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Optimal structural analysis with associated passive heat removal for AP1000 shield building

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HIGHLIGHTS

► The removal of decay heat and the stress distribution are crucial factors.
► Passive mechanisms have been widely used in various fields for enhancing heat transfer.
► Numerical models for heat transfer and stress analyses were developed and validated.
► An optimal parametric design in seismic analysis to improve cooling.

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ABSTRACT

The shield building of AP1000 was designed to protect the steel containment vessel (CV) of nuclear power plants. When the reactor is shutdown, the tank mounted above the shield building sprays water, and the intake of ambient air cools down the temperature of CV through buoyancy driven circulation. The result of heat transfer analysis indicates that the location of air intake at lower altitude is more effective than that in the original design. However, pursuing superior heat transfer may cause a conflict with the structural strength, particularly under the threat of an earthquake. Therefore, this study identified the optimal design for stress analysis to improve passive cooling. The results of structural analyses indicated that the maximal stresses developed under various water levels were in the acceptable range of yield stress limits for concrete. The water level does not pose considerable danger to the structure. In addition, the simulation result also indicated that an optimal parametric design for air intake must be implemented around the middle of the shield building, with 16 circular or oval shaped air intake.

1. Introduction

The AP1000 system, which was designed by Westinghouse, is one of the most popular units among the generation III^{+} nuclear power plants. The AP1000 safety system [1] is schematically shown in Fig. 1, which includes the facilities inside and outside of the containment vessel (CV). This system provides the safety functions of core shutdown reactivity control, reactor coolant inventory makeup, and core decay heat cooling during postulated accident conditions. The reactor coolant system (RCS), as shown in Fig. 2, consists of two heat transfer circuits, with each circuit containing one steam generator, two reactor coolant pumps, and a single hot leg and two cold legs for circulating coolant between the reactor and the steam generators.

The commercial AP1000 has been building in China with passive cooling mechanisms and has been considered to be great design. Related studies such as Wang et al. [2] analyzed three-dimensional turbulent flow and convective heat transfer through mixing split vane in a single-phase and steady-state sub-channel of AP1000 nuclear reactor core by using general computational fluid dynamics code. Wang et al. [3] investigated the available literature on thermal hydraulic phenomena that occurred during small break LOCAs in AP1000, which included the critical flow, natural circulation, and countercurrent flow limiting. Zhang [4] investigated In-vessel retention (IVR) analysis code in severe accident has been developed to evaluate the safety margin of IVR in AP1000 with

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Nomenclature

a	absorption coefficient
C	damping matrix
C_p	specific heat (J/kg K)
E	Young's modulus (GPa)
F	load vector
H_L	liquid height (m)
H_T	elevation of air intake (m)
I	intensity of radiation
K	stiffness matrix
M	mass matrix
p	amplitude of the force
q''	heat flux (W/m^2)
R	radii of shield building (m)
T	temperature (°C)
u	displacement (m)
$\vec{V}$	velocity (m/s)

Greek symbols

α, β	Rayleigh damping coefficient
ρ	density (kg/m^3)
σ_s	scattering coefficient
σ_{eqv}	equivalent stress (MPa)
ν	Poisson's ratio
κ	extinction coefficient
ε	surface emissivity
ω	circular natural frequencies (Hz)
t	wall thickness (m)
Δt	time step
ζ	damping ratio
γ	decay rate of acceleration

Subscript

b	black body
VM	von Mises
s	scattering
w	evaluated at wall conditions
net	net value

anticipative depressurization and reactor cavity flooding in severe accident.

The main function of the shield building that is currently used in AP1000 is to protect the containment vessel. It is also a part of the passive containment cooling system (PCCS), and includes a cooling air intake and gravity drain water tank above the shield building. When a nuclear reactor is shutdown, the shield building can immediately cool the containment vessel and passively remove decay heat with spray water and buoyancy driven air from the outside wall, as shown in Fig. 1. Since the heat eventually should be removed out of shield building effectively to ensure the nuclear safety, the present study points out a possible means in more appropriate selection in system parameters. In order to satisfy the requirement of heat transfer and structure, an optimal study has been implemented focusing on if the location and distribution of air inlets are optimal and how these inlets affect structural safety. The result could be used as the reference for improving the design of AP1000 shield building in the future.

