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Numerical investigation on flow characteristic of supersonic steam jet condensed into a water pool

Lun Zhou [a], Weixiong Chen [b], Daotong Chong [b], Jiping Liu [a,*], Junjie Yan [b]

[a] MOE Key Laboratory of Thermal Fluid Science and Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China
[b] State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China

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ABSTRACT

Three-dimensional steady method was employed to simulate the process of stable supersonic steam jet condensed into a water pool. A thermal equilibrium phase change model was inserted into Ansys as a user defined function to simulate the condensation process. To testify the correctness of simulation model, steam plume and radial temperature distribution were compared between experiment and simulation. Then four kinds of steam plume shapes, including contraction, expansion-contraction, double-expansion-contraction, and contraction-expansion-contraction shapes, were observed from numerical results as experimental results indicated. Combined with the corresponding contours of steam void fraction, the distribution of axial thermodynamic parameters, such as pressure, temperature and velocity were analyzed for each kind of steam plume. The theory of expansion and compression wave was employed to explain the flow mechanism in each kind of steam plume.

1. Introduction

When steam is injected into subcooled water, direct contact condensation (DCC) occurs. Because the violent transfer of mass and momentum across the phasic interface greatly enhances the heat transfer capacity of DCC, it has been widely used in many industrial occasions, such as safety depressurization system, negative water supply system in advanced pressurized-water reactor, feed water system of boiling water reactor, steam jet pump and mixing-type heat exchanger, etc [1].

It was found that operating conditions, such as steam mass flux, water temperature, configuration of nozzle and water flowing condition have a great influence on the flow pattern of DCC [2,3]. Condensation regime maps describing the flow pattern during the submerged jet into a water pool have been investigated by many researchers [2–5]. To be specific, seven types of flow patterns, including chugging, transient chugging, condensation oscillation, stable condensation jet, bubble condensation oscillation, interface condensation oscillation and no condensation, were observed [5]. When the velocity of steam leaving the nozzle exit is relatively high, steam can remain a good flow characteristic, and flow pattern shows steady characteristic under a lot of operating conditions. Stable condensation jet, as one kind of typical flow pattern, has drawn much attention, during which the shape of steam plume remains unchanged, approximately. Detailed investigation on stable condensation jet will be illustrated from the aspects of experiment and simulation, respectively.

According to the configuration of steam nozzle, stable condensation jet can be classified into sonic steam jet and supersonic steam jet [3]. A continuous and fixed steam region called as steam plume can be formed and there exists a stable phasic interface. Sonic condensation jet has been experimentally investigated by many researchers. Contraction and expansion-contraction shapes of steam plume were observed [6–8] for stable sonic steam jet. Condensation regime maps for sonic condensation jet has been established by some researchers [3,5,9]. When it comes to stable supersonic steam jet submerged into a water pool, it was only experimentally studied by few researchers [10–12]. Only two sets of penetrating length of steam plume was given by Kerney and Olson [12]. Much experimental work was conducted by Wu et al. [10,11]. It was found that the pressure of steam at the nozzle exit and water temperature have a great influence on the shape of steam plume. Compared with sonic steam jet, supersonic steam jet shows more complex flow characteristic. Apart from contraction and expansion-contraction steam plumes which have been observed in stable sonic steam jet, some new shapes of steam plumes including double-expansion–contraction, and contrac tion-expansion-contraction shapes were also observed [3,10]

* Corresponding author.
E-mail addresses: zl3112009010@stu.xjtu.edu.cn (L. Zhou), chenweixiong@mail.xjtu.edu.cn (W. Chen), dtchong@mail.xjtu.edu.cn (D. Chong), liujp@mail.xjtu.edu.cn (J. Liu), yanjj@mail.xjtu.edu.cn (J. Yan).

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Nomenclature

A_{fg}	interfacial area per unit volume, /m
d_g	steam bubble diameter, m
d_e	nozzle diameter at the outlet, m
d_0	bubble diameter at subcooling θ_0, m
d_1	bubble diameter at subcooling θ_1, m
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_f	thermal conductivity of liquid phase, W/m K
m_{fg}	rate of mass transfer, kg/s
m_s	steam mass flow rate, kg/s
N_{uf}	Nusselt number of liquid phase
P	static pressure, kPa
P_{in}	static pressure at steam inlet, kPa
P_r	Prandtl number
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
Re_r	relative Reynolds number between steam and water
T	static temperature, °C
T_f	liquid temperature, °C
T_s	saturation temperature, °C
T_w	temperature of subcooled water at water inlet, °C
X	axial distance from nozzle inlet, m
X_e	axial distance from nozzle exit, m
V	velocity, m/s

Greek letters

α_g	void fraction of vapor phase
θ	degree of liquid subcooling, °C

during stable supersonic steam jet. Additionally, a three-dimensional condensation regime map considering steam mass flux, water temperature and pressure ratio was also presented [3].

