様　式　Ｃ－１９、Ｆ－１９、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

平成 ２８ 年　 ６ 月 １５ 日現在

機関番号：１７１０２
研究種目：研究活動スタート支援
研究期間：2014～2015
課題番号：２６８８９０４４

研究課題名（和文）バブルダイナミクスに及ぼす表面性状効果を利用する最適沸騰面に関する研究

研究課題名（英文）Study of Effects of Surface Characteristics on Bubble Dynamics and Related Boiling Surface Optimization

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交付決定額（研究期間全体）：（直接経費）　　2,100,000円

研究成果の概要（和文）：　我々は空間的に異なる濡れ性を有する伝熱面（親水撥水複合面）を製作し，そのような伝熱面が優れた伝熱性能を示すことを明らかにした．大気圧において，親水撥水複合面上では沸騰開始過熱度が著しく低下する．これにより高効率な沸騰伝熱の低熱流束の用途への拡張が可能となる．また，減圧下では，沸騰開始時の大きなオーバーシュートを抑制できる．
　さらに，我々は拡散界面法を用いた2成分系の相変化に関する数値シミュレーションを行い，溶存ガスの濃度によって気泡挙動が異なるという結果を得ている．

研究成果の概要（英文）：We have designed and fabricated a heterogeneous boiling surface with spatially varying wettability, which exhibits exceptional heat transfer performance. At atmospheric pressure, the onset of nucleate boiling is lowered significantly (to negative levels) on the enhanced surface. The facilitated boiling incipience extends boiling to low-heat-flux applications as an effective means of heat transfer. At reduced pressures, the technical limitation of large incipience temperature overshoots is greatly mitigated by using heterogeneous surfaces with mixed wettability.
 Furthermore, we have performed a numerical study of phase transition of a two-component system by using a diffuse-interface method. The results show contrasting bubble behaviors with increasing concentrations of dissolved gas.

研究分野：熱工学

キーワード：プール沸騰　親水撥水複合　沸騰開始　減圧下沸騰　数値シミュレーション　拡散界面法

１．研究開始当初の背景

Boiling, one of the most common and ubiquitous phase-change phenomena, finds extensive application to a wide range of energy solutions from air-conditioning and refrigeration to nuclear and fusion reactor cooling. Boiling heat transfer is characterized by two important parameters: (i) *heat transfer coefficient* (HTC, defined as the ratio between the applied heat flux and the resulting wall superheat); and (ii) *critical heat flux* (CHF, corresponding to the peak in the boiling curve).

As regards boiling performance, among a variety of surface properties, wettability has a distinct role to play. On one hand, hydrophilicity often leads to a delay in the onset of film boiling by facilitating liquid supply to the heat transfer surface. On the other hand, hydrophobicity promotes bubble nucleation and consequently contributes to higher HTC. Current research has a focus on enhancement of CHF, whereas the onset of nucleate boiling (ONB) on hydrophobic surfaces can be effectively lowered, whose physical mechanism still lacks convincing explanations. For applications such as electronics cooling, efficient heat transport at low surface temperatures is essential for long-term operational stability, which makes elimination of heat transfer deterioration at reduced saturation temperature an urgent task.

２．研究の目的

The present study aims at developing a boiling surface suitable for efficient thermal management of electronic components, which includes two specific goals: (i) to improve our understanding of the bubble nucleation process on surfaces of different wetting properties, in an effort to extend the applicability range of boiling heat transfer by lowering ONB; (ii) to effectively lessen deterioration of boiling heat transfer at reduced pressures by optimizing surface wettability design.

３．研究の方法

To examine boiling heat transfer on surfaces with different wettability patterns, two custom-made boiling setups have been prepared (Fig. 1). In the open system, the boiling vessel was constantly exposed to the atmosphere, whereby a certain amount of ended up dissolved in the subcooled water. In the closed system, on the other hand, nearly complete elimination of dissolved gas can be achieved through

