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研究課題名（和文）Data-driven Visualization of Bubble Contact-line Dynamics on Heterogeneous Surfaces

研究課題名（英文）Data-driven Visualization of Bubble Contact-line Dynamics on Heterogeneous Surfaces

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交付決定額（研究期間全体）：（直接経費）　　3,400,000円

研究成果の概要（和文）：本研究では、低圧下における沸騰伝熱の向上を目指し、沸騰における複雑な接触線ダイナミクスを明らかにし、親水性と構造工学を組み合わせたハイブリッド表面の開発を行った。この加工表面には、減圧での劣化性間欠沸騰への移行が著しく遅れることを明らかにした。さらに、畳み込みニューラルネットワーク（CNN）ベースのモデルを構築し、沸騰特性の分析のための沸騰面の可視化データの高速解析を実現した。

研究成果の学術的意義や社会的意義
本研究は、効率的な沸騰伝熱を持続させるための蒸気トラップの重要性について新たな見方を提供した。ハイブリッド表面設計は、気泡離脱時の接触線のピンニングを利用し、減圧下の沸騰を著しく向上させ、コンピュータなどの次世代冷却ソリューションの開発にポジティブな影響を与えることができる。一方、機械学習ベースの解析フレームワークは、可視化データの処理を加速するために使用でき、沸騰現象に対する強力な研究ツールを加える。

研究成果の概要（英文）：The present study focused on enhancement of boiling heat transfer under low pressures. The role of complex contact-line dynamics during bubble release from the boiling surface was elucidated, which led to development of hybrid surface combining wettability and structural engineering. The hydrophobic-coated cavities introduced stronger contact-line pinning, which was responsible for more vapor trapping compared with flat surface. Consequently, the enhanced surface led to significantly delayed transition to deteriorating intermittent boiling at very low pressures.

Additionally, a Convolutional Neural Network-based model was built to achieve fast processing visualization data for analysis of boiling characteristics. Trained on time series of high-speed infrared thermographic images of the boiling surface, the model was able to identify the existence of microlayer at an accuracy of 90%.

研究分野：Thermal engineering

キーワード：Nucleate boiling　Subatmospheric　Wettability　Surface cavity　Vapor trapping　Artificial intelligence　Infrared thermography

１．研究開始当初の背景

Industries ranging from cement, steelmaking, to petrochemicals produce a massive amount of heat, which contributes significantly to annual global carbon emissions. To safely dissipate industrial heat of high-temperature and high-flux nature requires revolutionary advances in thermal management solutions. Among the short list of potential solutions, boiling heat transfer proves to hold special promise due to its high efficiency—hundreds of times that of single-phase heat conduction or convection. However, boiling can be particularly vulnerable to pressure variations as exceedingly long waiting times tend to be incurred between bubble nucleation cycles, which leads to detrimental transition to far less efficient mode of intermittent boiling. It will thus be of vital importance to study the mechanisms for heat transfer deteriorations of subatmospheric boiling so as to improve boiling surface design for low-pressure applications.

２．研究の目的

The transition to intermittent boiling under reduced pressures can be attributed to deactivation of bubble nucleation sites, which in turn relies on complex contact-line dynamics during bubble departure. The objectives of the present study are twofold, (i) to develop high-performance boiling surface for enhanced low-pressure boiling based on a refined understanding of contact-line pinning behavior; and (ii) to develop an artificial-intelligence framework for mapping bubble dynamics in boiling phenomena.

３．研究の方法

A series of boiling experiments were performed using a standard boiling test rig, which consisted of Pyrex-glass vessel and a heater assembly (including a heat transfer block and two sheath heaters of 700 W). The surface temperature and heat flux at the top surface of the heat transfer block were estimated using the temperature measurements of three thermocouples embedded along the block. For the development of data-driven analytical tool of bubble dynamics, CNN (Convolutional Neural Network), a deep learning algorithm that finds great success at image classification tasks, was built. High-resolution high-speed infrared thermographic images of the boiling surface—depicting the 2D distributions of heat transfer coefficient—were fed into the machine learning model as training data with labels indicating key bubble characteristics such as the presence of microlayer (see Fig. 1).

