Desalination 446 (2018) 12–20

Contents lists available at ScienceDirect

Desalination

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

# Experimental investigation on heat transfer characteristics in circulatory flash vaporization of aqueous NaCl solution

Yu Wang, Qi He, Gen Li, Qingzhong Yang, Junjie Yan*

State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China

ARTICLE INFO

*Keywords:*
Circulatory flash vaporization
Volumetric heat transfer coefficient
Non-equilibrium fraction
Aqueous NaCl solution

ABSTRACT

In this work, a series of experiments on circulatory flash vaporization of 10% and 20% NaCl solution was performed. The heat transfer characteristics in circulatory flash vaporization under different experimental conditions were presented. The non-equilibrium fraction of circulatory flash vaporization (*NEF*) was adopted to describe the extent of flash vaporization process completion. A volumetric heat transfer coefficient of circulatory flash vaporization ($h_v$) was introduced in the present study to evaluate the heat flux evolution from per unit volume of liquid pool under unit superheat degree. Moreover, the influences of superheat degree, pressure of flash evaporator, initial liquid level, circulating flow rate and concentration of NaCl solution on the volumetric heat transfer coefficient were also analyzed. Results suggested that the volumetric heat transfer coefficient increased with the superheat degree and flash chamber pressure. Lowering the initial liquid level and brine concentration promoted the heat transfer intensity. And Nusselt number of circulatory flash vaporization $Nu_A$ was proposed to describe the heat transfer performance of circulatory flash vaporization according to the definition of volumetric heat transfer coefficient. Moreover, a correlation between Nusselt number of circulatory flash vaporization and dimensionless parameters was obtained with the relative error between −31.1% and 32.8% for $1.5 \le \Delta T \le 20$ K, $400 \le Q \le 1200$ L h$^{-1}$, $7.4 \le P_f \le 31.2$ kPa and $0.05 \le f_m \le 0.2$.

## 1. Introduction

When a liquid with a certain temperature flows into a vessel with a pressure below its saturated pressure, intensive vaporization takes place immediately, and liquid temperature suddenly drops. Meanwhile, violent liquid-vapor phase change can be observed. Given its good heat and mass transfer performance, flash vaporization is widely applied in many industrial processes, including desalination process [1–4], spray flash vaporization cooling [5–7], food engineering [8] and recovery of waste heat [9,10].

Researches on flash vaporization have been extensively performed. Miyatake et al. [11,12] conducted an experimental investigation on static pool water flash vaporization. Non-equilibrium temperature difference (*NETD*) was defined as the temperature difference between instantaneous temperature $T_t$ of liquid at time $t$ and saturated temperature $T_e$ under the final equilibrium pressure of flash tank and non-equilibrium fraction (*NEF*) was defined as the ratio of instantaneous superheat degree $\Delta T_t$ at time $t$ and initial superheat degree $\Delta T_0$.

