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Experimental study on spray flash evaporation under high temperature and pressure

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ABSTRACT

Most leakage problems from pipe system breaches result in the formation of spray flash evaporation. In this study, a variety of experiments were carried out in the high temperature and high pressure (HTHP) steam-water test loop to study spray flash evaporation related to tube leakage problems. The focus of our study was on the flash evaporation from the highly superheated jet (the superheat degree can be up to 200 K) with a small injection rate. The temperature and relative humidity variations in the region of interest were measured in the experiment. As the transient relative humidity changes can enable better reflection of the characteristic of flash evaporation, non-dimensional relative humidity (NDRH) and the critical time of the relative humidity variation was proposed and used to analyze the flash evaporation. The effects of injection rate, injection direction, initial water temperature, and injection pressure were investigated. The experimental results showed that the increase of the injection rate and initial water temperature enhanced the flash evaporation. The corresponding critical time increased with the increase of spray angle. The injection pressure was found to result in better atomization and evaporation of the water on the premise that the injection pressure guaranteed complete flash evaporation.

1. Introduction

Pipelines, including the pressurizer surge line and main pipe, etc., are widely used in nuclear power plants. These pipes are easily subjected to thermal stratification due to non-uniform temperature distribution and thermal fatigue due to uneven distribution or concentration of stress. All such damage can bring about pipe leakage, characterized by the sudden drop of pressure for fluids. In fact, most leakage problems from pipe system breaches result in the formation of spray flash evaporation [1] in nuclear power plants. Therefore, in order to decrease avoidable losses due to pipe leakage, it is crucial to study spray flash evaporation related to pipe leakage problems.

Compared with simple evaporation, both the efficiency and the intensity of flash evaporation are quite high. Flash evaporation can be found in a number of fields. For example, flash evaporation is widely used in the desalination of sea water [2], with its significant performance on mass transfer and separation. As flash evaporation can lead to a significant temperature drop due to a sudden phase change, it can be used in the cooling of electronic components and hot parts of the shuttle [3,4]. Other than these advantages, flash evaporation can be found in some leakage problems, which can affect normal operation. Flash evaporation has attracted much attention from a significant number of researchers, both at home and abroad.

Flash evaporation is comprised of two main types: one is static flash evaporation including pool flash evaporation and liquid film flash evaporation, and the other is spray flash evaporation, characterized by the flash evaporation of fluids. Most researchers such as Miyatake [5,6], Gopalakrishna [7], Saury [8,9], Kim [10], Jin [11,12], Liu [13], Zhang [14–16], Augusto [17], Yang [18], Zhang [19] et al. have focused on static evaporation.

Spray flash evaporation is of interest to some researchers. Miyatake et al. [20,21] did preliminary researches on spray flash evaporation. They conducted an experimental study on a flashing jet in a low-pressure vapor zone with the jet inlet temperature of 333 K. They mainly obtained an empirical equation for predicting the liquid temperature variation over residence time based on the experimental results. At the same time, they concluded that the evaporation performance and the evaporation rate of the spray flash evaporation were higher than that of the flash evaporation emerging in other systems. Ikegami et al. [22] experimentally investigated the influence of injection direction on the spray flash desalination process with a superheated jet at 297 K, 303 K and 313 K. Their results showed that the upward jet method needed

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Nomenclature

Symbols

RH	relative humidity, %
C_p	specific heat of liquid, J/kg K
T	temperature, K
t	time, s
z	distance, m
u	flow velocity, m/s
h_{fg}	latent heat, J/kg
P	pressure, Pa
q	injection rate, kg/s
T_0	initial water temperature, K
L	distance between molecules, m
v	specific volume, m^3/kg
M	molar mass, kg/mol
N_A	Avogadro's number
d	diameter of nozzle, m
r	radius of bubble, m
A	area, m^2

Greek

ρ	density, kg/m^3
μ	dynamic viscosity,$N \cdot s/m^2$
σ	surface tension, N/m
ΔP	pressure difference, Pa
ΔT	temperature difference, K

