Nuclear Engineering and Design 327 (2018) 139–149

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

CFD investigation on thermal hydraulics of the passive residual heat removal heat exchanger (PRHR HX)

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ARTICLE INFO

Keywords:
CFD
PRHR HX
Porous media approach
Passive heat removal

ABSTRACT

Passive residual heat removal (PRHR) system is a very important component of the passive safety systems in advanced passive safety pressurizer water reactors (PWRs) such as AP1000. The passive residual heat removal heat exchanger (PRHR HX) is a C-shape tube bundle heat exchanger immerged in the In-containment refueling water storage tank (IRWST) which removes the core decay heat during the accident transients. The performance of the PRHR HX is significant for the safety of the nuclear power plant (NPP). In this paper, the thermal hydraulics characteristics of the PRHR HX in the IRWST is analyzed using computational fluid dynamics (CFD). The tube region is modeled by the porous media approach along with the distributed resistance method. Heat transfer from the primary side fluid inside the tube to the secondary side fluid in the IRWST is considered. The simulation is carried out by the commercial CFD package FLUENT. The calculation of the flow resistance and heat transfer in the tube region is implemented using the User Defined Functions (UDF) in FLUENT based on the local flow conditions. Three dimensional distributions of the fluid velocity and temperature in the IRWST are obtained and thermal stratification is observed. The PRHR HX heat transfer capacity and the primary side fluid temperature distribution inside tubes are analyzed.

1. Introduction

The advanced passive safety nuclear power plant such as AP1000, adopts passive safety systems to protect the nuclear reactor. Passive safety systems depend on the natural phenomena like gravity, buoyancy, natural convection, and contain no pumps and rotational machines, which is much simpler than the traditional PWR safety systems. The passive residual heat removal (PRHR) system of AP1000 includes a passive residual heat removal heat exchanger (PRHR HX). The PRHR HX is a C-shape tube bundle heat exchanger immerged in the In-containment refueling water storage tank (IRWST). It is connected to one of the reactor primary loops and protects the reactor against accident transients such as steam generator (SG) feedwater line breaks and steam line breaks (Schulz, 2006). The IRWST is an irregular shape water tank and acts as the heat sink absorbing the core decay heat removed by the PRHR HX. Fig. 1 shows that the PRHR HX is located on one side of the IRWST. The thermal hydraulics performance of the PRHR HX in the IRWST has received much attention in recent years.

Many researchers have investigated the thermal hydraulic characteristics of the PRHR HX in the IRWST both experimentally and numerically, in order to better understand the performance of PRHR system in AP1000 nuclear power plant (NPP). In general, the experiments can be categorized into two types, which are integrated effect experiments and mechanism experiments. Integrated effect experiments are usually conducted on integral test facilities. Yonomoto et al. (1998) studied the heat transfer performance of the PRHR HX using the ROSA-V Large-Scale Test Facility (LSTF), which is designed for the support of the Westinghouse AP600 advanced passive reactor. In ROSA test, the IRWST was modeled by a cylinder tank with top surface open to the atmosphere. The PRHR HX was simulated by a 7 × 7 C-shape tube bundle. The heat transfer characteristics of the PRHR HX under the small-break loss-of-coolant accidents was analyzed. APEX (Advanced Plant Experiment) is another integral test facility, including a PRHR HX and an IRWST (Reyes and Hochreiter, 1998). The performance of PRHR HX decay heat removal was investigated at the "subsystem" level. Due to the huge size and complexity of the prototype NPP and PRHR HX, it is hard to conduct a full-scale experimental research. Therefore, almost all the integral test facilities are built as scaled down models. As for the mechanism experiments, they are focused on the local thermal hydraulics characteristics of the PRHR HX tube bundle. Men et al. (2014) studied heat transfer characteristics of a C-shape tube immerged in a water tank. The experimental data were compared with different correlations from published literatures. But only one C-shape tube was used in their experiment and the interaction effect of adjacent

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https://doi.org/10.1016/j.nucengdes.2017.11.029
Received 15 June 2017; Received in revised form 16 November 2017; Accepted 17 November 2017

Nomenclature

A_s	heat transfer area
D_e	equivalent hydraulic diameter
d	tube diameter
f	flow resistance coefficient
g	gravity
h	heat transfer coefficient
k	turbulent kinetic energy
l	flow distance
Nu	Nusselt number
p	pressure
Pr	Prandtl number
Ra	Rayleigh number
Re	Reynold number
S	source term
Str	thermal stratification number
E	fluid energy
T	temperature
t	time
$\vec{u}$	velocity vector
V	cell volume

Greek symbols

μ_{eff}	effective viscosity
γ	porosity
ε	energy dissipation rate
ρ	density
λ_{eff}	effective thermal conductivity

