International Journal of Heat and Mass Transfer 99 (2016) 53–64

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Numerical analysis on pressure distribution for sonic steam jet condensed into subcooled water

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ARTICLE INFO

Article history:
Received 5 December 2015
Received in revised form 18 March 2016
Accepted 19 March 2016

Keywords:
Condensation
Pressure distribution
Thermal hydraulic
Two phase flow
Stable steam jet

ABSTRACT

When steam with high velocity is injected into quiescent subcooled water through a sonic nozzle, the phenomenon that the total pressure along central axis at the tail of steam plume can be larger than the total pressure of steam inlet was observed in some experiments, but the reason is not clear till now because of the restriction of experimental method. It is very hard to obtain the static pressure, the velocity of water and steam, as well as the dynamic pressure of steam and water. To reveal the reason, three-dimensional steady simulation was carried out to study stable steam jet in subcooled water. A thermal equilibrium phase change model was inserted into Fluent as a user defined function (UDF) to model the DCC process. After the simulation model being validated, the effect of steam mass flux and water temperature on the shape of steam plume was studied, and the thermal hydraulic behavior along axial direction was investigated. Then the phenomenon that the total pressure at the tail of steam plume can be larger than that of steam inlet was also observed in the simulation result. It was found that the axial locations where the total pressure and the dynamic pressure of water reached the peak were the same, and the locations were all located at the tail of steam plume. The inference that the dynamic pressure of water resulted in the total pressure at the tail of steam plume larger than that of steam inlet was made. The inference was still valid under different steam pressures and water temperatures. Then the reason why the dynamic pressure of water was the largest at the tail of steam plume was also investigated.

1. Introduction

Because of high efficiency of heat and mass transfer, direct contact condensation (DCC) of steam in subcooled water is used in many industrial occasions, such as direct contact feed water heaters, steam jet pumps, injectors as well as nuclear reactor emergency core cooling systems, e.g., the pressure suppression system of Boiling Water Reactors (BWRs) and the rapid depressurization system of current Pressurized Water Reactors (PWRs), etc. [1]. It has attracted many researchers' attention in the past three decades.

Stable steam jet is one of common condensation patterns during the process of DCC, and it is the objective of this manuscript. For stable steam jet, its steam plume and parameter of flow field don't change over time, approximately, and much effort has been devoted to the study of stable steam jet. Kerney et al. [2] and Weimer et al. [3] studied both experimentally and theoretically the behavior of sonic steam jet in quiescent subcooled water, and developed correlations for predicting the penetration length of steam plume. Various flow regime maps were proposed by Chan et al. [4] and Petrovic et al. [5]. Chun et al. [6] observed three types of steam plume shapes for stable sonic steam jet, i.e., conical, ellipsoidal and divergent shapes, and reported that the shape of steam plume depended on steam mass flux and water subcooling. They also proposed empirical correlations for predicting the penetration length of steam plume and the average heat transfer coefficient. Conical and ellipsoidal shapes of stable steam plumes were also reported by other researchers, such as Kostyuk et al. [7], Del Tin et al. [8] and Kim et al. [9]. Wu et al. [10] experimentally investigated the condensation of supersonic steam jet submerged in quiescent subcooled water and reported that the steam plume shape was controlled by the steam exit pressure and water temperature, and six steam plume shapes were observed. Kim et al. [11] investigated the heat transfer occurring around a stable steam plume in subcooled water, and proposed three different models,

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.03.070
0017-9310/

Nomenclature

A_{fg}	interfacial area per unit volume, /m
d_g	steam bubble diameter, m
d_0	bubble diameter at subcooling θ_0, m
d_1	bubble diameter at subcooling θ_1, m
H_{fs}	saturation enthalpy of water phase, J/kg
H_{gs}	saturation enthalpy of steam phase, J/kg
h_f	heat transfer coefficient of water phase, W/m^2 K
m_{fg}	rate of mass transfer, kg/s
Nu_f	Nusselt number of water phase
P_{in}	pressure at the inlet of steam nozzle, kPa
P_s	static pressure, kPa
P_t	total pressure, kPa
P_b	ambient pressure of water tank, kPa
P_v	dynamic pressure of steam, kPa
P'_v	dynamic pressure of steam concerning the void fraction of steam, kPa
P_w	dynamic pressure of water, kPa
P'_w	dynamic pressure of water concerning the void fraction of water, kPa
Pr	Prandtl number
Q_f	total heat flux from the interface to water phase, W/m^2
Q_g	total heat flux from steam phase to the interface, W/m^2
q_f	sensible heat flux from interface to water phase, W/m^2
T_{in}	temperature of steam at the inlet of steam nozzle, °C
T_s	temperature of steam along axial direction, °C
T_f	water temperature in a cell, °C
T_{sa}	saturation temperature, °C
T_w	water temperature in tank, °C
V_g	velocity of steam, m/s
V_w	velocity of water, m/s
X	distance along x axis from nozzle inlet, m
Xe	distance along x axis from nozzle exit, m
Void-w	void fraction of water phase
P_{peak}	peak of dynamic pressure of water, kPa

