Energy Proceedings
Vol 63, 2026

ISSN 2004-2965

Experimental Investigation of NaCl Salinity on Pool Boiling Heat Transfer Performance and Bubble Behavior[#]

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ABSTRACT

The boiling heat transfer characteristics of saline solutions, exemplified by seawater, play a critical role in the operational safety of industrial equipment. A clear understanding of the influence of salt concentration on heat transfer performance is therefore essential. In this study, pool boiling experiments were conducted using deionized water and saline solutions with concentrations of 1%, 3.5%, and 6% over a heat flux range of 20–200 kW/m². Two types of heating surfaces were employed: a plain and a structured pin-fin stainless steel surface. The results demonstrate that heat transfer performance deteriorates in saline solutions on both surfaces compared to deionized water. However, when the salt concentration exceeds 3.5%, further increases have a negligible impact on heat transfer. The wall superheat required for the onset of nucleate boiling (ONB) was found to increase with salt concentration: recorded as 7.01 K for pure water and 18.45 K for the 6% saline solution at plain surface. Compared to the plain surface, the pin-fin surface featuring a width-depth-pitch configuration of 500 μm significantly alleviated heat transfer degradation and reduced the wall superheat required for nucleation.

Keywords: NaCl solutions, pool boiling, heat transfer, bubble dynamic, plain surface, pin-fin surface

1. INTRODUCTION

In the seawater desalination and petroleum extraction industries, the treatment of concentrated brine and subsurface saline water remains an inevitable challenge[1]. Boiling heat transfer of highly saline fluids such as seawater constitutes an essential process in industrial applications, typically occurring within large-scale heat exchangers or multi-effect evaporators[2,3]. As a result, the heat transfer characteristics of saline solutions have garnered considerable research interest[4,5]. The introduction of non-volatile solutes interface and the bulk liquid. Alterations in thermophysical properties, combined with the interdependent effects of the concentration and thermal boundary layers, lead to boiling behaviors that deviate significantly from those observed in pure water. Moreover, these behaviors evolve dynamically with changes in solute concentration. Elucidating the boiling heat transfer mechanisms of saline solutions is therefore crucial for the design and operational safety of heat exchange equipment.

Several researchers have experimentally investigated pool boiling heat transfer in NaCl solutions and seawater. Huang and Pan [6] conducted steady-state pool boiling experiments using seawater, sodium chloride solution, and deionized water on a platinum wire heater with a coated surface. Their results indicated that NaCl solutions exhibit enhanced heat transfer performance relative to pure water. In contrast, Hamzekhani [7] performed boiling experiments with NaCl solutions on cylindrical heaters and reported that the bubble departure diameter increased with increasing salt concentration—a finding inconsistent with those of Huang et al., who observed larger bubbles in pure water. With a focus on practical applications involving plate-type heat exchangers, several studies have explored boiling in brine solutions on heated surfaces. For example, Fogaça and Mori [8] compared the heat transfer performance of 3.5% and 7% seawater with pure water on a copper surface. They concluded that salt concentration had a negligible influence at low heat fluxes, whereas a noticeable degradation in heat transfer occurred at higher heat fluxes. Previous studies on this topic have reported inconsistent results, and the underlying mechanism governing the effect of salt concentration remains unclear. Given that heat transfer characteristics and bubble behavior are strongly influenced by the intrinsic properties of the heating surface, this study employs stainless steel—a material widely used in practical applications—as the substrate

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[#] This is a paper for the 17th International Conference on Applied Energy (ICAE2025), December 8-12, 2025, Bangkok, Thailand.

for boiling experiments with saline solutions at varying concentrations. For comparison, a pin-fin surface, commonly utilized for heat transfer enhancement, is also adopted. The aim is to elucidate the influence of salt solution from the perspective of surface characteristics

