Annals of Nuclear Energy 83 (2015) 147–160

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Numerical and experimental investigation on the transient heat transfer characteristics of C-shape rod bundles used in Passive Residual Heat Removal Heat Exchangers

Yuhao Zhang [a,b,*], Daogang Lu [a,b], Zheng Du [c], Xiaoliang Fu [c], Guanghao Wu [a,b]

[a] School of Nuclear Science and Engineering, North China Electric Power University, No. 2, Beinong Road, Beijing 102206, China
[b] Beijing Key Laboratory of Passive Safety Technology for Nuclear Energy, North China Electric Power University, Beijing 102206, China
[c] State Nuclear Power Software Development Center, Beijing 100029, China

ARTICLE INFO

Article history:
Received 27 November 2014
Received in revised form 13 April 2015
Accepted 16 April 2015
Available online 4 May 2015

Keywords:
Numerical simulation
Experimental validation
C-shape heating rod bundle
PRHR HX
IRWST
Turbulence models

ABSTRACT

The heat transfer effect of Passive Residual Heat Removal Heat Exchanger (PRHR HX) and buoyancy-induced flow in the In-containment Refueling Water Storage Tank (IRWST) are of great importance for the efficient and safe removal of the residual heat in the AP1000 reactor. Although some numerical studies have been conducted, only the standard k–ε model has been applied. Experimental validation of the simulation results was also not sufficient because of the lack of appropriate experimental data. In the present work, the applicability of different Reynolds Average Navier–Stokes (RANS) turbulence models and Large Eddy Simulation (LES) were examined, utilizing the commercial CFD software CFX 14.5. Further, two types of grids were built for the high/low-Reynolds turbulence models, and the y+ values as well as grids sensitivity were carefully analyzed. Meanwhile, overall scaled IRWST and PRHR HX models were built to simulate the thermal–hydraulic process in the residual heat removal accident, which was a new overall scaled separate effect IRWST&PRHR HX experiment. More than 150 thermocouples were utilized to measure the temperature in the key regions, and Particle Image Velocimetry (PIV) was utilized for the measurement of the flow velocity. Based on the validation of turbulence models in simulating the overall variations of temperature and velocity field in the IRWST model, the transient heat transfer capacity of PRHR HX was then analyzed. The results indicated that the low-Reynolds Shear Stress Transport (SST) model with multi-sublayer grid was appropriate for the simulation of buoyancy-induced flow. Nusselt numbers obtained from numerical simulations, experimental data, and empirical correlations were further compared to analyze the heat transfer mechanism. Combination factors including the special C-shape, flow resistance, and turbulent mixing effects imposed important influences on the heat transfer effects of the PRHR HX model. It was confirmed by numerical results, experimental data, as well as empirical correlations that the heat transfer capability of the vertical section was better than the horizontal section.

1. Introduction

In advanced passive pressurized water reactor (PWR) design, passive safety systems are widely implemented. Typically, the large special-shape tank, In-containment Refueling Water Storage Tank (IRWST), has been applied in the Generation III advanced nuclear power plant AP1000. The C-shape Passive Residual Heat Removal Heat Exchanger (PRHR HX) immerged in the IRWST is a critical component in the Passive Residual Heat Removal System (PRHRS). The PRHR HX connects through the inlet and outlet lines to Reactor Coolant System (RCS) loop 1 and locates above RCS loops. During the Station Blackout (SBO) accident or the Loss of Coolant Accident (LOCA), the PRHR will be actuated by density contrast between PRHR HX and RCS loop (Schulz, 2006). As a result, the core decay heat is removed continuously by natural circulation and transferred to the IRWST via the PRHR HX.

Since the thermal–hydraulic phenomena related to PRHR HX are complicated, and the dimensions of the prototype equipment are too large, it is almost impossible to conduct the full-scale experimental research. With the rapid development of computational fluid dynamics (CFD), numerical simulation has become an effective technique to investigate the heat transfer characteristics of different kinds of heating rods and exchangers (Tseng et al., 2014; Liu

* Corresponding author at: School of Nuclear Science and Engineering, North China Electric Power University, No. 2, Beinong Road, Beijing 102206, China.