As for the study of steam condensation jet in a water pool, the main research tools mainly depend on high speed camera and measuring probe. High speed camera can record the flow pattern of the condensation jet near the nozzle exit. Temperature distribution can be obtained from the measuring probes. However, the velocity of steam in plume is relatively large, which can reach supersonic for stable steam jet. On one hand, it is hard for the probes to be fixed in steam plume owing to the strong impact of steam. On the other hand, detached shocked wave may generate owing to the existence of measurement probe in supersonic flow field, making it rather difficult to obtain accurate detail about the flow field. But, the internal flow detail is very important for a comprehensive understanding on the flow mechanism in steam plume during supersonic steam jet. Consequently, it is necessary to reveal the flow detail in steam plume by means of numerical method.

The condensation jet can be classified into stable jet and unsteady jet. When it comes to numerical work on unsteady condensation jet, some effort has been devoted to the condensation of chugging flow at relatively low mass fluxes [13–17]. They mainly focus on the dynamic characteristic, and little flow detail in steam plume was revealed. To ensure the convergence and save time for calculation, their numerical models mainly based on VOF multiphase model [13,14], 2D axisymmetric flow [15,16] or condensation model neglecting local flowing detail [17].

Compared with chugging flow, stable steam jet mainly appears at relatively high steam mass fluxes. The velocity of steam at the nozzle exit is relatively high, as a result, the condensation process is more violent and condensation rate is larger. Because steam plume can maintain its shape, the internal detail in steam plume is the main objective of research, which needs more information about the detail. Eulerian-Eulerian multiphase model is a two-fluid multiphase model, which solves the continuity, momentum and energy conservation equation for each phase. Current numerical study on stable stem jet was enumerated as follow. Three-dimensional CFD simulation to study sonic stable condensation jet was firstly conducted by Gulawani et al. [18], a thermal phase change model was inserted into commercial code CFX. Then steam plume shape and heat transfer coefficients were investigated, however, the expansion and compression wave was not obtained in their numerical results. When it comes to numerical investigation on supersonic steam jet submerged in a water pool, it is rather sparse. Numerical simulation on supersonic steam jet was only conducted by Shah et al. [19]. In his work, penetrating length of steam plume and average heat transfer coefficient were studied. Although the phenomenon that the steam plume of supersonic condensation jet presents different shapes under different operating conditions has been observed for years, however, four types of shapes of steam plume were not obtained. As different shapes of steam plume results from the difference in flow characteristic in steam plume, new numerical model needs to be employed to simulate the process and more details in steam plume were needed to reveal the flow characteristic in supersonic condensation jet. Given this circumstance, supersonic steam jet was simulated by means of improved numerical model. This paper aims at revealing the different flow mechanisms in different shapes of steam plume during stable supersonic steam jet.

2. Physical problem

With regard to supersonic steam jet, experimental work on steam plume shape was conducted by Wu et.al [3]. The sketch of experimental rig and dimension of supersonic nozzle are shown in Fig. 1 and Fig. 2, respectively. Experimental system mainly consists of an electric steam generator, a surge tank, a water vessel and some valves. Saturated steam is injected into a subcooled water pool through a supersonic nozzle, then the process of DCC occurs. The shape of steam plume was taken by a high speed camera. The dimension of cuboid water pool is 3000 mm × 1000 mm × 1200 mm.

Six types of steam plume shapes, including contraction, expansion-contraction, double-expansion–contraction, double-expansion-emanative, contraction–expansion–contraction, and contraction-expansion-emanative shapes, were observed in supersonic jetting flow. They are shown in Fig. 3. However, it is unsteady for some operating conditions. As for emanative steam plume when water temperature is relatively high, including double-expansion-emanative and contraction-expansion-emanative shapes, their phasic interfaces of steam-water two phases would become oscillating drastically [10], showing obviously unsteady characteristic. As steady numerical method was used, unsteady emanative shapes of steam plume are not in the scope of this paper. This paper mainly focuses on the four kinds of supersonic condensation jet showing obvious steady characteristic, i.e., contraction, expansion-contraction, double-expansion–contraction,