2. EXPERIMENTAL PROCEDURES

2.1 Experimental system

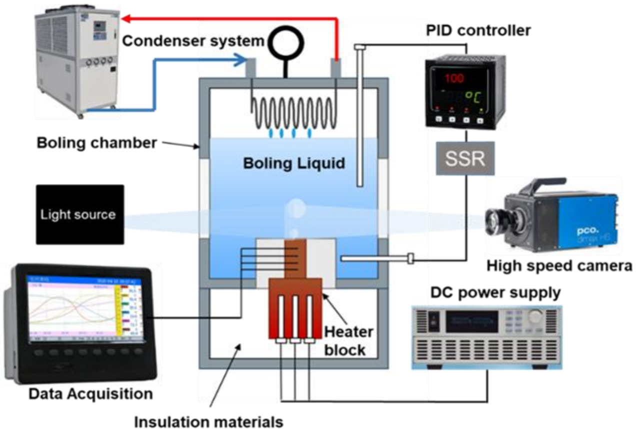

Fig. 1 Schematic diagram of experimental setups

The experimental setup for this study is illustrated in *Fig. 1*. Experiments were primarily conducted at atmospheric pressure, employing deionized water and 1%, 3.5%, and 6% NaCl solutions as working fluids. The experimental setup consists of a boiling chamber, heating module, data acquisition system, visualization system, and cooling system. To maintain operation at atmospheric pressure, a condenser coil connected to an external chiller is mounted at the top of the system to ensure rapid condensation of vapor. The temperature of the working fluid is monitored using a thermocouple immersed directly in the liquid.

The heating assembly utilizes copper columns known for their high thermal conductivity. The test surface is bonded to the copper conduction column using a specialized solder paste. Measurements obtained with a micrometer indicate that the solder layer has a thickness of approximately 0.3 mm. The bubble dynamics data were acquired using a high-speed camera operating at a frame rate of 2000 FPS and a resolution of 1280 × 1240 pixels.

2.2 Data process

The heat flux on the test surface was determined based on Fourier's law of heat conduction.

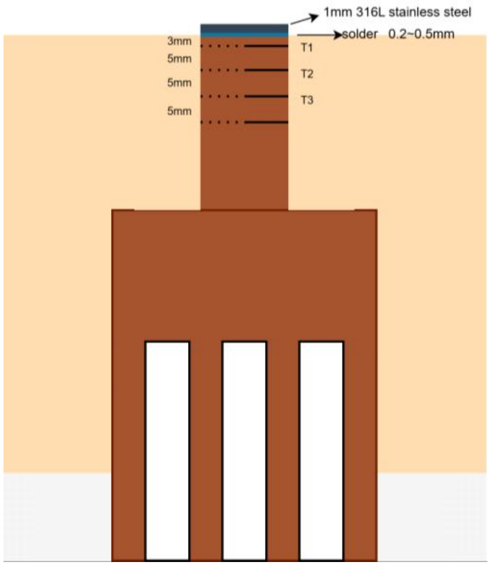

Fig. 2 Test Section Diagram

$$q = \lambda \frac{dT}{dx}$$

where λ is the thermal conductivity of copper, calculated using the following equation and taken as 395 W/(m·K)

The temperature gradient was calculated using the Least Squares Method：

$$\frac{dT}{dx} = \frac{\sum_{i=1}^{4} x_i T_i - \frac{1}{4}\sum_{i=1}^{4} x_i \sum_{i=1}^{4} T_i}{\sum_{i=1}^{4} x_i^2 - \frac{1}{4}(\sum_{i=1}^{4} x_i)^2}$$

Where the T_i represents the measured temperature at different locations, x_i denotes the distance from the temperature measurement point to the heating surface as shown in *Fig. 2*, with values of 3 mm, 8 mm, 13 mm, and 18 mm, respectively. The surface temperature T_w can be calculated as follow：

$$T_w = T_1 - q\left(\frac{x_1}{\lambda}\right)$$

The heat transfer coefficient can be calculated as：

$$h = \frac{q}{T_w - T_b}$$

Where T_b is the saturation temperature.

3. RESULTS

The pool boiling heat transfer curves for plain and pin-fin stainless steel at different salt concentrations are shown in Fig.3 and Fig. 4. The surface heat transfer coefficient increases with increasing heat flux density as shown in Fig 5 and Fig 6. This represents the progressive enhancement of pool boiling heat transfer.

Across the experimentally investigated range of heat flux densities, the heat transfer performance of water under saturated conditions was consistently superior to that of saline solutions on both types of surfaces.