Subscripts

R	flow resistance
E	energy
a	axial flow
c	cross flow
i	inner side of the tube
o	outer side of the tube

tubes on the heat transfer characteristics was not considered. Lu et al. (2016) built a scaled down PRHR HX and IRWST model to study natural convection thermal hydraulics characteristics. The PHRH HX tube bundle contained 12 C-shape tubes. Fluid velocity field in the IRWST was qualitatively measured by the PIV technique and thermal stratification phenomenon was observed. Revised heat transfer correlations were proposed. Chun and Kang (1996) investigated the pool boiling heat transfer characteristics in a scaled down IRWST for both horizontal and vertical tubes. The effects of tube surface roughness and diameter on the pool boiling heat transfer were studied and empirical heat transfer correlations were proposed according to the experimental data.

Although the experimental studies can obtain reliable results, the limitations are obvious. Almost all the test facilities are scaled down models and whether the experimental data can be applied to the real size geometry remains to be discussed. In addition, the cost of the experiments is usually high and time consuming. Therefore, many researchers would like to adopt computational fluid dynamics (CFD) to simulate the fluid flow and heat transfer of the PRHR HX secondary side fluid in the IRWST. Strohecker (1998) numerically investigated the flow pattern in the IRWST during the station blackout transient based on the APEX test facility. The IRWST was modeled as a cylinder tank and four tubes were contained in the PRHR HX. Thermal stratification in the IRWST was predicted and a good agreement with the experimental data was obtained. Zhang et al. (2015) simulated the transient heat transfer of a C-shape rod bundle with 9 tubes included using the CFX software. Different Reynolds Average Navier-Stokes (RANS) turbulence models and Large Eddy Simulation (LES) model were examined. The simulation results were compared with the experimental data and the heat transfer mechanism was analyzed. The above researchers adopted the realistic

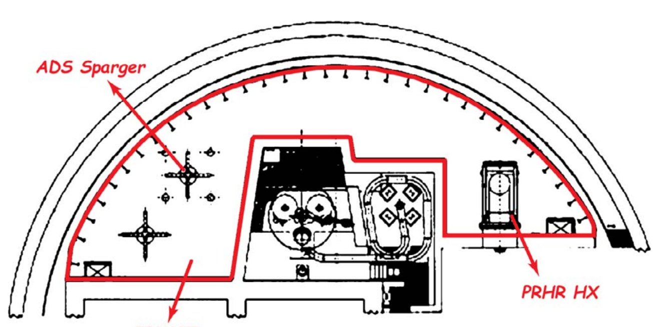

Fig. 1. Schematic of IRWST and PRHR HX.

modeling approach to build the PRHR HX, which means the heat transfer tubes are detailed represented in the geometry model. The realistic modeling approach is hard to be applied to the real size AP1000 PRHR HX, because the hundreds of heat transfer tubes require too many mesh elements and the high quality mesh generation is not practical. In addition, the required computation resource is also not affordable. Therefore, only a few heat transfer tubes were built in the above researchers' work. Some other researchers adopted the porous media approach to model the PRHR HX. Wright et al. (2006) developed a CFD code PRHRCFD to analyze the AP1000 PRHR HX and verify its operational performance. In PRHRCFD, the PRHR HX tube bundle containing 689 C-shape tubes was represented by porous media. The code was validated by the experimental data from the ROSA test. Both single phase and two phase operating conditions were evaluated. The computations were performed under steady state conditions.

In the present paper, a three dimensional thermal hydraulic transient simulation is performed using a full size AP1000 IRWST and PRHR HX model. The PRHR HX tube bundle is modeled by the porous media approach along with the distributed resistance. In the tube region, the heat transfer from the primary side fluid to the secondary side fluid is calculated by the empirical heat transfer correlations based on the local flow conditions. Three dimensional temperature and velocity fields of the fluid in the IRWST are obtained and thermal stratification is evaluated. In the present work, only single phase condition is considered which corresponds to the initial stage after actuation of the PRHR HX. The two phase flow regime is not considered herein. The simulation is carried out by the commercial CFD package FLUENT. In the following sections, the mathematical models and geometry model adopted in the simulation are described, respectively. Then, the calculation results are analyzed.

2. Mathematical model

2.1. Governing equations

The IRWST acts as the heat sink for the PRHR HX to absorb the decay heat from the reactor core. In the primary side, a natural circulation is established due to the pressure and density difference. The primary coolant is heated in the core and flows into the PRHR HX to cool down, then goes back to the primary loop through the associated steam generator outlet plenum and cold leg (Wang et al., 2012). For very small LOCA and non-LOCA accidents, the primary side fluid flow in the PRHR HX is single phase flow. In normal operating conditions,