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Subcooling effect on boiling heat transfer of inclined downward-facing surface under low flow and pressure

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ABSTRACT

The present study investigated the physical processes responsible for the variation in the boiling curve and critical heat flux (CHF) caused by liquid subcooling under atmospheric pressure in a rectangular flow channel; the flow channel was oriented 10° upward from the horizon. Bubble dynamics were examined using a high-speed camera and optical fiber microprobes. A solid copper block was utilized as a test heater and mounted above the flow channel to simulate the passive cooling system of an ex-vessel core catcher designed for nuclear power plants. Low mass flux and subcooling conditions ranging from 40–300 kg/m^2 s and 5–25 K, respectively, were applied at the inlet of the test section. At the mass flux value of 40 kg/m^2 s, large sliding bubbles were attributed to a key criterion for enhanced boiling heat transfer when the liquid subcooling was varied up to 15 K. The results showed that the CHF was weakly dependent on the degree of liquid subcooling, which deviates from the general trend reported by many researchers. A repetitive flow reversal along with a pressure shock appeared, owing to the rapid condensation at the exit, which added complexity to the analysis of the CHF. This study provides physical insights for understanding the subcooled flow boiling heat transfer mechanism (including the CHF) based on sophisticated experimental measurements, such as the visual capture of boiling dynamics using high-speed video and local void fraction.

1. Introduction

The vapor-liquid exchange process caused by density differences is considered one of the most central phenomena in boiling heat transfer. Desirable hydrodynamics is manifested in a boiling system where a departing bubble pumps a slug of hot liquid away from the heated wall and replaces it with a cooler liquid [1]. The vapor-liquid exchange mechanism could explain many experimental observations that the boiling curve is insensitive to degree of liquid subcooling [2–5]. Increase of subcooling brings out remarkable change in bubble dynamics via reduction of both bubble size and agitation intensity. Consequent degradation of fluid motion near the wall countervails the positive effect of subcooling on turbulent liquid convection.

However, many studies showed that variation of subcooling can make a significant change in boiling heat transfer. Some studies reported that, as subcooling increases, a boiling curve was shifted toward a higher wall superheat [6,7]. On the other hand, the shift of boiling curve toward a lower wall superheat via subcooling increase was observed by other investigator, who explained the enhancement of boiling heat transfer by considering improvement of the convective heat transfer [8–13]. These conflicting reports may arise from the complex nature of the physical mechanism through which subcooled liquid affects the bubble size, nucleation frequency, and bubble dynamics related to bubble growth and collapse. Here, it should be pointed out that the significance of subcooling generally appears in the regime of partial nucleate boiling, whereas subcooling has a negligible influence on a fully developed boiling curve [8,9,11,13]. Such negligible influence can be explained by remarkable reduction of the effective area for convection owing to vigorous nucleation activity in the fully developed nucleate boiling regime.

In addition, it is worth noting the heater orientation effect on subcooled boiling characteristics because the orientation would considerably affect the bubble dynamics along the heater. For the specific case of downward-facing heater, boiling curves at various subcoolings are expected to merge into a virtual asymptote even under an intermediate heat flux condition, because bubble dynamics along downward-facing heater is quite similar to that in the fully developed boiling regime. In case of downward-facing heater,

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Nomenclature

Acronym	Description
BHTC	Boiling heat transfer coefficient
CHF	critical heat flux
CIWH	condensation-induced water hammer
DAQ	data acquisition
PID	Proportional–integral–derivative
RTD	resistance temperature detector
SS	stainless steel
Symbol	Description, Unit
h_B	boiling heat transfer coefficient, W/m^2-K
k_{Cu}	thermal conductivity of copper, W/m-K
L	length between the heated surface and position of T_w, m
m	proportionality constant
n	average slope of the P-T curve, Pa/K
q''	heat flux, W/m^2
q''_{CHF}	critical heat flux, W/m^2
$q''_{CHF,sat}$	critical heat flux under saturated state, W/m^2
$q''_{CHF,sub}$	critical heat flux under subcooled state, W/m^2
r_c	cavity mouth radius, m
T_w	temperature in the heating block at distance of 4.7 mm from the heater surface, °C
T_m	temperature in the heating block at distance of 14.7 mm from the heater surface, °C
T_d	temperature in the heating block at distance of 24.7 mm from the heater surface, °C
T_{sat}	saturation temperature, °C
T_s	temperature at the heater surface, °C
T_{bulk}	temperature of liquid in bulk region, °C
ΔT_{sub}	liquid subcooled degree, °C
$U_{\mathrm{m\ (arbitrary)}}$	absolute uncertainty of the subscripted parameter (m)
Δx	distance between the vertically aligned thermocouples, m

Greek Symbol	Description, Unit
σ_l	Surface tension, N/m

thicker thermal boundary layer and consequent higher nucleate site density facilitate the bubble coalescence process [14], which results in formation of a large vapor mass even at low heat flux. Such large vapor mass is pushed against the heater wall by buoyancy. Only a few reports of subcooled boiling curves on downward-facing heater are available in the literature. Haddad and Cheung reported that subcooling had little effect on the boiling curve over a wall superheat of 7 K by using a hemispherical surface as a heater [15]. In short, influence of subcooling is still unclear, and therefore a more thorough investigation should be conducted to improve the prediction capability for subcooled boiling heat transfer along the downward-facing heater.