http://dx.doi.org/10.1016/j.anucene.2015.04.022
0306-4549/

Nomenclature

c_p	specific heat of constant pressure (J/(kg K))
D_e	hydraulic diameter (m)
Er	relative error percentage (%)
g	gravitational acceleration (m/s^2)
Gr	Grashof number (–)
k	turbulence kinetic energy (J/kg)
L	length (m)
Nu	Nusselt number (–)
p	pressure (Pa)
Pr	Prandtl number (–)
q	heat flux (W/m^2)
q_v	volume heat source (W/m^3)
q_s	surface heat flux (W/m^2)
r	radial length (m)
R	radius (m)
Ra	Rayleigh number (–)
Re	Reynolds number (–)
$\bar{S}$	rate-of-strain tensor (s^{-1})
t	time (s)
T	temperature (K)
$\bar{u}$	averaged velocity component (m/s)
V	velocity (m/s)
x	any distance along the length of IRWST model tank (m)
x^*	normalized length (–)
X	total length of IRWST model tank (m)
y	any distance along the width of IRWST model tank (m)
y^*	normalized width (–)
Y	total width of IRWST model tank (m)
y^+	dimensionless distance from the wall (–)
z	axial length (m)
z^*	normalized height (–)

Greek symbols

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (K^{-1})
δ	Dirichlet function (–)
κ	von Kaman constant (–)
λ	thermal conductivity (W/(m K))
ρ	density of fluid (kg/m^3)
μ	dynamic viscosity (N s/m^2)
ν	kinematic viscosity (m^2/s)
τ	stress strain tensor (N/m^2)

Subscripts

0	initial value (or reference value)
ave	average value
i, j	tensor
m	model
p	prototype
r	value at the radial direction
R	ratio between the model and prototype
t	turbulent
z	value at the axial direction

Abbreviation

CCD	charge coupled device
CFD	computational fluid dynamics
DF	distortion factor
IRWST	In-containment Refueling Water Storage Tank
LES	Large Eddy Simulation
PIV	Particle Image Velocimetry
PRHR HX	Passive Residual Heat Removal Heat Exchanger
RANS	Reynolds Average Navier–Stokes
RNG	renormalization-group
SBO	station breakout accident
SST	shear stress transport

et al., 2012; Ikeda et al., 2006). In the previous researches, Pan (2010), Xue et al. (2010, 2012) and Ming and Wang (2003) employed the commercial CFD software FLUENT to simulate the thermal hydraulics phenomena related to PRHR HX. In the mentioned researches, major simplifications on the shape and arrangement of PRHR HX have been employed. Only the standard k-ε turbulence model was utilized in calculating the overall temperature-field and flow-field. However, experimental validation of the simulation results was not sufficient because of the lack of experimental data. In addition, Krepper et al. (2007) conducted CFD simulations to investigate the heat transfer capability of the emergency condenser in Economic Simplified Boiling Water Reactor (ESBWR), and the calculated results were validated by the experimental data. This research also contributed to a better understanding of the passive residual heat transfer process.

In the aspect of experiment, the Westinghouse Electric Corporation has performed PRHR HX separate effect experiment (Lin and Yu, 2008) for AP600, utilizing 3 vertical tubes to validate the heat transfer capability of the PRHR HX. However, the horizontal sections of PRHR HX were neglected, and big simplifications were conducted on the IRWST. However, the horizontal sections of the PRHR HX were further elongated in the actual design of the AP1000 reactor. As a result, the influence of the horizontal sections should be taken into consideration in the experiment. In addition, although some integral effect experiments such as APEX (Reyes et al., 2004; Jose and Hochreiter, 1998), ROSA (Takeda et al., 2009), etc. contained PRHR HX model equipment, attentions were mainly concentrated on the integral system functions, rather than the local heat transfer effect. Besides, Chun and Kang (1996) studied the effects of the heat exchanger tube geometries on heat transfer in a scaled tank using 3 straight heating rods. Various combinations of tube diameters, surface roughness, and tube orientation were discussed. Li et al. (2011) performed experiment on the heat transfer effect of vertical tube bundle immerged in an elevated tank during the initial operation stage of the PRHR HX. Gandhi et al. (2013) and Ganguli et al. (2010) conducted single heating tube experiment, and utilized CFD simulation to investigate the extent of stratification, the velocity distributions, and the turbulent parameters, etc.

In the present work, the transient heat transfer characteristics of the C-shape rod bundle model used in PRHR HX were investigated in depth by the commercial CFD software CFX 14.5. Meanwhile, an overall scaled special-shape IRWST model including the C-shape PRHR HX model has been built to investigate the thermal–hydraulic phenomena. The numerical results, experimental data, as well as the empirical correlations were employed for the heat transfer analysis of PRHR HX model.

2. Experimental set-up

2.1. Scaling analysis

In the experiment, the IRWST and PRHR HX were scaled down based on the scaling criteria obtained from dimensionless