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Preliminary exergy analysis of static flash of pure water

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ABSTRACT

The waterfilm was selected as control volume and exergy transfer within it during static flash of pure water at different flash speeds was analyzed. Exergy balance during differential time was set up and exergy destruction was also deduced. It suggested that static flash was an irreversible process and boiling temperature difference (*BTD*) played a major role for exergy destruction. In order to measure the effectiveness of static flash on exergy transfer during entire flash duration time, exergy efficiency of flash (*EE*) was introduced as the fraction of the delivered exergy to the total released exergy from unit mass of initial waterfilm. Exergy efficiency of flash steam (EE_{stm}) was defined as the fraction of exergy contained in latent heat of flash steam to the total released exergy from unit mass of initial waterfilm. Both efficiencies were evaluated and analyzed according to our former experimental results with initial temperature ranging between 46.5 and 104.6 °C, superheat between 1.78 and 43.9 K, initial height of waterfilm between 0.10 and 0.30 m, flash speed between 4.8×10^{-4} and 2.18 s^{-1}. Results suggested that, first, *EE* varies between 0.86 and 0.99, and EE_{stm} varied between 0.037 and 0.99 in current experimental range. Second EE_{stm} could be improved by increasing initial temperature of waterfilm while at the same time reducing superheat, or initial height of waterfilm, or flash speed. At last, on basis of an empirical formula for *BTD* fitted from experimental results, a pair of calculation formulae for *EE* and EE_{stm} were set up within acceptable error range.

1. Introduction

Flash defines the phenomenon that when liquid at certain temperature is exposed to sudden pressure drop below its saturation pressure corresponding to its temperature, it suddenly evaporates, leading its temperature to drop significantly and generating massive flash steam. At the same time, some superheated liquid is entrained away by the flash steam through steam-carrying effect. Flash can be classified into static flash or dynamic flash according to whether the superheated liquid has macroscopic velocity during flash. Static flash includes flash from static waterfilm, flash from static droplet and so on. Dynamic flash includes flash from horizontally moving waterfilm (named as circulatory flash in our previous works), flash from water jet, and so on. Study in this paper focuses only on flash from static waterfilm, so this kind of flash, in following, is named as static flash for short. According to the working fluid, flash can also be classified into flash of pure water, flash of aqueous salt solution, and so on. Flash is a complex phenomenon including both heat and mass transfer. Macroscopically, heat transfer is caused by evaporation only, while mass transfer is caused by both evaporation and steam-carrying effect.

Due to its good performance on heat transfer, flash is widely used in energy recycle, such as geothermal power plant [1]. Besides, flash can also be used to separate nonvolatile solute and volatile solvent from their solution, such as desalination [2] and thin film deposition [3]. Because steam is easier to be transported than liquid, and the latent heat of steam is much larger than the specific heat of liquid water, the latent heat contained in flash steam is the most concerned energy in industrial flash systems. For example, in geothermal power plant, flash is used to convert thermal energy from low-temperature heat source into the latent heat of flash steam that is used to drive steam turbine and deliver work output. While in each unit of MSF (multi-stage flash), the generated flash steam is condensed at upper part of flash chamber and its latent heat is used to heat original seawater in order to improve thermal performance of the entire system. Therefore, mechanism of flash and its thermodynamic properties, especially properties of flash steam, receive wide attention.

Static flash was the simplest form of flash evaporation and thus was always selected as prototype to examine its mechanism. Miyatake et al. [4,5] presented experimental study on static flash of pure water with superheat varying between 3 and 5 K. They

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Nomenclature

A	cross-section area of flash chamber (m^2)
BTD	boiling temperature difference (K)
c	specific heat ($kJ\ kg^{-1}\ K^{-1}$)
D	orifice diameter (mm)
e	error (–)
EE	exergy efficiency of flash (–)
EE_{stm}	exergy efficiency of flash steam (–)
E_x	exergy (kJ)
e_x	specific exergy ($kJ\ kg^{-1}$)
$e_{x,H}$	flow exergy ($kJ\ kg^{-1}$)
$e_{x,U}$	nonflow exergy ($kJ\ kg^{-1}$)
FDE	fraction of destroyed exergy (–)
FS	flash speed (s^{-1})
FUE	fraction of utilized exergy (–)
h	specific enthalpy ($kJ\ kg^{-1}$)
H	height of waterfilm (m)
h'_{fg}	equivalent specific latent heat of vaporization for superheated water ($kJ\ kg^{-1}$)
h_{fg}	specific latent heat of vaporization ($kJ\ kg^{-1}$)
H_r	relative waterfilm height (–)
m	mass (kg)
NEF	non-equilibrium fraction (–)
p	pressure (MPa)
Q	heat (kJ)
s	specific entropy ($kJ\ kg^{-1}\ K^{-1}$)
s'_{fg}	equivalent specific entropy of vaporization for superheated water ($kJ\ kg^{-1}\ K^{-1}$)
t	temperature (°C)
T	absolute temperature (K)
T_{fg}	equivalent heat absorption temperature (K)
u	specific internal energy ($kJ\ kg^{-1}$)
v	specific volume ($m^3\ kg^{-1}$)
V	volume (m^3)
W_i	boundary work (kJ)