Greek letters

ρ	density of steam, kg/m^3
α	void fraction of steam phase
θ	degree of water subcooling, °C

i.e., the interfacial transport model based on turbulent intensity, the surface renewal model and the shear stress model to calculate heat transfer coefficient.

Flow field parameter during the process of stable steam jet in subcooled water has been measured by some researchers. The axial and radial temperature distributions were studied by Kim et al. [9] experimentally. In his experiment, when the steam mass flux was relatively low, the axial temperature decayed to the ambient water temperature, however, when steam mass flux was relatively high, the axial temperature decreased first, then undergone a peak, and decayed to the ambient water temperature finally. The distribution characteristic of total pressure along the axial direction was measured by Wu et al. [12] with a Pitot tube probe. They found that the total pressure at some axial locations can be larger than the total pressure of the steam inlet, and the maximum of total pressure nearly located at the tail of steam plume. Similar total pressure distribution was observed in Del Tin's experiment [8].

Although a large number of theoretical and experimental studies have been conducted, the DCC process is rather complex which refers to massive phase change, highly turbulent, compressible and the existence of expansion and compression wave. Consequently, there are some problems not well understood till now. The detailed information about the flow and heat transfer characteristic in the field, especially the region of steam plume, can give us a better understanding about the process of DCC. However, the details, such as steam void fraction, velocity, pressure and so on, are very hard to obtain from experiment owing to the restriction of measurement method. Fortunately, in addition to experimental method, Computational Fluid Dynamic (CFD) simulation is also a useful way to investigate the phenomenon of DCC with the development of computer science.

Gulawani et al. [13] first carried out three-dimensional CFD simulations to study the DCC phenomenon using a thermal phase change model with commercial code CFX. Parameters such as the penetration length of steam plume, radial and axial temperature distributions as well as heat transfer coefficient were studied. Shah et al. [14–16] investigated the supersonic steam jet in subcooled water and steam jet pumps using commercial CFD software Fluent 6.3, and the simulation results were in fairly good agreement with experimental data. Patel et al. [17] carried out CFD simulations of DCC at a very low steam mass flux using NEPTUNE_CFD and OpenFOAM. Two DCC models based on the surface renewal and the surface divergence theories were used to model the interfacial heat transfer between steam and water. The results of surface renewal model showed larger condensation rate than that of actual DCC process. The simulation results of surface divergence model were relatively accurate. In order to investigate the chugging flow during DCC in BWR suppression pools, Tanskanen et al. [18] performed CFD simulation by NEPTUNE_CFD software with two-dimensional method. Hughes–Duffey model was adopted in the simulation to calculate the heat transfer coefficient between steam and water. Li et al. [19] conducted the simulation of chugging flow with VOF multiphase model and LES turbulence model with unsteady method, and compared the simulation results with experimental work by Chan and Lee [4].

By summarizing the research previous, although the phenomenon that the total pressure at the tail of steam plume is larger than that of the steam inlet has been observed by many researchers [8,12] for some years, the reason is still not clear, whether it is from the aspect of experiment method or simulation way. As for experimental work, the details in steam plume and two phase region are hard to obtain. When it comes to numerical simulation, little numerical work has been devoted to the issue. However, the mechanism is very important to the understanding of flow and heat transfer characteristic of DCC process, as well as the design of related DCC equipment, thus it is particularly worthy of academic investigation.

To reveal the reason why the total pressure at the tail of steam plume can be larger than that of steam inlet of stable steam jet, numerical studies were carried out to investigate sonic steam jet in this paper. At first, simulation results were compared with published experimental results to testify the validity of simulation. Then the effect of steam pressure and water temperature on the shape of steam plume was studied. Moreover, the thermal hydraulic behavior along the axial direction was investigated, and the phenomenon that the total pressure at the tail of steam plume was larger than the total pressure of steam inlet was also observed in simulation result. Then the inference that it was the dynamic pressure of water that results in the total pressure at the tail of steam plume larger than that of steam inlet was made by analyzing