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# 科学研究費助成事業　　研究成果報告書

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研究課題名（和文）ナノスケールで制御された高温固体表面における相変化現象の解明と熱輸送制御

研究課題名（英文）Droplet impact on super-heated nanoengineered surfaces

研究代表者

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研究成果の概要（和文）：ナノスケールで構造制御された高温固体表面に衝突する液滴の動力学および固液界面における熱輸送機構を探究するために(1)リソグラフィー技術・コーティング技術による固体表面のナノスケール構造と濡れ性の独立制御超高速ビデオ撮影による固液界面における液滴挙動の動力学の解析時間領域サーモリフレクタンス法(TDTR)の高速性（時間分解能1m秒）を生かした固液界面熱伝達計測，の3項目を実施する．表面におけるナノスケール構造とコーティング層が濡れ性に及ぼす影響を把握し構造と濡れ性が独立に制御された固体表面と液滴の動的・熱的相互作用を理解することによって噴霧冷却に与える個々の因子の影響を把握した

研究成果の概要（英文）：Combination of optical thermometry using the two photon absorption and time domain thermoreflectance was utilized to capture the dynamics of surface temperature and interfacial thermal resistance between droplet and heated substrate. This helped to better understand the underlying physics at high frequency rates to develop a phase diagram for the droplet impingement studies based on Weber number.

研究分野：thermal engineering

キーワード：phase change　nanoscale

## １．研究開始当初の背景

Impact behaviour of a liquid droplet on a heated solid surface is relevant to a broad range of industrial processes. Today, there is still a need to understand and manipulate drop impact for applications like printing, spray coating, heat transfer control or the prevention of icing. When the substrate's temperature is sufficiently high above the boiling point, the droplet can levitate itself from the substrate instead of experiencing sudden boiling due to the well-known Leidenfrost effect.

For efficient heat transfer purpose, it is desirable for the droplet to have less contact time with the heat transfer surface. Liu et al. [*Nat. Phys. 10, 515-519, 2014*] using micro-engineered surfaces with hydrophobic coating demonstrated a novel way to reduce the contact time of the droplets on a solid surface. Similarly, Bird et al. [*Nature, 503, 385-387, 2013*] designed surfaces in such a way that impacting droplets can split into two child droplets which can bounce faster than the parent drop by approximately ~ 40%.

Despite exciting findings, how the morphology of the sub-micron features affects the timescale of the droplet bouncing on super-heated surfaces is not investigated yet. Advanced measurement techniques with high spatial and time resolution is required to capture the underlying physics behind the droplet impingement on super-heated surfaces.

## ２．研究の目的

The key objective of proposed research is to understand the dynamics of impinging droplets on surface engineered super-heated surfaces. The specific objectives of the research are as follows:

(1) Understanding the role of nanoscale texturing and wettability

The morphology of the nanoscale features and its effect on the timescale of the droplet bouncing on super-heated surfaces is critical to develop efficient heat transfer surfaces.

(2) Formulation of phase diagram of droplet impingement on nano-engineered surfaces

It is significantly necessary to rationally control the residence time and quantitatively predict the critical Weber number for the occurrence of 'pancake' bouncing. A phase diagram similar to the p-v diagram in thermodynamics will be formulated considering the critical factors into account which will facilitate improved physical understanding the phase change phenomena.

(3) Development of time domain thermoreflectance and high speed visualization for simultaneous measurements of interfacial thermal transport and surface temperature

Advanced measurement techniques with high spatial and time resolution is required to capture the underlying physics behind the droplet impingement on super-heated surfaces especially the rate of vapour layer formation beneath the hot surface and the temporal response of surface temperature.

The novelty of this work was the first attempt to investigate the mechanisms of droplet impingement on nano engineered surfaces exhibiting 'pancake' like bouncing behaviour at super-heated regime while previous works were limited to room temperature. Furthermore, on superheated surfaces, the residence time of droplet is often captured using high speed videography [*Richard et al. Nature, 417,811-813, 2002*]. Similarly, the amount of heat transfer during droplet impingement is measured by monitoring the surface temperature using thermocouples and infrared thermometry. However, the time resolution of such measurements are limited to the order of few seconds. Another novelty of this work is to combine the advantages of using high speed visualization and time domain thermoreflectance to simultaneously capture the thermal boundary resistance between the impinging droplet and the solid surface, residence time, surface temperature of the solid at a spatial resolution of 20-50 µm and a faster time resolution of ~1 ms.