Subscripts

cr	critical
f	feed water
in	injection
sat	saturation
sup	superheat
v	vapor
l	liquid
IB	inner bubble

a shorter distance to complete the flash evaporation than the downward jet method. El-Fiqi et al. [23] carried out a series of experiments, with the inlet temperature ranging between 313 K and 343 K, vacuum ranging from 60 to 250 mbar, and feed flow rate ranging between 4 and 15 kg/h. They found that with the increment of the superheat degree, the flash efficiency first increased and then remained constant. Different from the relation between the flash efficiency and superheat degree, the flashed vapor presented an increase proportional to the superheat degree. Mutair et al. [24,25] conducted experiments with the superheat degree from 2 to 13 K and initial temperature between 297 K and 313 K. They focused on the effects of influencing factors including flow velocity, initial temperature, superheat degree and injection nozzle diameter on the intensity of the flash evaporation along the vertical distance by means of analyzing the inflection point of the Boltzmann sigmoid curve. Furthermore, Balaji et al. [26] investigated the spray flash evaporation of the low temperature thermal desalination (LTTD) process. The effects of nozzle geometries typical of different heights on the flash evaporation rate as well as on the non-equilibrium temperature difference (NETD) were discussed. In addition, they compared the experimental results of flash evaporation with two mathematical models from [27,28,23]. They found that the model from [27,28] presented a better agreement with the experimental results. They also compared the flash efficiency from the experiment with that calculated using correlations suggested by Faisal Al-Juwayhel et al. [29] and Miyatake et al. [30]. As the residence time of the splashed water exposed to the vacuum zone was insufficient, the predicted flash efficiency was greater than the experimental value. Ji et al. [31] experimentally studied spray flash evaporation with initial temperature from 408 K to 423 K and the corresponding superheat degree from 30 K to 46 K. They focused on the effects of influencing factors including initial temperature, saturation pressure and injection direction (upward jet and downward jet) on the amount of generated vapor. The empirical equation between flash efficiency and the superheat degree was proposed.

From the review of flash evaporation introduced above and the key parameters in previous studies on spray flash evaporation summarized in Table 1, two important points can be obtained. On one hand, the emphasis of most researchers was on the investigation and analysis of static flash evaporation with water in a fixed container. The study of spray flash evaporation with higher evaporation performance than that of static flash evaporation was limited. On the other hand, it can be concluded from Table 1 that the initial feed water temperature was relatively low for the analysis of spray flash evaporation in the previous literature. At the same time, most of the work in the literature concerning flash evaporation was done on low superheated liquids with relatively low injection pressure. However, the working fluid was under high temperature and high pressure in the reactor coolant system (RCS). In addition, few researchers applied relative humidity variations to study spray flash evaporation. In our study, the experiment was carried out under high temperature and high pressure. The flash evaporation from highly superheated jets with small diameter and high initial water temperature was investigated. The relative humidity and temperature distributions which reflect the performance of spray flash evaporation were extracted and analyzed by means of temperature and humidity (T&H) detectors with high sensitivity. The effects of influencing factors such as the injection rate of the feed water, injection direction, initial fluid temperature and injection pressure were also investigated.

Table 1
Main parameters in former researches.

Authors	q (kg/s)	T_0 (K)	P_{in} (MPa)	ΔT_{sup} (K)	d (mm)	u (m/s)
Miyatake [20]	–	333	–	0–21.9	3.46–8.15	5.92–13.8
Miyatake [21]	–	313,353	–	0–21.9	3.4–8.15	5.77–14.1
Ikegami [22]	–	297,303,313	–	2.5–12.5	20	1.74–3.62
El-Fiqi [23]	0.0011–0.0042	313–343	0.6	2–18	0.4	–
Mutair [24,25]	–	297–313	–	2–13	54.4–107	0.8–3.56
Balaji [26]	110–190	–	0.017	3.5–10	–	–
Muthunayagam [27]	–	299–305	0.1–0.4	–	300	–
Miyatake [30]	0.008–0.058	363–393	–	0–80	1.99–4.01	–
Ji [31]	2.78–5.56	408–423	–	30–46	–	–