Progress 100 Symposium
and
the Second
ThermaSMART Annual Workshop

New Advances and Key Questions in Phase-Change Cooling

Monday 2 – Wednesday 4 December 2019
I^{2}CNER HALL, KYUSHU UNIVERSITY
Fukuoka, Japan

Programme

九州大学
KYUSHU UNIVERSITY

I^{2}CNER

THERMASMART

Progress 100 Symposium and The Second ThermaSMART Annual Workshop

— New Advances and Key Questions in Phase-Change Cooling —

Schedule:

Mon 2 Dec, 2019	13:00 – 17:05	Technical sessions
	17:30 – 19:00	Reception
Tue 3 Dec, 2019	9:30 – 12:20	Technical sessions
	13:20 – 15:20	Lab tour
	15:20 – 17:20	ThermaSMART meeting
Wed 4 Dec, 2019	9:30 – 16:30	Technical sessions
	17:30 – 19:00	Symposium dinner

Venue: I^2CNER Hall, International Institute for Carbon-Neutral Energy Research (WPI-I^2CNER), Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

Registration: General 20,000 JPY (180 EUR, 160 GBP, 200 USD)
Student 10,000 JPY (90 EUR, 80 GBP, 100 USD)

About the meeting:

Following the successful First Annual ThermaSMART Workshop held in Tianjin in 2018, ThermaSMART and the International Institute for Carbon-Neutral Energy Research (WPI-I^2CNER), Kyushu University will jointly hold a meeting with approximately 40 international experts from 10 countries and 5 continents to discuss problems related to phase-change, interfacial phenomena and multiphase flows.

We would like to take this opportunity to foster a dialogue exchanging the state-of-art in the underlying principles and technology of phase-change cooling. In particular, we expect more questions to be raised and key issues to be brought forward. These issues could be:

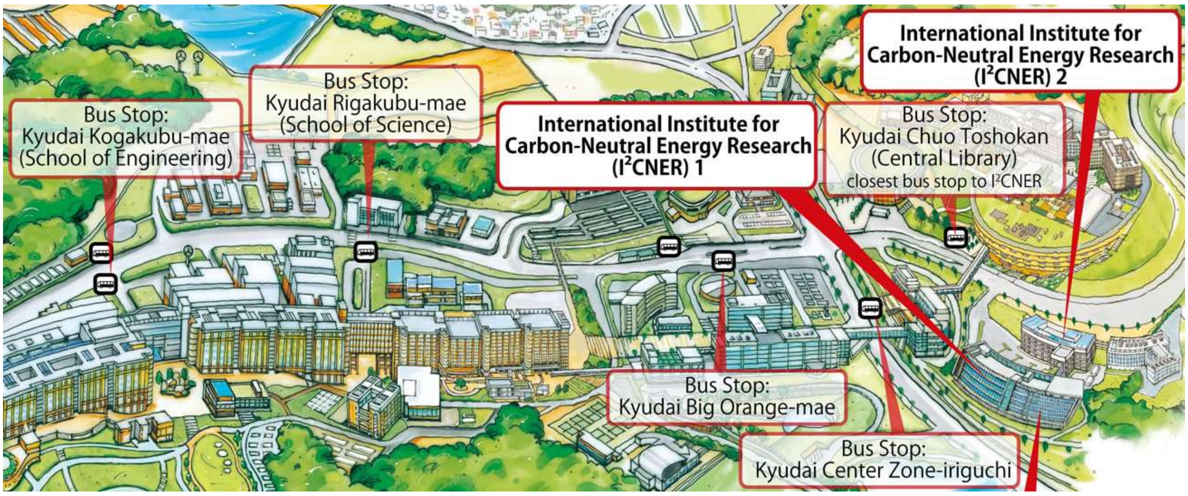
- **Fundamental questions**: phase-change heat transfer mechanisms, dynamics of interface/ triple-phase contact line, multiphase flow instabilities, multiscale phenomena
- **Experimental challenges**: efficacy of experimental methodology, measurement limits
- **Theoretical questions**: role of boundary conditions and their validity
- **Numerical questions**: appropriate methods

Meeting organisers:

Yutaku Kita, Kyushu University — Symposium Chair
Yasuyuki Takata, Kyushu University — Co-chair