## ３．研究の方法

In the present work, the impact behaviour of droplets on heated surface and the time taken to bounce back namely the residence time and the lateral spreading length is of paramount importance which decides the heat transfer efficiency. To understand the mechanism and achieve superior heat transfer efficiency, we propose the following stage by stage plan:

Stage 1 – Nano-engineered surfaces fabrication

Surfaces with desired morphology will be fabricated using soft lithography facility at Kyushu University as shown in figure 2. Functional hydrophobic coatings on desired areas were coated using self-assembled mono layers (SAMs) to manipulate the wettability of the surfaces or graphene nanosheets.

Stage 2 – Characterization of nano-engineered surfaces

Surfaces prepared using soft lithography were characterized using SEM/TEM to visualize the patterns.

Stage 3 – Experiments using time domain thermoreflectance and high speed visualization

Droplet impact measurements were carried out on heated substrate along with the high speed visualization. To simultaneously measure the surface temperature changes and interface thermal conductance, two photon absorption and time domain thermoreflectance measurements were carried out.

Stage 4 – Experimental measurements

Combination of optical thermometry using the two photon absorption and time domain thermoreflectance was carried out to capture the dynamics of surface temperature and interfacial thermal resistance between droplet and heated substrate. This has resulted in understanding the underlying physics to develop a phase diagram for the droplet impingement studies based on Weber number.

## ４．研究成果

Combination of optical thermometry using the two photon absorption and time domain thermoreflectance was utilized to capture the dynamics of surface temperature and interfacial thermal resistance between droplet and heated substrate. This will enable us to understand the underlying physics at high frequency rates which is helping to develop a phase diagram for the droplet impingement studies based on Weber number.

## 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

〔雑誌論文〕（計　8　件）

All the articles are peer-reviewd.

1. V. Sharma, D. Orejon, Y. Takata, V. Krishnan, <u>S. Harish</u>, Gladiolus dalenii based bioinspired structured surfaces for water vapor condensation and fog harvesting, *ACS Sustainable Chemistry & Engineering*, Volume 6, Issue 5, 2018, pp 6981 - 6993.
DOI: 10.1021/acssuschemeng.8b00815

2. P.M. Sivaraman, <u>S. Harish</u>, M. Premalatha, A. Arunagiri, Performance analysis of solar chimney using mathematical and experimental approach, *International Journal of Energy Research,* Volume 42, Issue 7, 2018, pp 2373 - 2385.
DOI: 10.1002/er.4007

3. C. Selvam, R. Solaimalai raja, D. Mohan lal, <u>S. Harish</u>, Overall heat transfer coefficient

improvement of an automobile radiator with graphene based suspensions, *International Journal of Heat and Mass Transfer,* Volume 115 (part B), 2017, pp 580 - 588.

DOI: 10.1016/j.ijheatmasstransfer.2017.08.071 N.

4. Das, Y. Takata, M. Kohno, S. Harish, Enhanced melting behavior of carbon based phase change nanocomposites in horizontally oriented latent heat thermal energy storage system, *Applied Thermal Engineering*, Volume 125, 2017, pp 880 - 890.

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2. S. Harish, M. Kohno, Y. Takata Enhanced heat transport and phase change behavior of nanocomposites for thermal energy storage applications, *6th International Symposium on Micro and Nano Technology*, March 2017, Fukuoka, Japan.

3. S. Harish, N. Das, M. Kohno, Y. Takata, Phase change behavior of carbon based nanocomposites in horizontal shell-tube latent heat thermal energy storage systems, *2nd Thermal and Fluids Engineering Conference*, April 2017, Las Vegas, USA.

4. S. Harish, N. Das Enhanced melting of phase change nanocomposites in latent heat thermal storage systems, *Asia Pacific Conference on Energy Storage and Conversion,* September 2016, Hsinchu, Taiwan.

〔図書〕（計　0　件）

**〔産業財産権〕**

**○出願状況（計　0　件）**

**名称：**
**発明者：**
**権利者：**
**種類：**
**番号：**
**出願年月日：**
**国内外の別：**

**○取得状況（計　0 件）**

**名称：**
**発明者：**
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**種類：**
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**〔その他〕**

**ホームページ等**

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