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A sequential-parallel interdependent complement scaling approach with its applications to AP1000 passive containment cooling system

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ABSTRACT

For AP1000 passive containment cooling system, the decay heat is removed by sequential heat transfer processes and it at last is transferred to the surrounding atmosphere. Based on this feature of passive containment cooling system, a Sequential-Parallel Interdependent Complement Scaling (SPIC) approach, sourced from the H2TS, three-level and FSA methods, was proposed and it emphasized the systematic top-down approach. SPIC core lay on its interdependent complement scheme among the sequential and parallel systems or subsystems to offset main distortions and based on SPIC, the interpedently coupled features of the sequential and parallel processes for passive containment could be fully used to minimize the distortions during scaling. For its preliminary application, general analyses were then systematically made on AP1000 containment. Decomposition was performed and governing equations were established for every subsystem or block system. These equations were then nondimensionalized. Scaling criterion group was finally formed and by preliminary analyses, it showed that the scaling-down for the specific structure dimension was restricted by more than one dimensionless number and accordingly their distortions could not be directly avoided. When the current interdependent complement is used, most distortions could be avoided.

1. Introduction

Scaling is necessarily important for designs of the integrated thermal-hydraulic test facilities (Zuber et al., 1998, 2007; Auger, 1989; Ishii et al., 1998), as it could help form a series of similarity criteria on phenomena or processes between the full-scale (prototype) plant and the integrated test facility (model). NRC broadened the scaling application to code calculations or special models. A Severe Accident Scaling Methodology (SASM) development program was implemented and they addressed the Hierarchical, Two-Tiered scaling (H2TS) for the complex system (Zuber et al., 1998). His scaling method is derived from Auger (Auger, 1989) for dynamics and thermodynamics system. H2TS is applicable for the integrated system, which is composed of multi-subsystems. It generally includes the top-down and the bottom-up approaches. The levels in such a hierarchy are isolated from each other as they operate at different scales. The top-down approach mainly focuses on the processes of relative macro scale level but ranked high importance and it does not focus on the local processes or boundaries of the components on the local micro-scale levels (such as pump performance, critical heat flux occurrences in fuel rods or a special but local phenomenon). Thus, although this top-down could form main scaling criteria by nondimensionalizing equations for physical fields, the specific requirements or boundary conditions during the heat removal process cannot be fully specified. However, its bottom-up approach supplements these. Finally, they together achieve the closure for boundary conditions for an integrated system. Roughly at the same time, the three-level scaling approach was developed (Ishii et al., 1998). The three-level scaling is similar to H2TS in its roadmap or technical approach, but its top-down approach includes the integral response and control volume scaling sections. Its emphasis of integral response scaling makes it applicable to deal with problems of system flow and local flow resistances. Then, the fractional scaling analysis (FSA) is used for LOCA applications (Zuber et al., 2007). Their scaling is based on the integral (appose to differential) equations in spatial–temporal scaling. Similarly to H2TS, it also includes the hierarchical levels of process, component and system. It focuses on the identification