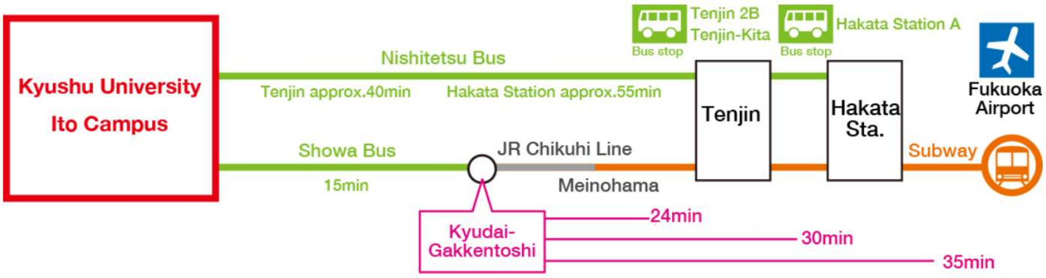
Prashant Valluri, University of Edinburgh — ThermaSMART Coordinator
Kate Morris, University of Edinburgh — ThermaSMART Project Manager

Venue Information – I^{2}CNER Building 1



Address: Kyushu University, Ito Campus, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

Directions (from Fukuoka Airport)



Recommended route:

1. Go to the subway station (Fukuoka Airport Domestic Terminal).
2. Take Fukuoka City Subway (Kuko-line) bound for “Nishikaratsu” or “Chikuzen-Maebaru”.
3. Stop at “Kyudaigakkentoshi Station” (35 min ride, ticket: 560 JPY).
4. Take Showa Bus bound for Ito Campus and stop at “Central Library”. (ticket: 250 JPY)
   There are several routes to the venue such as:
   (a) bound for East Gate <u>via Gakuendori</u> (12 mins) – **recommended!**
   (b) bound for Athletic Field (or Ito Harmony House) via Yokohama Nishi (17 mins)
   (c) bound for Athletic Field (or Ito Harmony House) via Susenji Station (19 mins)

For more information, visit http://www.isc.kyushu-u.ac.jp/supportcenter/en/map

Accommodation – The Residential Suites Fukuoka (TRS Fukuoka)

1-3-70 Momochihama, Sawara-ku, Fukuoka 814-0001

https://www.trs-fukuoka.co.jp/english/

*Fee is **NOT** included in the registration fee

Directions (from Fukuoka Airport)

1. Go to the subway station (Fukuoka Airport Domestic Terminal).
2. Take Fukuoka City Subway (Kuko-line) – any destination is fine.
3. Stop at “Nishijin Station” (20 min ride, ticket: 300 JPY) and walk to Exit 1.
4. Walk north along Sazaesan Street for about 10 mins.

To the venue (I^{2}CNER)

There will be shuttle buses to and from the meeting venue on 2-4 Dec.

Monday 2 Dec

10:30am Pick up at TRS Fukuoka	–	11:30am Arrival at I^{2}CNER
8:00pm Pick up at I^{2}CNER	–	9:00pm Arrival at TRS Fukuoka

Tuesday 3 Dec

8:00am Pick up at TRS Fukuoka	–	9:00am Arrival at I^{2}CNER
(for Non-ThermaSMART Attendees)		
3:30pm Pick up at I^{2}CNER	–	4:00pm Arrival at TRS Fukuoka
(for ThermaSMART Attendees)		
5:30pm Pick up at I^{2}CNER	–	6:30pm Arrival at TRS Fukuoka

Wednesday 4 Dec

8:00am Pick up at TRS Fukuoka	–	9:00am Arrival at I^{2}CNER
5:30pm Pick up at I^{2}CNER	–	6:00pm Arrival at Tanikyu (Dinner)
8:00pm Pick up at Tanikyu	–	9:00pm Arrival at TRS Fukuoka

Subway (Nishijin Station): Take “Kuko-line” bound for “Nishikaratsu” or “Chikuzen-Maebaru” and follow the same direction as in the previous page.

Technical Programme

Keynote speakers:

Ranga Narayanan, PhD
Distinguished Professor and William P. and Tracy Cirioli Term Professor
University of Florida, United States
"***Evaporative suppression of Rayleigh-Taylor instability in pure and binary mixtures***"
1:20 pm – 1:50 pm, Monday 2 December 2019

Tomohide Yabuki, DEng
Associate Professor
Kyushu Institute of Technology, Japan
"***High-resolution measurement of fundamental heat transfer processes in pool nucleate boiling***"
3:40 pm – 4:10 pm, Monday 2 December 2019

Stephen K. Wilson, DPhil
Professor, 1984 Chair in Mathematics
University of Strathclyde, United Kingdom
"On the evaporation of multiple sessile droplets"
9:30 am – 10:00 am, Wednesday 4 December 2019

Stephen Shaw, PhD
Associate Professor
Xi'an Jiaotong – Liverpool University, China
"***Development of a two-phase compressible Euler numerical solver with applications to shock wave interactions with gas bubbles***"
1:40 pm – 2:10 pm, Wednesday 4 December 2019