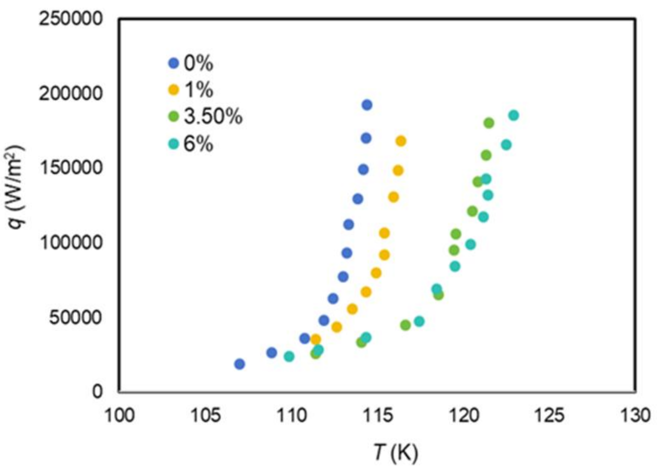

Fig. 3 Boiling curves on plain surface

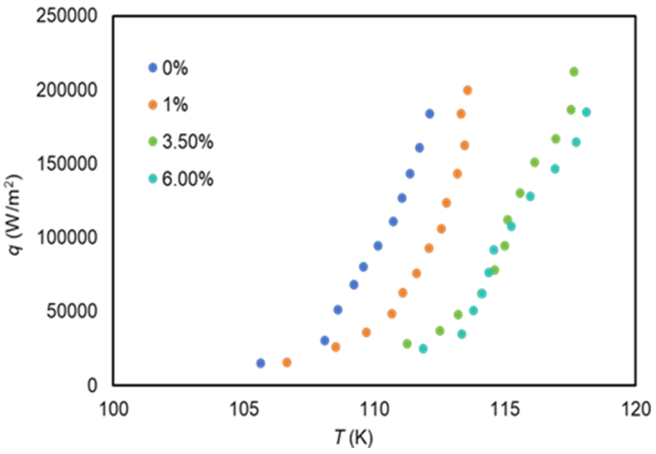

Fig. 4 Boiling curves on pin-fin surface

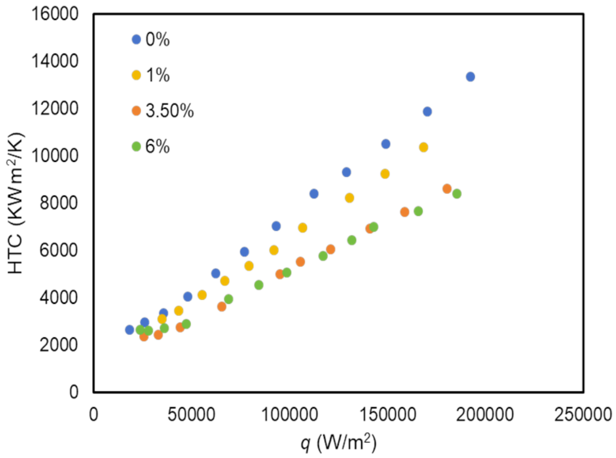

Fig. 5 Boiling curves on pin-fin surfac

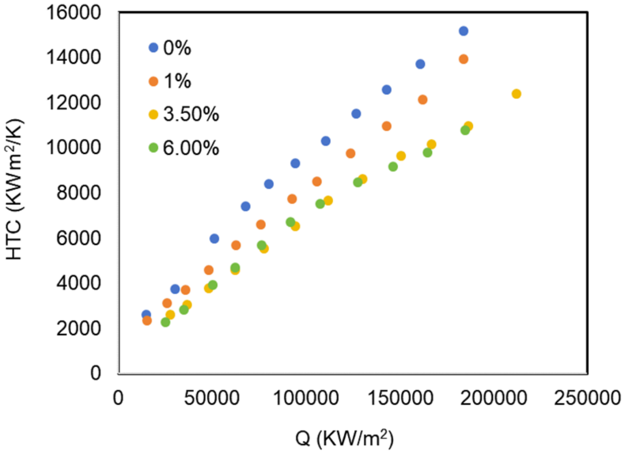

Fig. 6 Heat transfer coefficient with heat flux on pin -fin surface

Table 1. Some pool boiling heat transfer parameters

Plain Surface	△T@ONB (K)	HTC@60KW/m2 (W/m2/K)	HTC@90KW/m2 (W/m2/K)	HTC@120KW/m2 (W/m2/K)
0%	7.01	5012.79	7042.17	9322.31
1%	11.45	4128.56	6016.47	8224.95
3.5%	18.55	3622.68	5002.02	6034.92
6%	18.45	3929.97	5048.58	5771.97
Pin-Fin Surface	△T@ONB (K)	HTC@60KW/m2 (W/m2/K)	HTC@90KW/m2 (W/m2/K)	HTC@120KW/m2 (W/m2/K)
0%	5.65	7391.92	9294.940465	11486.24
1%	8.53	5689.39	7725.72	9764.20
3.5%	11.24	4577.04	6508.42	8622.05
6%	11.86	4710.11	6719.86	8461.10

plain and pin-fin surface at 60 KW/m^2、90 KW/m^2、120 KW/m^2 were analyzed further as shown in *Fig. 7*.