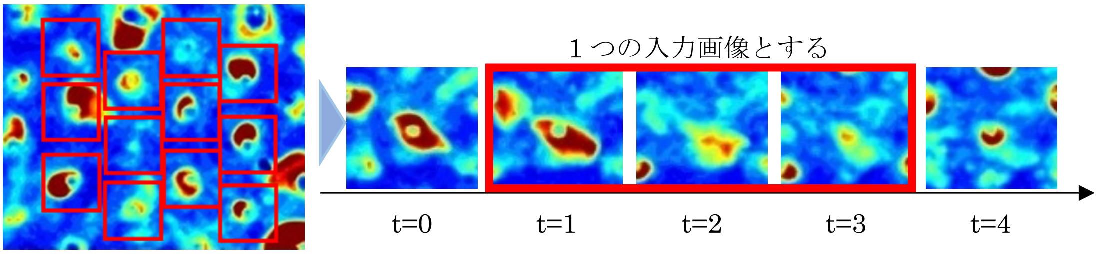

Fig. 1. Preparation of training data of CNN

４．研究成果

As shown in Fig. 2, surfaces with overlapping wettability and cavity patterns were fabricated taking the following steps:

(1) The top surface of the heat transfer block was polished to a mirror finish;

(2) An array of dimples was drilled onto the surface using a computer-aided precision desktop mill;

(3) The surface cavities were spray-coated with hydrophobic polytetrafluoroethylene (PTFE) coating.

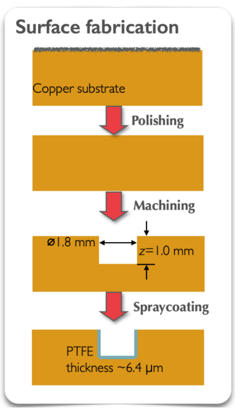

Fig. 2. Fabrication of dimpled biphilic surface.

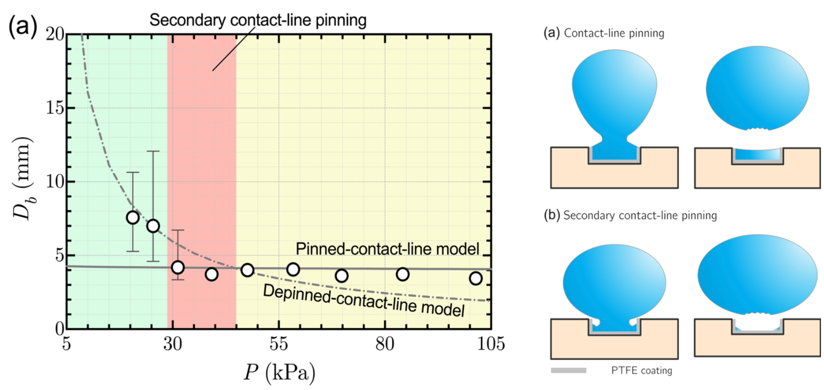

Fig. 3. Extra pinning of contact line during bubble departure on the hybrid surface.

The hybrid surfaces were found to lead to different contact-line dynamics. Fig. 3 shows the high-speed visualization of bubble departure behavior, i.e., the bubble departure diameter D_b versus pressure P on the dimpled biphilic surface of 1.8 mm in cavity diameter and 1.0 mm in cavity depth. In addition to the transition between the contact-line pinning mode at relatively high pressure and the contact-line depinning mode at relatively low pressure, a new regime emerged for the intervening pressures. The apparently extended range of the former model is believed to be caused by ‘secondary contact-line pinning’ inside the hydrophobic cavity. Since the PTFE coating was applied to both the bottom and side walls of the cavity, it is reasonable to suspect that underneath a growing bubble, the entire cavity would be filled with vapor, with the contact line possibly extended as far as the cavity edge. When the moment of departure approaches, with the contact line firmly pinned (at relatively high pressures), we expect the bubble detachment to progress similarly to that on the flat surface, which includes, namely, necking to be followed by partial departure of the bubble. When pressure further decreases, the contact line could instead become increasingly prone to receding from its original position atop the cavity during bubble departure. The hydrophobic nature of the coated inside of the cavity is likely to create conditions that enable trapping of vapor in the corners. The extra pinning of the contact line makes sure that bubble departure leave behind vapor residues leading to continued bubble growth without waiting time, which constitutes essentially the same behavior found with flat biphilic surfaces but at high pressures where continuous boiling regime prevails.

Significant enhancement of subatmospheric boiling was found with the hybrid surface design. Fig. 4(a) and 4(b) show the boiling curves at different pressures for the flat biphilic surface (with a 0.5-mm diameter and 3.0-mm pitch) and dimpled biphilic surface (same pattern but over 0.3-mm-deep cavities), respectively. The latter seems to engender greater enhancement of heat transfer coefficient for the same pressure reductions. It is interesting to note that the enhancement declined sharply with decreasing pressure, which suggests diminished effectiveness of the hybrid surface in delaying the transition to intermittent boiling.