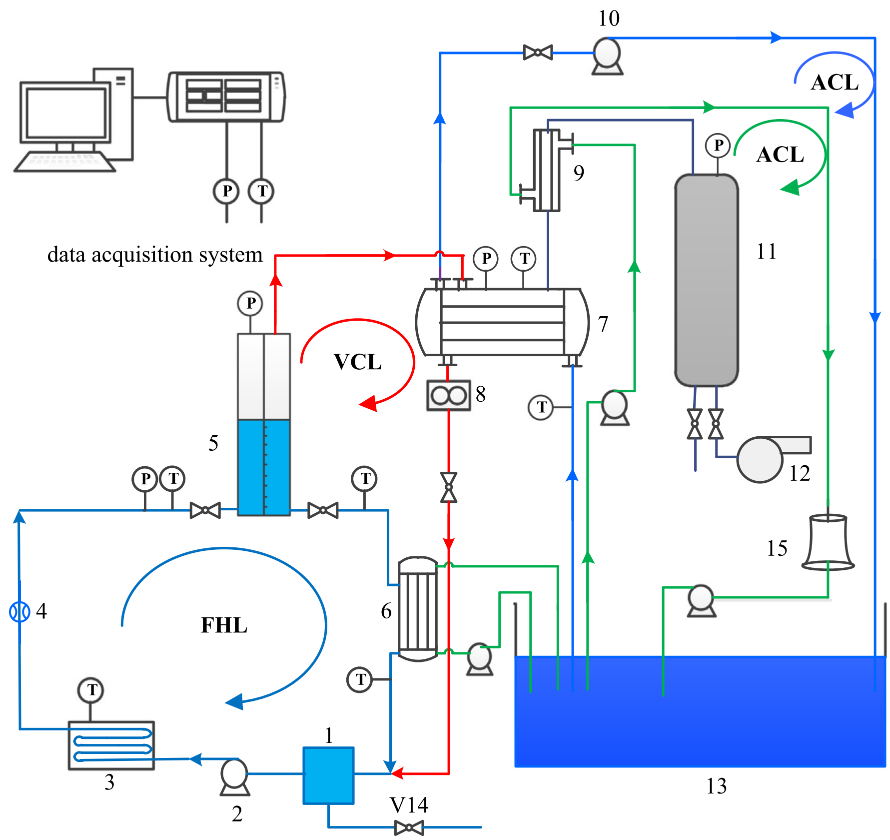
$$NETD = T_t - T_e \quad (1)$$

$$NEF = \frac{\Delta T_t}{\Delta T_0} = \frac{T_t - T_e}{T_0 - T_e} \quad (2)$$

Results suggested that *NEF* experienced two decaying stages. Kim et al. [13] studied the critical transitions during the pool flash vaporization of water. The cumulative number of bubbles increases with superheat degree. A minimum *NETD* exists with the increase of initial water temperature. Lior et al. [14] conducted an experimental research on the total evaporative heat of flash vaporization in horizontal flash vessel. Fresh water and NaCl solution were employed as the working medium. Results showed that the total evaporative heat transfer rate increased with superheat degree. Moreover, they also summarized the correlations of *NEF* [15]. Results suggested *NEF* reduced with the rise of stage equilibrium temperature. Gopalakrishna et al. [16] conducted an experimental investigation on the quiescent pool flash vaporization of fresh water and 3.5% NaCl solution and evaluated the flashing mass versus time and superheat degree. The experimental investigations on flash vaporization of static water pool were conducted by Saury et al. [17,18]. The evolutions of *NEF* versus flashing time were illustrated. Results suggested that *NEF* first decreased rapidly and then became flat. And the evaporated mass increased with time. The depressurization

* Corresponding author.
*E-mail address:* yanjj@mail.xjtu.edu.cn (J. Yan).

https://doi.org/10.1016/j.desal.2018.08.017
Received 30 March 2018; Received in revised form 3 August 2018; Accepted 22 August 2018




1.water tank 2.circulating pump 3.tubular electric heater 4.metal rotor flowmeter 5.flash chamber 6.heat exchanger 7.condenser 8.Coriolis mass flowmeter 9.auxiliary condenser 10.cooling water pump 11.vacuum chamber 12.vacuum pump 13.cooling water tank V14.drain valve 15. cooling tower
FHL: fundamental hydrothermal loop
VCL: vapor cooling loop
ACL: auxiliary cooling loop

**Fig. 1.** Diagrammatic sketch of experimental system.

rates had no influence on the final evaporated mass. Augusto et al. [19,20] conducted experimental studies on low-pressure-vaporization of the quiescent free water. The influence of initial liquid volume and temperature on low-pressure-vaporization process was comprehensively analyzed. The higher initial liquid temperature and smaller liquid volume yielded the faster decreases of liquid temperature after the flash point. Yan et al. [21] investigated the heat and mass transport characteristics of static and circulatory flash vaporization comparatively. A universal correlation of *NEF* of static and circulatory flash vaporization was proposed. And the non-equilibrium and heat transfer characteristics in static flash vaporization of pure water and NaCl solution have been studied [22,23]. Results suggested that a maximum volumetric heat transfer coefficient $h_v$ existed corresponding to a certain flashing time. As the initial liquid level drops the heat transfer intensity increases. The $h_v$ linearly increased with static flashing speed. Yang et al. [24] investigated the heat transport performance of static flash vaporization of high-salinity NaCl solution. It was found that $h_v$ increased with superheat degree. Moreover, the crystallization enhanced the heat transfer performance of flash vaporization. Zhang et al. [25] studied the heat transfer coefficient of pure water of circulatory flash vaporization. And mass flow rate of flashing vapor condensate measured with a mass flow meter was used to compute the $h_v$. The authors also conducted experimental study on *NEF* of low-concentrated NaCl solution (mass fraction of NaCl 0, 5% and 10%) circulatory flash vaporization [26]. The influence of circulating flow rate, pressure of flash chamber, initial liquid level and brine concentration on *NEF* was analyzed. And the liquid droplet entrainment phenomenon was presented [27]. Result suggested the entrained liquid droplet can influence the mass flow rate of flash steam. In our previous study [28], experimental investigation of 15% NaCl solution circulatory flash vaporization was conducted and the circulatory flashing speed was defined as the mean change rate during residence time in flash chamber. It was found $h_v$ decreased as the circulatory flash speed dropped.

Previous investigations mainly focused on the quiescent water pool flash vaporization and the working fluids were fresh water or solution with low concentration. However, with the increasing demand of fresh water and the urgent need of environmental protection, the brine with high salinity rejected by desalination process and energy chemical industry must be managed effectively [29–31]. Flash vaporization is an effective method used to achieve an advanced treatment of high-salinity brine [30]. It is of great necessity to investigate the heat transfer performance in circulatory flash vaporization of NaCl solution with high concentration. *NETD* and *NEF* can describe the extent of the flashing process completion. But the indicators cannot represent the heat transfer intensity of the flashing process. And previous researches were devoid of correlations of heat transfer performance of circulatory flash vaporization of concentrated NaCl solution.

In this work, an experimental investigation on circulatory flash