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Numerical investigation of three-dimensional natural circulation phenomenon in passive safety systems for decay heat removal in large pools

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ABSTRACT

Many advanced designs of nuclear reactors adopt a methodology of passive safety systems in order to avoid the occurence of a severe accident. In one of such systems, the decay heat generated from a reactor is transferred by natural circulation into large pool of water called the Gravity Driven Water Pool (GDWP). Three-dimensional (3D) convection flows develop, which in turn affect the heat transfer process and hence the temperature pattern. The heat transfer process can get compromised by the possible stratification of the temperature. Further, the material of construction of GDWP may have certain temperature limitations and puts bounds on the extent of stratification. The objective of this study is to investigate the 3D natural circulation phenomenon in GDWP. The present work is in continuation of our earlier work Gandhi et al. [1,2] where the natural convection has been analyzed in 0.025 and 0.21 m^3 vessels. Now, we have reported the simulation for 9247 m^3 GDWP tank. Single phase CFD simulations using open source CFD code [OpenFOAM-1.6] have been performed for a geometry (ID = 12 m, OD = 50 m and height (H_T) = 5 m). In order to reduce the thermal stratification, various geometrical modifications have been incorporated on the heat exchanger design, such as (1) distributing the heat transfer area of heat exchanger among single, double and multiple heat sources (2) to optimize the location of heat exchanger inside the GDWP (3) provision of passive elements such as draft tubes (single or concentric multiple) around the heat source at the center, which can act as a chimney. A detailed CFD analysis of three dimensional temperature and velocity distribution in the secondary side of GDWP has confirmed the mitigation of thermal stratification phenomenon by optimizing the distribution and position of heat exchangers. Passive draft tubes also result in significant enhancement in natural circulation and hence reduction in thermal stratification.

1. Introduction

In order to avoid the occurence of a severe accident, many advanced designs of nuclear reactors adopt a methodology of providing a passive safety system to remove the decay heat during accidental conditions. During passive decay heat removal system (PDHRS) operation, the decay heat generated from the core is removed by coolant (subcooled water initially at a temperature of 258 °C and 7 MPa pressure) circulating in the primary system. In the process of decay heat transfer, coolant is converted into two phase mixture which is then separated into steam and water inside a steam drum. The steam thus formed is injected into and condensed in the PDHRS heat exchangers (ICs) submerged in a large pool of water called the GDWP which is considered as a near infinite heat sink. The condensing heat is transferred to the GDWP, the heat of which is removed by the heat up and eventual boiling of the stored inventory. Considering the weak driving forces of passive systems based on natural circulation, careful design of heat exchanger is necessary to facilitate the efficient decay heat removal. Such a PDHRS also cools the core to the desired temperature with a continuous reduction in saturation temperature with respect to time.

In a passive decay heat removal system, the heat transfer from the isolation condenser is concentrated in a limited zone of a large

