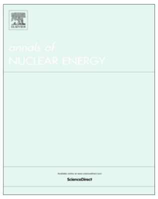
ARTICLE IN PRESS

Annals of Nuclear Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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



Numerical study on flow pattern of sonic steam jet condensed into subcooled water

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ARTICLE INFO

Article history:
Received 24 April 2016
Received in revised form 13 July 2016
Accepted 28 August 2016
Available online xxxx

Keywords:
Steam condensation
Submerged jet
Flow characteristic
Flow pattern

ABSTRACT

For stable sonic steam jet, conical and ellipsoidal steam plumes were observed by many researchers. Restricted by experimental method, the difference in flow and heat transfer characteristic between conical and ellipsoidal steam plumes was still unclear. To reveal the difference between the two kinds of steam plumes, three-dimensional steady numerical simulations were carried out with Eulerian multiphase model, and a thermal equilibrium phase change model was inserted into Fluent as a user defined function (UDF) to investigate the condensation phenomenon. The CFD results were compared with experimental results to testify the correctness of simulation, and good agreement was observed. Then steam pressure was varied to study its effect on the process of condensation jet. Conical and ellipsoidal steam plumes were obtained under different operating conditions. For conical steam plume, it is compressed near nozzle exit along radial direction, and the pressure in steam plume is larger than ambient pressure. However, when it comes to ellipsoidal steam plume, it expands near the nozzle exit along radial direction, when steam plume expands to the maximum extend, the pressure in steam plume is reaching the bottom, almost the same as ambient pressure. Besides, the influence of flow characteristic of steam in plume on axial temperature and steam plume shape was analyzed. When steam in plume reaches supersonic, the shape of steam plume shows ellipsoidal shape, and there is a peak along axial temperature distribution. Otherwise, it presents conical shape and axial temperature decays to ambient water temperature monotonously.

1. Introduction

Direct contact condensation (DCC) is a typical condensation phenomenon. Compared with film condensation and drop condensation, DCC has much larger capacity of heat and mass transfer, having widely existed in many engineering applications, such as steam jet injectors, direct contact feed water heaters, underwater propulsion systems and nuclear reactor emergency core cooling systems (Wu et al., 2007). As a result, much effort has been devoted to the research of DCC.

According to operating conditions, condensation pattern of steam injecting into subcooled water can be divided into stable jet and unsteady jet (Chan and Lee, 1982). Regime maps for DCC were studied by many researchers (Chan and Lee, 1982; Cho S, et al., 1998; Petrovic de With et al., 2007; Wu et al., 2009b). To be specific, seven flow patterns, including chugging, transient chugging, condensation oscillation, stable condensation jet, bubble condensation oscillation, interface condensation oscillation and no condensation, were observed (Cho et al., 1998). When stable steam jet occurs, there exists a stable steam region, called as steam plume. For stable steam jet, its shape doesn't change over time, approximately. The shape of steam plume for stable steam jet is significant to the study of steam jet. With regard to sonic steam jet, conical and ellipsoidal steam plume shapes were observed (Kostyuk V.I, 1985; Tin et al., 1983; Chun et al., 1996; Kim et al., 2001). When it comes to supersonic steam jet, six types of steam plume shapes were observed in Wu's work (Wu et al., 2007). To describe the size of steam plume, dimensionless penetrating length and the maximum expansion ratio was proposed (Wu et al., 2007). Some empirical correlations predicting the penetrating length were established by many researchers (Chun et al., 1996; Kerney et al., 1982; Kim et al., 2001; Weimer et al., 1973; Wu et al., 2007). The maximum expansion ratio of steam plume was studied (Kim et al., 2004; Song et al., 2000). Moreover, flow field parameter, such as total pressure or temperature has been measured (Kim et al., 2001; Wu et al., 2009a, 2010). Besides, the heat transfer

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http://dx.doi.org/10.1016/j.anucene.2016.08.024
0306-4549/

Please cite this article in press as: Zhou, L., et al. Numerical study on flow pattern of sonic steam jet condensed into subcooled water. Ann. Nucl. Energy (2016), http://dx.doi.org/10.1016/j.anucene.2016.08.024