Monday, 2 December 2019

Time Beg	*- End*	*Duration*	*Title*	*Speaker*	*Affiliation*
12:00	13:00	01:00	Registration + Lunch		
13:00	13:20	00:20	Opening and Introduction		
			Session 1 (Chair: Prashant Valluri)		
13:20	13:50	00:30	Evaporative suppresion of Rayleigh-Taylor instability in pure and binary mixtures	Ranga Narayanan	University of Florida
13:50	14:10	00:20	Thermal management challenges on integrated electric powertrain-drivers, difficulties and	Bo Li	University of Nottingham
14:10	14:30	00:20	An application of machine learning in flow regime identification	Wil Jones	Flow Capture/University of Edinburgh
14:30	14:50	00:20	Drag reduction on free-falling Leidenfrost droplet	Muhammad Sofwan	Universiti Malaysia Perlis
14:50	15:10	00:20	TBA	Davide Masiello	University of Edinburgh
15:10	15:40	00:30	Coffee/tea break		
			Session 2 (Chair: Josua Meyer)		
15:40	16:10	00:30	High-resolution measurement of fundamental heat transfer processes in pool nucleate boiling	Tomohide Yabuki	Kyushu Institute of Technology
16:10	16:30	00:20	Effects of surface prosity and wettability on saturated boiling of ethanol	Biao Shen	Kyushu University
16:30	16:50	00:20	The influence of laminar flow conditions on the onset of flow boiling in a horizontal tube	Marilize Everts	University of Pretoria
16:50	17:10	00:20	Advanced instrumentation and diagnostics for two-phase flow mechanisms research	Jungho Kim	University of Maryland, College Park
17:30	19:30	02:00	Reception@I2CNER LOBBY		

Tuesday, 3 December 2019

Time Beg	*- End*	*Duration*	*Title*	*Speaker*	*Affiliation*
			Session 3 (Chair: Panagiotis Theodrakis)		
09:30	09:50	00:20	Dropwise condensation on structured surfaces	Daniel Orejon	University of Edinburgh
09:50	10:10	00:20	Simulation studies on droplet nucleation and thin film heat/mass transfer	Hongtao Gao	Dalian Maritime University
10:10	10:30	00:20	Numerical simulation of nucleation and droplet growth of carbon dioxide in supersonic flows	Chuang Wen	University of Nottingham
10:30	11:00	00:30	Coffee/tea break		
			Session 4 (Chair: Rachid Bennacer)		
11:00	11:20	00:20	Thermodynamic analysis for a pulsating heat pipe	Xiangzhi Zhang	University of Nottingham, Ningbo China
11:20	11:40	00:20	Experimental investigation on the surfactant influence on the heat transfer performance of pulsating heat pipe	Xuehui Wang	University of Nottingham
11:40	12:00	00:20	Effects of operating conditions on refrigeration performance of reciprocating room temperature active magnetic regenerator	Georges El-Achkar	Tianjin University of Commerce
12:00	13:00	01:00	Lunch		
13:00	15:00	02:00	Labtour	Optional	
			Shuttle bus from KU to TRSF for non-ThermaSMART attendees		
15:00	17:00	02:00	ThermaSMART project meeting	ThermaSMART members only	
17:00	17:10	00:10	ThermaSMART Photo session		

