Experimental study on evolutions of temperature and height of waterfilm during static flash

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ABSTRACT

The temperature and height of waterfilm were a pair of coupled characteristic parameters indicating the instant heat/mass transfer during static film flash of pure water. Their evolutions and interactions were studied through experiments with initial height of waterfilm ranging between 0.15 and 0.3 m, initial temperature between 80.2 and 93.0 ℃, initial pressure of vacuum chamber between 0.013 and 0.061 MPa. Results suggested both height and decrease rate of temperature of waterfilm experienced a rapid increase to peak value and a gradual decline after that. Considering most of heat transfer happened within waterfilm, volumetric evaporation coefficient was introduced as the total heat flux transferred through all bubble interfaces within unit volume of waterfilm under unit superheat. This coefficient increased significantly with rising volumetric void fraction of waterfilm. Except vapor generation, mass transfer during static flash also included the overflowing of vapor. Its overflowing speed increased with initial height of waterfilm. According to these results, a model was set up to calculate the evolutions of temperature and height of waterfilm from given evolution of saturation temperature corresponding to the pressure of flash chamber.

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1. Introduction

Flash stands for sudden evaporation of liquid when its pressure drops below the saturation pressure corresponding to its temperature. During flash, the liquid temperature decreases. The superheated liquid gradually reaches a new equilibrium state.

Flash has lots of applications due to its good performance on heat transfer and separation. Its heat-transfer use mainly includes flash cooling [1,2], steam generation [3,4]. Its separation use includes desalination [5,6,7,8], concentrating of dilute solution [9,10], desiccation [11], thin film deposition [12] and so on. Flash could be classified in different ways. According to whether the liquid has macroscopic velocity, it can be classified into dynamic flash and static flash. According to the shape of superheated liquid, it could be classified into droplet flash, film flash and spray flash.

As the most basic form, static film flash was always used as the prototype to examine flash's mechanism. Miyatake et al. [13,14] studied static film flash of pure water with superheat between 3 and 5 K. Results showed that the waterfilm temperature (t_l) decreased rapidly at beginning, but the decrease rate gradually declined (Fig. 1). It suggested the energy release during flash was

not uniform. Thus, the process of static film flash was divided into fast evaporation stage and gradual evaporation stage. They defined the duration of fast evaporation stage as flash time (τ_{tp}), during which most of heat/mass transfer was supposed to be accomplished. Besides, they also suggested the saturation temperature (t_{se}) corresponding to final equilibrium pressure of flash chamber (p_{fe}) as theoretical equilibrium temperature, and defined the superheat, or the driving force for flash [15] as the difference between initial waterfilm temperature (t_{l0}) and t_{se} (Eq. (1), Fig. 1). In order to compare the completeness degree of different flashes, they nondimensionalized waterfilm temperature into non-equilibrium fraction (*NEF*) as Eq. (2), and examined its dependence on superheat, initial temperature/height of waterfilm. At last, an empirical formula to estimate *NEF* at the end of flash time (*NEF*$_{tp}$) was proposed.

$$\Delta T = t_{l0} - t_s(p_{fe}) \tag{1}$$

$$NEF = \frac{t(\tau) - t_s(p_{fe})}{t_{l0} - t_s(p_{fe})} = \frac{t(\tau) - t_s(p_{fe})}{\Delta T} \tag{2}$$

Gopalakrishna et al. [16] studied the total evaporated mass during static film flash of aqueous NaCl solution with concentration between 0 and 0.035 (mass fraction), and proposed an empirical formula for it. J Kim and N Lior et al. [17] examined static film flash

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Nomenclature

A_f	cross section of flash chamber (m^2)
A_i	total area of bubble interface (m^2)
c_m	distribution density of vapor within waterfilm ($kg\,m^{-3}$)
c_p	specific heat ($kJ\,kg^{-1}\,K^{-1}$)
FS	flash speed (s^{-1})
h_{fg}	latent heat of vapor ($kJ\,kg^{-1}$)
H_{fo}	height of waterfilm (m)
k_f	heat transfer coefficient at bubble interface ($kW\,m^{-2}\,K^{-1}$)
K_f	volumetric evaporation coefficient ($kW\,m^{-3}\,K^{-1}$)
m	mass (kg)
NEF	non-equilibrium fraction (–)
$NETD$	non-equilibrium temperature difference (K)
p	pressure (MPa)
t	temperature (°C)
D_f	speed of overflowing vapor ($m\,s^{-1}$)

Greek symbols

ΔT	superheat (K)
ρ	density ($kg\,m^{-3}$)

τ	time (s)
ψ	volumetric void fraction of waterfilm (–)