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Nomenclature

C_P specific heat of fluid (kJ kg^{-1} K^{-1})
ΔT temperature driving force in Table 4 (K)
G gravitational constant in Table 4 (m s^{-2})
h height of liquid level in the GDWP tank (m)
H_{df1} height of first draft tube (m)
H_{df2} height of second draft tube (m)
H_{df3} height of third draft tube (m)
H_T height of GDWP tank (m)
H height of heat sources in Table 5 (m)
ID inner diameter of GDWP tank (m)
j axial locations for calculating stratification number in Eq. (9) (–)
J total number of nodes per lateral location in calculating stratification number (–)
K turbulent kinetic energy in Table 5 (m^2 s^{-2})
l characteristic length in Table 4 (m)
L length of heat source in Table 3 (m)
L_{df1} length of first draft tube (m)
L_{df2} length of second draft tube (m)
L_{df3} length of third draft tube (m)
M mixing number in Table 7 $[(g\beta\Delta Tl^3)/(V_c l)^2]$ (–)
OD outer diameter of GDWP tank (m)
P/V power per unit volume (W/m^3)
Ra Rayleigh number in Table 4 $(g\beta\Delta Tl^3/\nu\alpha)$ (–)
R_o outer radius of GDWP tank (m)
R_i inner radius of GDWP tank (m)
C clearance i.e. the distance between the bottom of the tank and bottom of the IC
S stratification number (–)
t_{df} thickness of draft tube in Table 5 (m)
t time (s)
T_j temperature of j node for calculation of stratification number in Eq. (9) (K)
T_{j+1} temperature of $j+1$ node for calculation of stratification number in Eq. (9) (K)
$T_{\max}$ maximum temperature (K)
$T_{\min}$ minimum temperature (K)
T_w wall temperature in Table 4 (K)
$\langle\Delta T\rangle$ average temperature driving force in Table 4 (K)
T_0 initial temperature in Table 4 (K)
T_w heat source wall temperature (K)
θ_T length of GDWP tank in tangential direction (degrees)
θ_h length of heat source in tangential direction (degrees)
θ_{df1} length of first draft tube in tangential direction (degrees)
θ_{df2} length of second draft tube in tangential direction (degrees)
θ_{df3} length of third draft tube in tangential direction (degrees)
θ_h length of heat source in tangential direction
θ_{df} length of draft tube in tangential direction
u_r radial component velocity (m s^{-1})
u_θ tangential component velocity (m s^{-1})
u_x x-component velocity (m s^{-1})
u_y y-component velocity (m s^{-1})
u_z z-component velocity (m s^{-1})
V_c average circulation velocity in Table 7 (m s^{-1})
V total liquid volume in tank (m^3)
W width of heat source in Table 5 (m)
w mean axial velocity (m s^{-1})
x any distance along the width of the rectangular tank (m)
y any distance along the length of the rectangular tank (m)
y^+ dimensionless distance from the wall (–)
z any distance along the height of the rectangular tank (m)
Δz distance between each axial location for calculating stratification number in Eq. (9) (m)

Greek symbols
α thermal diffusivity in Table 4 (m^2 s^{-1})
α constant in Table 6 (–)
α_1 constant in Table 6 (–)
α_2 constant in Table 6 (–)
β thermal expansion coefficient in Tables 4 and 6 in (K^{-1})
β_1 constant in Table 6 (–)
β_2 constant in Table 6 (–)
β^* constant in Table 6 (–)
Δ difference in a quantity e.g. temperature (–)
ν_t turbulent kinematic viscosity in Table 6 (m^2 s^{-1})
ω specific dissipation rate (s^{-1})
ρ density of fluid (kg m^{-3})
$\sigma_{\omega 1}$ constant in Table 6 (–)
$\sigma_{\omega 2}$ constant in Table 6 (–)
σ_{k1} constant in Table 6 (–)
σ_{k2} constant in Table 6 (–)
σ_ω turbulent Prandtl number for specific dissipation rate in Table 6 (–)
θ_{mix} mixing time Table 7 in (s)
ν kinematic viscosity in Table 4 (m^2 s^{-1})
ν_{eff} effective viscosity in Table 6 (m^2 s^{-1})

Subscript
b buoyancy as in G_b
c circulation
df draft tube
E eddy
eff effective
H_{S1} single heat source
H_{S2} two heat source
I integral
k kinetic energy as in k
L liquid
max maximum
min minimum

Abbreviation
CFD computational fluid dynamics
HTC heat transfer coefficient
GDWP Gravity Driven Water Pool
PDHRS passive decay heat removal system
PRHRS passive residual heat removal system
MHT main heat transport
PIV particle image velocimetry
SST shear stress transport
IC isolation condenser
HT heat transfer
IC1 single heat source (isolation condenser)
IC2 two heat sources (isolation condenser)
IC36 36 heat sources (isolation condenser)
DF0 no draft tube
DF1 single draft tube
DF3 three draft tubes