The technology used in the passive systems of the AP1000 is now a mature concept. Passive mechanisms have been widely used in various fields of applications in enhancing heat transfer. For example, Hung and Fu [5] and Hung [6] modified attached substrates of PC boards with openings to allow air-flow between upper and lower channels to passively enhance chip cooling. Tseng et al. [7] analyzed the passive cooling design that is even better than the inclusion of forced flow, and can reduce the damage probability caused by the cooling failures for electronic systems. A passive reactor air cooling system was also used in Sodium Advanced Fast Reactor (SAFR) [8], in which Hung et al. (2011) implemented CFD simulations to approach the optimal pool design by reducing the maximal pool temperature. The experiments conducted by Anderson et al. [9] attempted to simulate the behavior of the PCCS system of a Westinghouse AP600. In addition, the authors aimed to produce a parametric study of the phenomenon of condensation.

For seismic analysis, two main methods, response spectrum analysis (RSA) [10] and response history analysis (RHA) [11], are

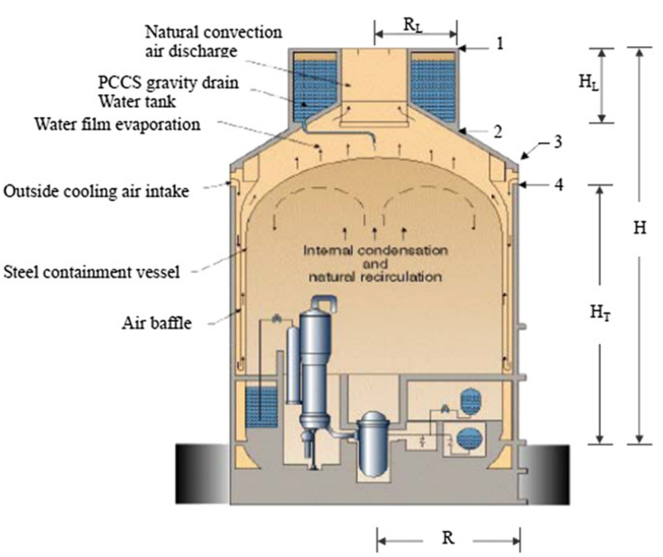

Fig. 1. The schematic passive containment cooling system of AP1000 [1].

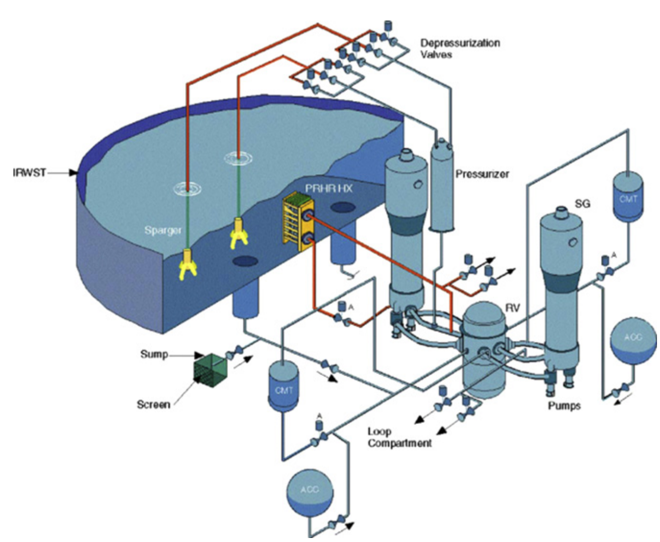

Fig. 2. Passive AP1000 reactor cooling system [1].