into the containment, resulting in increases of both pressure and temperature in the containment. After the pressure and temperature reach a certain value, cold water contained in a water tank at the top of the containment structure will be released and a water film will form outside the steel containment wall. Due to the temperature difference between the atmosphere and the hot containment wall, a natural flow of air will form in the path between the concrete structure and the steel shell. By steam condensation inside the containment and falling film evaporation outside, heat will be removed from the containment safely (Schulz, 2006).

Several experiments have been carried out by WEC to investigate the performance of the PCCS of AP600 and AP1000. One of the main conclusions of the experiments is that film evaporation is the key heat removal process outside the containment shell, though natural convection and thermal radiation also play important roles in the process (WEC, 2004). A joint research project called DABASCO (Cheng et al., 2001) was conducted by nine European institutions to provide an experimental data base for containment thermal–hydraulic analysis. Three separate-effect test programs were set up to study passive containment cooling by means of natural and mixed gas convection coupled with water film evaporation. The obtained data confirm that the analogy between heat and mass transfer is suitable for evaporation under PCCS conditions. Kang and Park (2001) conducted an experiment in a vertical duct to investigate evaporative mass transfer at the surface of a falling water film. They found evaporation rate is strongly affected by water temperature and air mass flow rate. Based on the experimental data a new correlation on evaporative mass transfer coefficient was developed. Huang et al. (2015) designed a similar experiment facility to study falling film evaporation for the design and improvement of passive containment cooling system. The experimental data they obtained confirmed Kang's main conclusions.

As for numerical simulations, there are few public resources available on PCCS outside cooling. Li et al. (2013) numerically investigated the thermal–hydraulic phenomena of a simplified PCCS outside path. A containment mathematical model in their study was built based on experimental correlations and was solved using Fortran 90 program. They found that evaporative heat transfer is the main heat transfer mechanism outside the PCCS and more than 90% of total heat is removed by this mechanism. However, few details on the transport process can be provided by this kind

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Nomenclature

C_p	specific heat ($J/kg \cdot K$)
C_{vap}	phase change constant
D	diffusion coefficient (m^2/s)
L	latent heat (kJ/kg)
P	pressure (Pa)
S	source term
T	temperature (K)
W	mass fraction
g	gravitational acceleration (m/s^2)
h	film height (m)
k	turbulent kinetic energy (m^2/s^2
m	mass source per unit area (kg/m^2)
t	time (s)
u	velocity (m/s)
V	velocity (m/s)

Greek symbols

ε	turbulent dissipation rate (m^2/s^3)
λ	thermal conductivity ($W/(m \cdot K)$)
τ	shear stress (Pa)
μ	molecular viscosity ($Pa \cdot s$)
v	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)

Subscripts

a	air
f	film
i	x direction
j	y direction
l	liquid
s	steam
sat	saturation
t	turbulent
w	wall
eff	effective

of lumped code. Ambrosini et al. (2002) studied evaporation film cooling with a CFD approach. Falling film was neglected and evaporation was modeled as source terms added in the cells next to the heated wall. The model was validated against EFFE (Experiments on Falling Film Evaporation) experiment and satisfactory results were obtained. However, this model is limited by its failure to consider the influence of falling film on evaporation.

In the current study, a CFD approach is applied to investigate the AP1000 PCCS outside cooling using ANSYS FLUENT. The Eulerian Wall Film model, which is new model incorporated into ANSYS FLUENT since version 14.0, is used to model falling film evaporation. The model is validated against experimental data from EFFE. The thermal–hydraulic phenomena of the AP1000 PCCS are analyzed.

2. CFD model

Some assumptions are made before the CFD model is built.

1. Thermal–hydraulic phenomena are uniform in the circumferential direction of the PCCS vessel. Water film stripes on the vessel wall and the formation of dry patches are not considered in the current study.
2. Steady state condition is assumed.
3. The gas mixture is treated as ideal gas.
4. Wavy structures on the falling film are neglected.
5. Mist in the gas phase is not considered.
6. Radiation heat transfer is negligible compared to the total heat transfer.

2.1. Govening equations

In the gas phase, ANSYS FLUENT (2013) solve continuity and momentum equations as well as energy, species and turbulence equations in this study.

The continuity equation is written as follows

$$\frac{\partial}{\partial x_i}(\rho u_i) = S_{mass} \tag{1}$$

The momentum equation is described by

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_j}{\partial x_j}\right)\right] + \frac{\partial}{\partial x_j}(-\rho\overline{u_i' u_j'}) + S_{mon-i} \tag{2}$$

where $-\rho\overline{u_i' u_j'}$ is Reynolds stress, which is modeled based on Boussinesq hypothesis.

$$-\rho\overline{u_i' u_j'} = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\rho k \delta_{ij} \tag{3}$$

Turbulent heat transport is given by

$$\frac{\partial}{\partial x_i}[u_i(\rho E + P)] = \frac{\partial}{\partial x_i}\left(\lambda_{eff}\frac{\partial T}{\partial x_i}\right) + S_{energy} \tag{4}$$

where E is the total energy, λ_{eff} is the effective thermal conductivity.

In this study, the realizable k–ε turbulence model is used. For realizable k–ε model, the effective thermal conductivity is given by

$$\lambda_{eff} = \lambda + \frac{C_p \mu_t}{\mathrm{Pr}_t} \tag{5}$$

where $\mathrm{Pr}_t = 0.85$.

Turbulent species transport equation is given by

$$\frac{\partial}{\partial x_i}(\rho u_i W_s) = \frac{\partial}{\partial x_i}\left[\left(\rho D + \frac{\mu_t}{Sc_t}\right)\frac{\partial W_s}{\partial x_i}\right] + S_{species} \tag{6}$$

where W_s is the mass fraction of steam, Sc_t is the turbulent Schmidt number.

The k transport equation in realizable k–ε model is given

$$\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + G_k + G_b - \rho\varepsilon + S_k \tag{7}$$

G_k and G_b, representing the generation of turbulence energy due to the mean velocity gradients and the generation of turbulence kinetic energy due to buoyancy, respectively. σ_k is the turbulent Prandtl number for k, which equals to 1.0.

The ε equation in realizable k–ε model is described as

$$\frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_1 S\varepsilon - \rho C_2\frac{\varepsilon^2}{k + \sqrt{\nu\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b + S_\varepsilon \tag{8}$$