Nomenclature

A_{fg}	interfacial area per unit volume, /m
d_g	steam bubble diameter, m
d_{ex}	maximum diameter of steam plume, m
d_e	the diameter of nozzle exit, m
d_0	bubble diameter at subcooling θ_0, m
d_1	bubble diameter at subcooling θ_1, m
G_s	steam mass flux at nozzle exit, kg/m^2 s
H_{fs}	saturation enthalpy of liquid phase, J/kg
H_{gs}	saturation enthalpy of vapor phase, J/kg
h_f	heat transfer of liquid phase, W/m^2 K
H_f	volumetric heat transfer coefficient of liquid phase, W/m^3 K
k	adiabatic exponent of steam
k_f	thermal conductivity of liquid phase, W/m K
m_{fg}	rate of mass transfer, kg/s
N_{uf}	Nusselt number of liquid phase
P	static pressure, kPa
P_b	ambient pressure, kPa
P_r	Prandtl number
P_t	Total pressure at steam nozzle inlet, kPa
Q_f	total heat flux from liquid phase to the interface, W/m^2
Q_g	total heat flux from vapor phase to the interface, W/m^2
q_f	sensible heat flux from liquid phase to the interface, W/m^2
R	molar gas constant, J/kg K
r	radial distance from central axis, m
Re_r	relative Reynolds number between steam and water
T	axial temperature distribution, °C
T_f	liquid temperature, °C
T_d	dynamic temperature, °C
T_s	saturation temperature, °C
T_w	temperature of subcooled water at water inlet, °C
V	velocity, m/s
X	axial distance from nozzle inlet, m
X_e	axial length from nozzle exit, m
Greek letters	
α_g	void fraction of vapor phase
θ	degree of liquid subcooling, °C

characteristic of steam jet was also studied (Chun et al., 1996; Simpson and Chan, 1982; Wu et al., 2009a). However, the existence of measuring probe may destroy the flow and temperature field. Besides, it is also hard to fix the measuring point due to the strong impact of high speed steam, making it rather difficult to obtain accurate detail in steam plume and two phase flow region. It will lead to an obstacle for a deeper understanding of stable steam jet. Fortunately, with the development of computer science, Computational Fluid Dynamics (CFD) simulation is also a useful way to reveal the internal detail in steam jet without destroying the flow field.

Three-dimensional CFD simulations to study DCC phenomenon by commercial code CFX was first conducted (Gulawani et al., 2006). Shah et al. (2010, 2011, 2013a) investigated the DCC process of supersonic steam jet in subcooled water and steam jet pumps, and the simulation results matched well with experimental data. Numerical work on sonic steam jet was also conducted by Zhou et.al, the pressure distribution characteristic along axil direction was analyzed, and it was found that the dynamic pressure of water resulted in the peak of total pressure at the tail of steam plume (Zhou et al., 2016). Steam condensed into subcooled water with air involved was simulated by Qu et al. (2015, 2016), and they found that the existence of air in steam deteriorates the condensation heat transfer. By means of NEPTUNE_CFD and OpenFOAM, CFD simulation of DCC at a very low steam mass flux was carried out (Patel et al., 2014). 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 more accurate. Tanskanen et al. (2014) performed CFD simulation to study the chugging flow during DCC in boiling water reactor (BWR) suppression pool with two-dimensional method. Li et al. (2015b) 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 (Chan and Lee, 1982). Then, the process of steam discharged into subcooled water flow in a tee junction was studied (Li et al., 2015a).

As for numerical work on stable steam jet, because the steam is of high velocity, there may exist expansion and compression wave. Besides, the flow is of high turbulence, leading to violent condensation, and the heat transfer coefficients can reach the level of 1.0 M W/m^2 K. They all increase the difficulty of simulation. Although some numerical work has been reported in some literature (Gulawani et al., 2006; Shah et al., 2010, 2011, 2013b; Zhou et al., 2016), little work has been devoted to revealing the difference in the flow and heat transfer characteristic between conical and ellipsoidal steam plumes in sonic steam jet. Meanwhile, conical and ellipsoidal steam plumes were observed in many experiments for years, the difference between conical and ellipsoidal steam plume was not clear till now. However, the difference between conical and ellipsoidal steam plumes is significant to the understanding of internal flow mechanism of sonic steam jet during the process of DCC, which will be helpful to the design and safe operation of related DCC equipment. To reveal the internal difference between conical and ellipsoidal steam plume in sonic steam jet, numerical work was conducted in this manuscript.

2. Physical problem and numerical method

2.1. Physical model

Stable steam jet is a common condensation pattern among steam jet of DCC process. As for stable sonic steam jet submerged in a quiescent water pool, two types of stable steam plumes, including conical and ellipsoidal steam shape, were observed by many researchers (Chun et al., 1996; Kostyuk, 1985; Kim et al., 2001; Tin et al., 1983). Among them, typical experimental work studying the flow pattern of stable steam jet was conducted by Kim et al. (2001). In his experiment, saturated steam was injected into a water pool from a straight nozzle, then DCC phenomenon occurs. Two typical steam plume shapes could be observed depending on the operating conditions, as shown in Fig. 1. When G_s = 280 and 600 kg/m^2 s with T_w = 40 °C, the steam plume shows conical and ellipsoidal shape, respectively.

To reveal the internal mechanism and difference between conical and ellipsoidal steam plume, numerical work was conducted

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