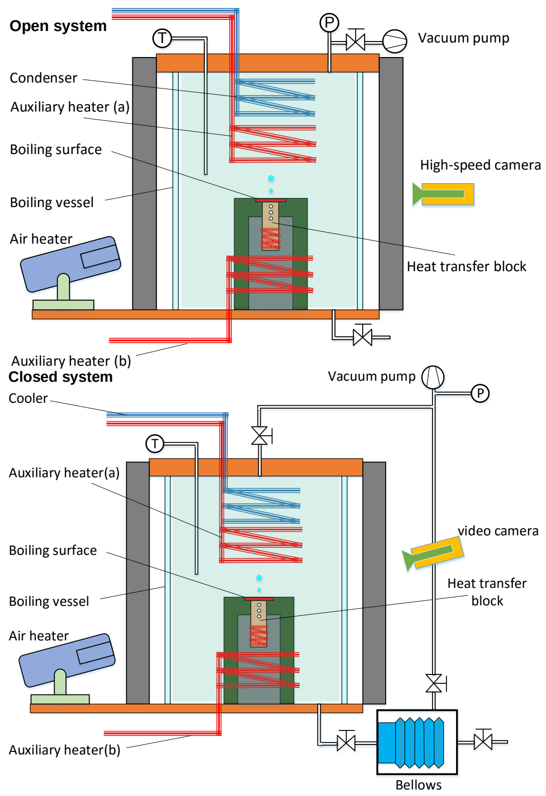

Fig. 1 Experimental setups

vacuum degassing. Control of the system pressure was managed by means of a rubber bellows that was connected to the boiling vessel. Hermetically sealed from the surroundings, the closed system offered opportunities to study both subcooled boiling in the absence of dissolved gas and subatmospheric boiling. Surface temperature and heat flux were determined by extrapolating the measurements of three thermocouples embedded in the heat transfer block. Here heat conduction was assumed to dominate heat transfer along the block.

Bubble dynamics were studied both experimentally and numerically. Visualizations of bubble nucleation and growth from an artificial nucleation site were carried out using a high-speed camera. Numerical simulations of bubble behaviors in a binary mixture (water-nitrogen) were performed using the free-energy-based diffuse-interface method. The governing equations were solved by a finite-element solver, which was generated automatically by the symbolic computational toolbox femLego.

４．研究成果

(1) Enhancement of subcooled boiling due to negative ONB

A thin layer of TiO_2 was sputter-deposited onto a copper substrate. On its top arrays of hydrophobic islands (contact angle>120°) were made by PTFE (polytetrafluoroethylene) coating. The remainder of the surface was rendered superhydrophilic (contact angle≈0°) by continuous UV irradiation for over 12 hours. As shown in Fig. 2, subcooled pool boiling on the resulting biphilic surface was found to improve considerably compared with a surface with uniform wettability: (i) the ONB was lowered significantly, even to the *negative* territory (ii) consistently higher heat transfer rates prevailed over a wide range of surface superheats.

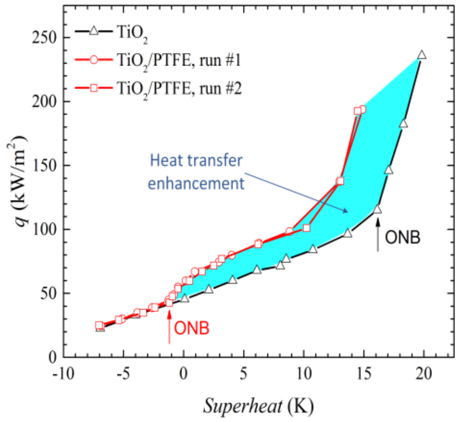

Fig. 2 Enhanced subcooled boiling

(2) Enhancement of subatmospheric boiling due to suppressed intermittent boiling

As shown in Fig. 3, patterned electroplating of fine nickel and FTEO (tetrafluoroethylene oligomer) particles (contact angle>140°) onto a copper substrate (contact angle ≈80°) was found to increase HTC by over 300% compared with a mirror finished copper surface at a reduced pressure of 14.0 kPa. Strong pinning of the hydrophobic surface leads to partial departure (necking) of bubbles from the surface, which essentially delays the

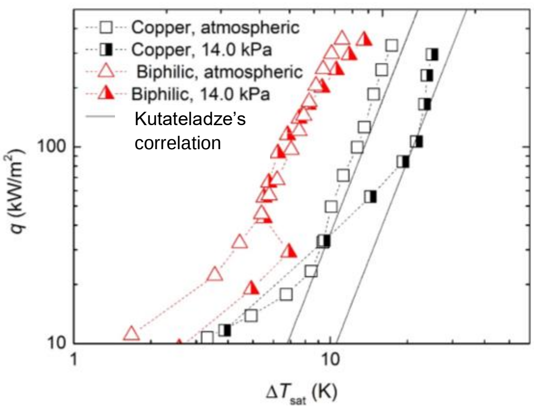

Fig. 3 Enhanced subatmospheric boiling

transition to intermittent boiling (that is, sudden deactivation of all nucleation sites on the surface due to excessive cooling effect caused by departures of considerably enlarged bubbles).