Nucleation site density is a key factor influencing heat transfer. In pool boiling of pure water, a higher density of nucleation sites can be observed. As the salt concentration increases, the number of nucleation sites under the same heat flux gradually decreases until the concentration reaches 6%, beyond which no further reduction occurs. The higher nucleation site density on pin-fin surfaces compared to plain surfaces is also a critical factor enhancing heat transfer for solutions at all concentrations.

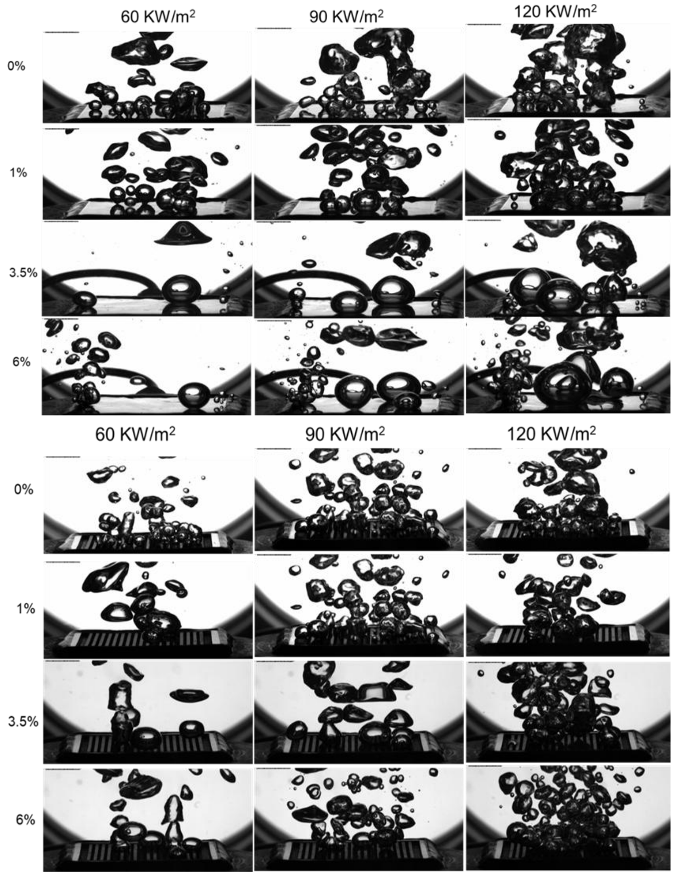

Fig. 7. Comparison of nucleation sites and bubble diameter

On both surfaces, the departure diameter of salt solution bubbles is larger than that of pure water. This is due to the reduced number of nucleation sites, which leads to higher surface superheat and promotes rapid bubble growth in the solution, resulting in a larger departure diameter. Additionally, the experiment revealed that pure water bubbles exhibit a greater tendency to coalesce compared to saltwater bubbles. The lateral coalescence of small bubbles releases surface energy, further facilitating bubble departure and thus resulting in a smaller departure diameter for pure water bubbles. The bubble departure diameter on pin-fin surfaces is smaller than that on plain surfaces at corresponding concentrations, which is influenced by different pinning mechanisms during the departure stage.

5、CONCLUSIONS

The effects of NaCl concentration and surface characteristics on pool boiling heat transfer and bubble dynamics were investigated experimentally. The principal findings are summarized as follows:

(1) The presence of salt ions delays bubble nucleation, leading to an increase in the wall superheat at the onset of nucleate boiling (ONB) with rising solution concentration, up to a saturation threshold, on both plain and pin-fin surfaces.
(2) The pin-fin surface exhibits a lower ONB wall superheat and higher nucleation site density across all concentrations compared to the plain surface. At a heat flux of 120 kW/m², the heat transfer coefficient (HTC) for pure water on the pin-fin surface showed a 23% improvement over that on the smooth surface.
(3) The bubble departure diameter increases with salt concentration until reaching a critical value, beyond which it stabilizes. Surface microstructures effectively attenuate the heat transfer degradation associated with enlarged bubble sizes.

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