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Modeling the influence of tube support plates on flow boiling and dryout of once-through steam generators

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ABSTRACT

Considering the tube support plates installed among the tube bundle of actual once-through steam generator, the mathematical model suitable for smooth channel was modified to numerically simulate the two-phase flow and heat transfer and dryout under three structures (no tube support plates, tube support plates with and without gaps). The results show that the slip ratio increases rapidly when fluid flows through the tube support plates, and then decreases rapidly under the strong disturbance caused by the turbulence transition at the downstream position of tube support plates. The maximum slip ratio for the case of TSPs with gaps is lower than that for the other two cases, which is conducive to prevent interphase slipping. The turbulence transition and great steam quality caused by heat transfer enhancement at the downstream position of tube support plates both have positive effects on tearing the annular liquid film, resulting in the dryout position being at the upstream position of that for the case of no tube support plates. The damage of dryout deterioration can be relieved significantly when considering tube support plates, and the corresponding rising amplitude of wall temperature at dryout position reduces from 300 K for the case of no tube support plates to 200 K. With the development of flow and heat transfer, the non-uniform levels of circumferential wall temperature for the cases of tube support plates with and without gaps show completely opposite trends.

1. Introduction

As the key heat exchanger between primary and secondary sides, the once-through steam generator (OTSG) plays a role in transferring the heat from primary coolant to secondary feedwater, and then the work is done by secondary feedwater carrying the heat into steam turbine. However, for the OTSG with the advantage of high efficiency and compact form, superheated steam with the capacity of carrying more heat is produced in secondary outlet. So the heat transfer deterioration-dryout, alternation of wetting and drying and impurity deposition inevitably occur in the secondary side of the OTSG during the operation of the nuclear system [1], causing the flood hole and gap blockage of tube support plates (TSPs) that are installed in secondary side to fix the tube bundle (as shown in Fig. 1), and further water-level oscillation [2]. The TSPs also have a significant influence on the two-phase flow boiling and dryout deterioration of OTSGs. Under this background, many useful works have been carried out.

The characteristics of convective heat transfer coefficient in a small-size helical tube were investigated by changing the inlet pressure, heat flux and mass flow rate [3]. The one-dimensional three-flow-field model was used to calculate wall temperature and dryout position, in which the three flow-fields were liquid, vapor and droplets interspersed in vapor. It was proved that the model has high accuracy at the pressure range of 0.3–13.5 MPa and the mass flux range of 50–800 $kg/(m^2\ s)$ by comparing the simulation results with various experimental data [4]. The relationship between two-phase frictional pressure drop and operating parameters in a helical tube was experimentally studied, and the results showed that it was difficult to predict two-phase frictional pressure drop using the existing empirical correlations [5]. The drift flow model was used to numerically investigate the dryout of annular liquid film in a tube, and the different semi-empirical models were combined in constitutive equations. And then the obtained results were compared with published experiment data to found optimal combination under present load [6]. The dryout of steam-liquid two phases in a vertical tube during countercurrent heat transfer was experimentally studied, and the results showed that the inlet subcooling had a significant influence on dryout at low mass fluxes, while there was no influence at moderate and high mass fluxes. Finally, the one-dimensional heat and mass

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Nomenclature

English symbols

t	time, s
$\vec{U}$	velocity vector, m/s
m_l	mass transfer rate between continuous liquid film and continuous steam, kg/(m^3 s)
m_d	mass transfer rate between discrete droplets and continuous steam, kg/(m^3 s)
S	mass transfer rate, kg/(m^3 s)
p	pressure, MPa
g	gravity, m/s^2
F_{vd}	drag force between steam and droplets, N/m^2
F_{vl}	drag force between steam and liquid film, N/m^2
$\vec{F}_{lift}$	buoyancy lift, N/m^2
h	enthalpy, kJ/kg
A	flow area, m^2
q	heat flux, W/m^2
q_{vl}	heat flux per unit volume between steam and its interface with the liquid film, W/m^3
q_{vd}	heat flux per unit volume between steam and its interface with the droplets, W/m^3
q_{lv}	heat flux per unit volume between liquid film and its interface with the steam, W/m^3
q_{dv}	heat flux per unit volume between droplets and their interface with the steam, W/m^3
G	mass flux, kg/(m^2 s)
C	inertial loss coefficient
k	turbulence kinetic energy, J/kg
x	coordinate axis
R	gas constant, J/(kg K)
q_{wil}	heat flux between wall and the interface of steam-liquid film, W/m^2
q_{wid}	heat flux between wall and the interface of steam-droplets, W/m^2
C_l	lift coefficient
D_h	hydraulic diameter, m
T	temperature, K
X	steam quality
I	unit tensor
$\vec{n}$	volume fraction gradient

Greek symbols

α	volume fraction
ρ	density, kg/m^3
∇	gradient
τ	shear stress, N/m^2
τ^{Re}	Reynolds stress, N/m^2
χ_c	heating perimeter, m
μ	dynamic viscosity, Pa s
ξ	permeability, H/m
δ	thickness, m
ϕ^2	two-phase multiplier
ω	kinematic viscosity, m^2/s
Pr_t	turbulent Prandtl number
γ	adiabatic exponent
v	kinematic viscosity, pa s
λ_{RT}	Rayleigh-Taylor instability wavelength, m
λ	thermal conductivity, W/(m K)
σ	surface tension coefficient
$\otimes$	tensor product of the two vectors: the original normal and the transformed normal

Subscripts

i	steam, liquid film or droplet
v	steam
l	liquid film
d	droplet
E	entrainment
D	deposition
w	wall
TSP	tube support plate
1, 2, 3	coordinate direction
t	turbulence
q	$q = l, d$
vo	vorticity
k	$k = v, l$
DO	dryout

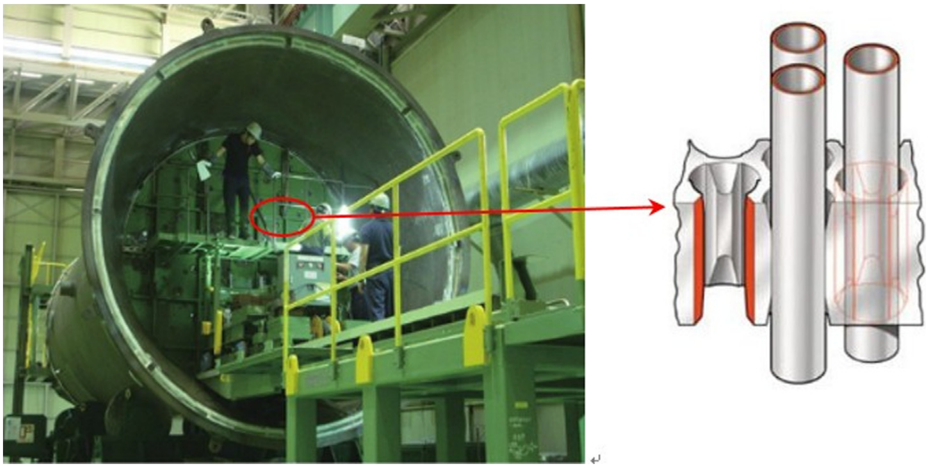

Fig. 1. Geometry of the OTSG with the location of the TSPs.