Greek symbols

ΔH	height drop of waterfilm (m)
ΔT	superheat (K)
ρ	density ($kg\ m^{-3}$)
τ	time (s)

Subscript

0	start of flash
bm	benchmark for exergy calculation
cal	calculated value
CV	control volume
dp	dividing point between fast and gradual evaporation stages
e	equilibrium
exp	experimental
f	flash chamber
fit	fitting value
im	integral mean
l	liquid
r	relative
rf	reference
s	saturation
sc	steam-carrying
sh	superheated
stm	steam
tg	tangent point
v	vacuum chamber

found that waterfilm temperature dropped quickly at start, then the drop speed slowed down and the temperature equalized at certain value in the end. Thus, they divided flash into fast evaporation stage and gradual evaporation stage. Besides, they also introduced non-equilibrium fraction (*NEF*, will be clearly introduced in Section.2) to measure completion degree of flash, and suggested that 1-*NEF* was a measure of energy conversion efficiency for flash. On basis of these concepts, they examined heat transfer properties of flash during fast evaporation stage and found that higher superheat or lower initial height of waterfilm caused flash to take place faster and evaporate more. Saury et al. [6] examined energy conversion during static flash of pure water with superheat ranging between 1 and 35 K. Results suggested that the sensible heat released in the temperature drop of waterfilm could be considered to all change into the latent heat of flash steam. Saury et al. [7] also changed depressurization rate of flash chamber through an adjusting valve installed between flash and vacuum chambers. Result suggested that depressurization rate had nearly nothing to do with final evaporated mass. Kim and Lior [8] also examined static flash and revealed several critical transition points in temperature evolution of waterfilm. Liu et al. [9] performed experiments on flash from aqueous NaCl droplet, and found evaporation rate decreased with increasing environment pressure. Gopalakrishna et al. [10] did experiment of static flash of aqueous NaCl solution with Superheat ranging between 0.5 and 10 K, concentration of NaCl between 0 and 0.035 (mass fraction), and finally proposed a calculation formula for final evaporated mass.

In recent years, our research team also did a series of experimental study for static flash of pure water [11] and aqueous NaCl solution [12] at different flash speeds [13]. In our experiments, waterfilm concentration varied between 0 and 0.15 (mass fraction), superheat between 1.7 and 53.9 K. Flash speed was defined as mean decreasing rate of *NEF* during fast evaporation stage, and in experiment this speed was adjusted by adding throttle orifice plate with different orifice diameters (5–80 mm) between flash and vacuum chambers. In our research, theoretical height drop of waterfilm during flash was defined as the drop that calculated by heat balance. It was found that actual height drop of waterfilm measured in experiment was always far greater than the theoretical height drop, suggesting that some superheated liquid was directly entrained away by flash steam without taking part in evaporation. This phenomenon was named as steam-carrying effect. Steam-carrying ratio was also proposed as the mass ratio of entrained liquid to flash steam. Experimental results indicated that this ratio varied between 1.7 and 65.4 in current range, thus this effect cannot be neglected. Therefore, properties of boiling heat transfer and steam-carrying effect were studied together by our research team. Results suggested that, increasing flash speed or initial height of waterfilm significantly intensified steam-carrying effect, but had weak influences on boiling heat transfer. While increasing superheat could intensify the two aspects simultaneously. At last, a fitting formula for *NEF* evolution and a semi-empirical calculation model for steam-carrying effect at different flash speeds were proposed [14], [15]. Besides, according to the first law of thermodynamics, energy conversion during static flash was also analyzed with steam-carrying effect taken into consideration [16].

Studies on dynamic flash was also prevailing. Sami Mutair [17] investigated flash from superheated water jet. Hanshik Chung et al. [18] examined flash of pure water from horizontally moving waterfilm. Our research team also carried out experimental study