Compared to inconsistent reports on nucleate boiling characteristics, it has been consistently reported that liquid subcooling enhances critical heat flux (CHF). CHF can be presented as a linear function of liquid subcooling (ΔT_{sub}), as shown in Eq. (1):

$$q''_{CHF,sub} = (1 + m \cdot \Delta T_{sub})(q''_{CHF,sat}) \quad \text{where } \Delta T_{sub} = T_{sat} - T_{bulk} \qquad (1)$$

where $q''_{CHF,sub}$ and $q''_{CHF,sat}$ are the CHF under subcooled and saturated boiling conditions, respectively. m is an empirically determined proportionality constant. Such a linear relationship between liquid subcooling and the CHF was observed in numerous experimental studies when various fluids were adopted, such as water, HFE7100, PF5060, FC72, FC86, R113, methanol, and isopropanol, and when several heater configurations were adopted, such as an upward-facing heater, vertical plate, and horizontal wire [11,16–29].

Positive linearity between the liquid subcooling and resulting CHF could also be confirmed in case of downward-facing heater [16,21,30–32]. Note that El-Genk and Parker [21] studied the combined effect of heater orientation and liquid subcooling and showed that the subcooling effect was rapidly diminished when the heater orientation changed from 30° to 0° (downward-facing horizontal surface). However, it should be noted that aforementioned works used either very small or curved heaters. Thus, their work might obfuscate the complex physics associated with heater size.

As pointed out by Theofanous et al., Rouge, Cheung and Haddad, and Sulatskii et al., the CHF on a downward-facing surface is highly reliant on the local mass flow rate induced by natural convection, which itself is a function of geometric characteristics such as surface orientation to the gravity vector and heater geometry [33–36]. Among the aforementioned studies, only Sulatskii et al. thoroughly investigated the effect of subcooling on the CHF at various subcooling degrees on a large downward-facing flat heater with a slight inclination [36]. Interestingly, a nonlinear characteristic between subcooling and the CHF was observed in their work. They discovered a regime in which subcooling negatively affected the CHF. This unusual instance of CHF dependence on subcooling was simulated in their CHF model by incorporating the negative influence of subcooling on local mass flow rate along the heater surface. Specifically, a term representing single-phase heat transfer to the subcooled liquid was added in calculation of the vapor mass flow rate. Their CHF model could successfully predict the anomalous dependence of subcooling on the CHF observed in their experiments. Note that the anomalous dependence can be interpreted as a weak contribution of the additional sensible energy needed to heat the subcooled liquid to a saturated state. Another interpretation may be thought of as a strong contribution of vapor layer motion on the CHF. It is apparent that a strong vapor layer motion contribution comes from the large geometry of the heater surface.

The literature review described thus far revealed that there exists a lack of knowledge for the accurate prediction of subcooling effect on the CHF, accordingly motivated us to establish the experimental basis for large-scale cooling systems. The cooling systems of interest include ex-vessel core catcher cooling systems designed for nuclear power plants, such as ABWR, VVER-1000, ESBWR, and EU-APR1400 [37–40]. These systems have a common feature, which utilizes boiling heat transfer to remove residual heat after a core meltdown. Particularly for EU-APR1400, the heat transfer surface was designed to be inclined at 10° from the horizontal plane to facilitate vapor venting.

In this study, beyond a specific liquid subcooling and heat flux level, we faced two-phase instability, which is quite similar to the geysering phenomenon explained by Ruspini et al. [41]. This instability can be characterized by the repetitive pressure shocks and momentary flow reversal. Physically, the instability can be regarded as repetitive occurrence of the condensation-induced water hammer (CIWH), but its pressure amplitude was confirmed to be far insufficient to break a pipeline in the present study. Owing to safety concerns regarding the water hammer, it has been investigated in various industrial fields for the last few decades [42–44]. Note that the observed instability may cause a significant disturbance in the bubble behavior along the heater surface through a physical coupling between the induced pressure shock and the bubble ebullition cycle. This may affect the boiling crisis phenomenon significantly.