It was found that to trigger intermittent boiling on a biphilic surface, a much lower pressure level was needed. Figure 4 plots the boiling curves at various pressures. It seems that a sharp transition from continuous to intermittent boiling occurred between 8.8 kPa and 6.9 kPa, resulting in significant deterioration of HTC.

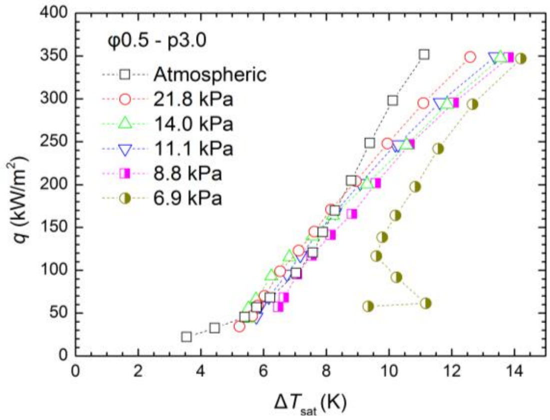

Fig. 4 Boiling curves at various pressures

Nearly immune to diminishing pressures, the enhanced surface is proved to be highly promising as its application in the evaporator design of a loop-heat-pipe resulted in a state-of-the-art thermosiphon performance (Fig. 5).

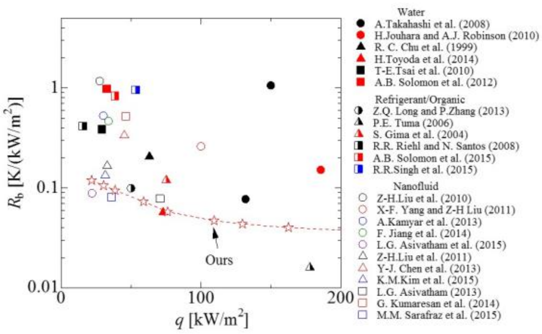

Fig. 5 Heat transfer performances of various thermosiphon designs

(3) Elucidation of the impact of dissolved gas on bubble dynamics

It was revealed by the numerical simulations that thanks to an unusual accumulation of incondensables (nitrogen), bubbles can grow large enough to (partially) depart or pinch off; otherwise, stationary bubbles remain firmly anchored to the surface due to strong condensation from the subcooled water (see Fig. 6). Thus, heat transfer gains in the open system can be attributed to the strong Marangoni flows (thermocapillary convection) along the bubble interface, which was largely driven by the significantly declining condensation temperature as a result of the growing accumulation of incondensables near the apex of the bubbles.as a result of the accumulation of impurities near the apex of the bubbles.

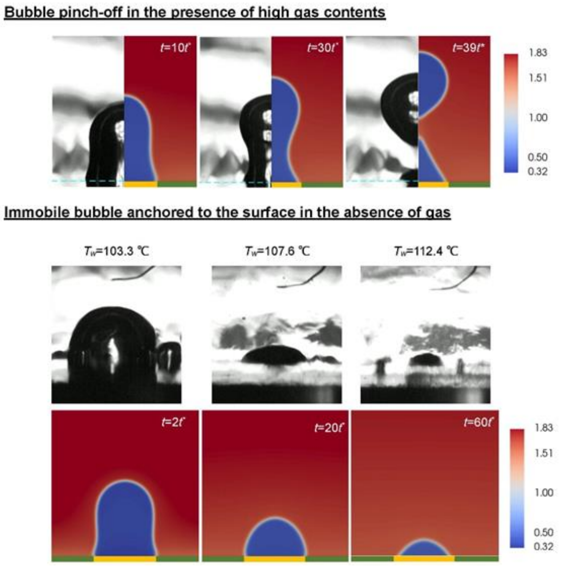

Fig. 6 Bubble dynamics with and without gas

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

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