Subscript

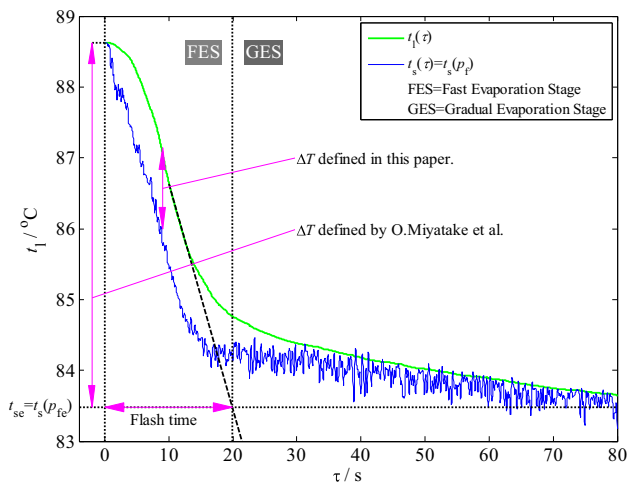|	
–	decrease
+	increase
0	initial state
b	bubble
cal	calculated
e	equilibrium
exp	experimental
f	flash chamber
fo	foam (waterfilm)
l	liquid
s	saturated
tp	turning time from fast evaporation stage to gradual evaporation stage
v	vapor

Fig. 1. Typical temperature evolution of waterfilm and 2 definitions of superheat.

of pure water with superheat ranging between 2 and 7 K. They found some critical transition points for *NEF* evolutions and suggested it might be related to the number and location of bubbles within waterfilm. D Saury et al. [18,19] conducted static film flash of pure water at different depressurization rates (0–3.5 bar s⁻¹) with superheat of 1–35 K. They noticed that morphological evolution of waterfilm (waterfilm height) during flash coupled with the heat/mass transfer process within it. Specifically, most of the heat transfer was supposed to happen within waterfilm, generating lots of bubbles and raising the height of waterfilm. Its maximum height increased with rising depressurization rate. Besides, their experimental results also suggested that the sensible heat released during flash could be considered to completely change into the latent heat of flash vapor. Thus, a correlation between mass flow rate of evaporation and depressurization rate was proposed. Pinhasi et al. [20] studied bubble growth and the expanding of free surface during static flash. They suggested that the heat transfer during flash mainly happened at bubble interface. The heat transfer coefficient and the total area of bubble interface all highly depended on the volumetric void fraction of waterfilm.

Once the superheated waterfilm moved at certain macroscopic velocity, it was named as dynamic film flash. Its heat/mass transfer highly depended on this velocity and flowing distances. These dependences were examined by scholars [21,22]. Besides, there were also many works on droplet flash [23,24], spray flash [25,26,27] as well as their applications in industrial flash system [28–31].

Our research team has also been studying static film flash for years. In our experiments, pure water [32] and aqueous NaCl solution [33,34] were used as working fluid. Superheats ranged between 1.7 and 53.9 K, initial heights between 0.050 and 0.40 m. The initial concentration of waterfilm (f_{m0}) ranged from 0 to its saturation value of 0.26 (mass fraction). In order to compare the speed of energy release during flashes, flash speed (*FS*) was introduced as the mean drop rate of *NEF* during flash time (Eq. (3)). In our experiments, orifice plate with different diameters were used to throttle flash vapor and create different *FS*.

$$FS = \frac{1 - NEF_{tp}}{\tau_{tp}} \tag{3}$$

Results suggested that, first, with increasing f_{m0}, NEF_{tp} reduced initially, but once crystallization took place, it rose up [35]. Second, with increasing *FS*, large amount of liquid was entrained away from waterfilm by flash vapor, which was named as steam-carrying effect [36]. In our experiment, this effect could be greatly suppressed by using orifice plate with diameter less than 5 mm [37]. Finally, a empirical formula for *NEF* evolution at different flash speeds and the thermal criterion for crystallization were set up [38]. Besides, we also studied dynamic film flash of pure water and aqueous NaCl solution [39–41], and compared their heat/mass transfer characteristics with that of static film flash [32]. At last, the effectiveness of static film flash on energy [42,43] and exergy transfer [44] were also evaluated.

Previous studies indicate that the heat/mass transfer during static film flash is not uniform in time domain. Parameters introduced by previous scholars, such as NEF_{tp}, evaporated mass, *FS*, etc. are all used to measure the overall heat/mass transfer characteristics during flash time. In order to achieve precise control and miniaturization that required by current industrial flash system (e.g. separation of multi-component of aqueous saline solution,