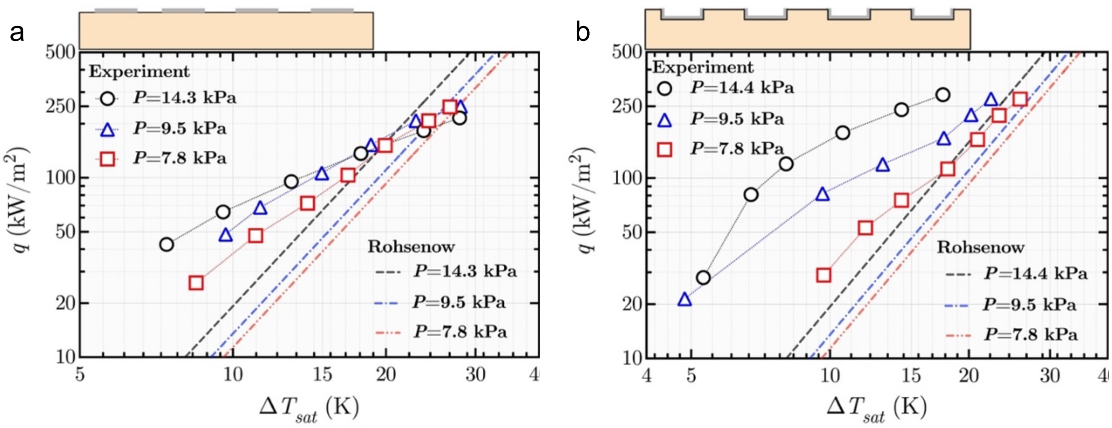

Fig. 4 Boiling curves at different pressures for (a) flat biphilic surface and (b) dimpled biphilic surface

On the data-science front, a CNN-based image processing tool for boiling heat transfer was developed. Compared with conventional boiling visualization analyses—which were often performed manually and thus required days to complete—the machine-learning approach was able to finish the task within seconds and achieve a similar if not better accuracy. More importantly, the model could be used to derive crucial characteristics about boiling heat transfer, such as microlayer size and lifetime, projected area of bubble base and bubble cycle frequency, in an automated manner (Fig. 5). Future improvement of the present CNN framework could lead to powerful analytical tool for comprehensive assessment of boiling heat transfer that can reveal new insights with regard to heat transfer mechanisms of boiling heat transfer otherwise hidden in troves of experimental data.

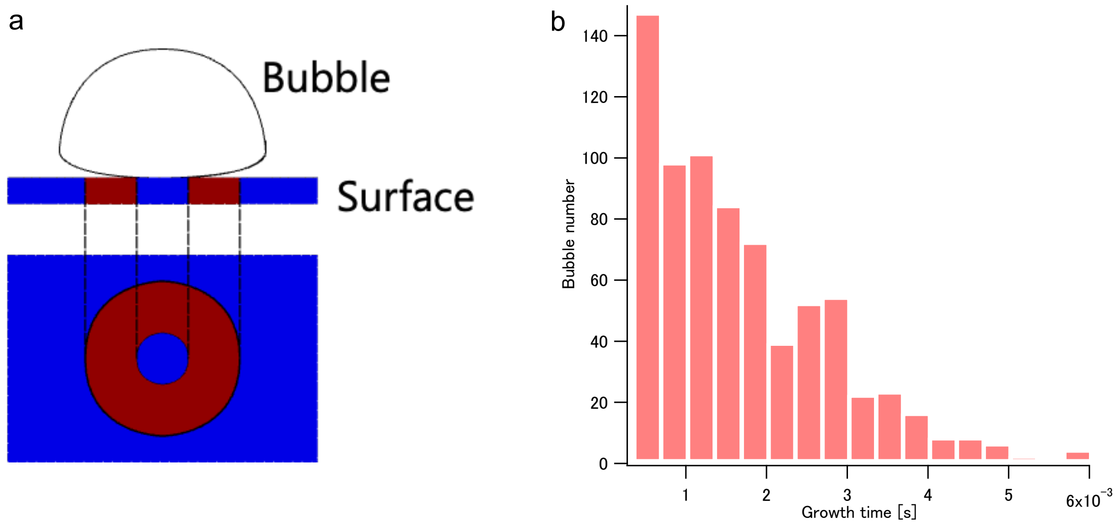

Fig. 5. Examples of CNN-based postprocessing of visualization data for (a) detection of microlayer and (b) bubble growth period distribution.

５．主な発表論文等

〔雑誌論文〕　計1件（うち査読付論文　1件／うち国際共著　0件／うちオープンアクセス　0件）

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2．論文標題	5．発行年
Limited Enhancement of Subatmospheric Boiling on Treated Structured Surfaces With Biphilic Pattern	2021年
3．雑誌名	6．最初と最後の頁
Journal of Heat Transfer	101601-1~12
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1115/1.4051056	有
オープンアクセス	国際共著
オープンアクセスではない、又はオープンアクセスが困難	－

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3．学会等名
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１．発表者名 岩田 直樹，喜多 由拓，ビャオ シェン，日高 澄具，高橋 厚史，高田 保之
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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関