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Nomenclature

Roman symbols

A	area, m^2
A_{eff}	water coverage area, m^2
Bi	biot number, $Bi = h\delta_e/\lambda_e$,–
Bi_c	equivalent Biot number for condensation boundary, $Bi = h\delta_e/\lambda_e$, –
Bi_e	equivalent Biot number for evaporation boundary, $Bi = h\delta_e/\lambda_e$, –
c_p	constant pressure specific heat, J/kg
$c_{v,a}$	constant volume specific heat for air, J/kg-K
$c_{v,v}$	constant volume specific heat for water steam, J/kg-K
D	containment diameter, neglecting its thickness, m
d	differential, –
d	diameter or equivalent diameter, m
d_j	jet diameter, m
Fo	Fourier Number, –
Fo_e	equivalent integral Fourier Number, –
f	frictional resistance coefficient, –
g	gravity, acceleration, m^2/s
H	height, m
H_c	chimney path length, m
H_d	dome path length, m
H_j	wall jet height, m
H_r	riser path length, m
h	heat transfer coefficient for equivalent condensation or evaporation, W/m^2-K
h_{evap}	evaporation mass transfer coefficient, m/s
h_f	specific enthalpy for water condensate, J/kg
h_{fg}	latent heat for vaporization, J /kg
h_j	total enthalpy for energy release, J/kg
h_w	convection heat transfer coefficient for water film, W/m^2-K
k	constant for water line rate, m-s/kg
L_j	distance from the broken pipe to the jet ceiling, m
l	arc length, m
M	wall jet momentum, kg-m/s
M_j	jet momentum, kg-m/s
M_v	water steam mass, kg
m_e	evaporation rate, kg/s
m_c	condensation rate, kg/s
m_j	mass release rate from the broken pipe, kg/s
m_w	cold water mass rate, kg/s
Nu	Nusselt number, –
P_j	thermal power, $P_j = m_j h_j$, W
p_a	air partial pressure, Pa
p_v	water steam partial pressure, Pa
Q	heat rate, W
Q_j	volumetric rate of mass release, m^3/s
$Q_{j,z}$	local volumetric rate of mass release at location z, m^3/s
Q_r^+	dimensional heat rate from the riser passage, –
$Q_{subcooling}$	subcooling heat rate, m^3/s
q	heat flux, W/m^2
R_a	gas constant for air, J/kg-K
R_v	gas constant for water steam, J/kg-K
Re	Reynolds number, $Re = (uL)/\nu$, –
$Re\delta$	wall jet Reynolds number, $Re = (u\delta)/\nu$, –
Ri	Richardson number, $Ri = (\Delta\rho g L/(\rho u^2)$, –
Sh	Sherwood number, –
t_w	local water temperature, K
$t_{w,in}$	inlet water temperature, K
t_s	external containment surface temperature, K
U	gas internal energy within a control volume, J
u	mean velocity, m/s
u_j	jet velocity, m/s
V	pressurized space volume, m^3
V_r	space volume within the riser passage, m^3
W	mean steam mass concentration, kg/m^3
W_s	steam mass concentration at the interface, kg/m^3
w	width of the riser, m
x	radial coordinate, m
z	axial coordinate, m
z_a	compressibility factor for dry air, –
z_v	compressibility factor for water vapor, –

Greek symbols

α	thermal diffusion coefficient, $\alpha = \lambda/\rho c_v$, –
α_s	equivalent thermal diffusion coefficient for internal structures or wall jet, –
α_s	thermal diffusion coefficient for internal structures or wall jet, –
Δ	difference, –
δ_s	thickness for internal structures or wall jet, m
δ_ε	thickness for containment shell or fall wall jet boundary layer, m
δ_j	thickness for wall jet boundary layer, m
δ_e	equivalent integral thickness for internal structures, m
$\Phi_{c,sink}$	phase change heat transfer rate due to condensation, J/kg
ϕ	water coverage fraction, $\phi = A_{eff}/A$, –
κ	buoyancy jet constant, –
λ_e	equivalent thermal conductivity of internal structures, W/m-K
λ_s	thermal conductivity of internal structures, W/m-K
λ_{shell}	thermal conductivity of the containment shell, W/m-K
Π	scaling criterion, –
Π_m	model scaling criterion, –
Π_p	prototype scaling criterion, –
Π_R	scaling ratio, –
$\Pi_{R,m}$	scaling ratio for mass conservation equation, –
$\Pi_{R,e}$	scaling ratio for energy conservation equation, –
$\Pi_{R,M}$	scaling ratio for momentum conservation equation, –
θ	radian, rad
ρ_a	density around the surrounding environment, kg/m^3
$\rho_{a,r}$	mean density in riser path, kg/m^3
ρ_g	air mixture density, kg/m^3
ρ_V	density within the riser passage, kg/m^3
ρ_j	jet steam density, kg/m^3
σ	entrainment constant, $(m^3/kg)^{1/2}$
τ	time, s
τ_0	reference time, s
ν	kinetic viscosity, m^2/s
ξ	equivalent local flow resistance coefficient, –

Subscripts

0	parameter state for dimensionless analyses, –
ave	mean, –
c	condensation, –
j	round jet, –
R	ratio, –

Superscripts

+	dimensionless, –