Wednesday, 4 December 2019

Time Beg - End		*Duration*	*Title*	*Speaker*	*Affiliation*
			Session 5 (Chair: Khellil Sefiane)		
09:30	10:00	00:30	On the evaporation of multiple sessile droplets	Stephen Wilson	University of Strathclyde
10:00	10:20	00:20	New perspectives in modelling heat transfer and multiphase flow	Lennon O Naraigh	University College Dublin
10:20	10:40	00:20	Experimental investigation on the behavior of ferromagnetic fluid droplet in a magnetic field	Li Wang	University of Nottingham
10:40	11:00	00:20	Mechanisms of vapor absorption into hygroscopic ionic solution droplets	Zhenying Wang	Kyushu University
11:00	11:30	00:30	Coffee/tea break		
			Session 6 (Chair: Harish Sivasankaran)		
11:30	11:50	00:20	Molecular-scale modelling of droplet evaporation in phase-change: A coupled Monte Carlo - Kinetic Monte Carlo (KMC2) scheme	Panagiotis Theodrakis	Polish Academy of Sciences
11:50	12:10	00:20	Influence of capillary origami of elastic membranes on the evaporation of sessile drops	Yuhong Chen	University of Edinburgh
12:10	12:30	00:20	In-situ observation of water inside hydrophilic and hydrophobic CNTs	Yoko Tomo	Kyushu University
12:30	12:40	00:10	Photo session		
12:40	13:40	01:00	Lunch		
			Session 7 (Chair: Lennon O Naraigh)		
13:40	14:10	00:30	Development of a two-phase compressible Euler numerical solver with applications to shock wave interactions with gas bubbles	Stephen Shaw	Xian Jiaotong Liverpool University
14:10	14:30	00:20	Asymmetric droplet breakup by bifurcation in multiple-layer microsystem	Yong Ren	University of Nottingham, Ningbo China
14:30	14:50	00:20	Numerical two-phase flows study in channels with variable cross-section	Gustavo Anjos	Federal University of Rio de Janeiro
14:50	15:10	00:20	Chaotic orbits of tumbling ellipsoids in viscous and inviscid fluids	Erich Essmann	University of Edinburgh
15:10	15:40	00:30	Coffee/tea break		
			Session 8 (Chair: Daniel Orejon)		
15:40	16:00	00:20	Crystallisation-induced flows in evaporating aqueous saline drops	John Christy	University of Edinburgh
16:00	16:20	00:20	Evaporative parameters, controlling particle formation in evaporating microdroplets	Justice Archer	University of Bristol
16:20	16:40	00:20	Thermocapillary migration of a self-rewetting liquid droplet	Hongyu Zhao	University of Edinburgh
16:40	17:00	00:20	The distribution of droplet deposition patterns affected by thermal strategies	Zeyu Liu	University of Nottingham
17:00	17:25	00:25	Closing		
18:00	19:30	01:30	Meeting dinner@Tanikyu		

Evaporative suppression of Rayleigh-Taylor instability in pure and binary mixtures

Dipin S. Pillai[1] and Ranga Narayanan[2]

1. Department of Chemical Engineering, IIT Kampur, Uttar Pradesh, India
2. Department of Chemical Engineering, University of Florida, Gainesville, FL, US

In this work, we explore the configuration of an interface between a heavier liquid lying above its lighter vapor. This configuration is well-known to be unstable due to the classic Rayleigh-Taylor instability. The stability of the interface in this heavy-over-light configuration is investigated in the presence of evaporation. To this end, a model configuration of a liquid lying above its vapor confined between two flat plates is chosen. The system is heated from the vapor side by maintaining the temperature of the plate in contact with the vapor higher than that in contact with the liquid. This simple model aims to mimic a pool boiling scenario frequently observed in heat transfer units such as conventional heat exchangers and modern heat pipes. A weighted residual-integral boundary layer (WRIBL) model based on the long-wavelength approximation is developed for this system. Unlike most earlier one-sided models with a passive vapor phase, we consider both liquid and vapor phases to be active, thereby ensuring that the total mass of the system always remains conserved. The role of mechanical and thermal inertia is also ascertained by using the WRIBL method.

We show that strong evaporation (large ΔT) can linearly stabilize Rayleigh-Taylor instability. Interestingly, when evaporation is weak (lower ΔT) and the system is linearly unstable, it can still evolve nonlinearly to a steady stable interface configuration that sustains a stable layer of vapor. Momentum inertia is shown to slow down the rate at which the interface reaches its steady configuration. It also results in nonmonotonic evolution of the interface. The thermal inertia is shown to have a stabilizing role. On further weakening of evaporation (negligible ΔT), the interface approaches the bottom plate. Under such conditions, the system exhibits features of a pure Rayleigh-Taylor and exhibit hydrodynamic sliding as observed earlier by Lister and co-workers. The study is extended to the case of a binary mixture where solutal Marangoni effect is also considered. We study a specific choice of binary mixture (ethanol-sec butanol), wherein the less volatile component (ethanol) has higher surface tension. It is shown that the solutal Marangoni effect associated with such a binary mixture renders the system more unstable compared to pure component system, but never unstable enough that a binary system can cause the interface to fall while a pure system might cause it to be stably suspended.

Certain interesting observations and open questions that remain are:

(a) The unreasonable power of phase-change that offers stabilization to an otherwise unstable interface. Even mild amount of evaporation (ΔT as low as 0.1K for water-water vapour system) is found to be enough strong to sustain a thin stable film of vapour underneath the heavier liquid. This warrants the need to design novel and effective means to delay dryout in thermal management.

(b) The exact mathematical description of the interface between a liquid and its vapour undergoing phase change. While several models exist base on equilibrium and various versions of non-equilibrium models,

they can result in widely different interfacial phenomena. An example being the purely monotonic instability predicted by equilibrium model (Ozen and Narayanan) as compared to oscillatory instabilities (McFadden and Coriell (2009)).
(c) The role of bounding wall topography and thereby non-rectilinear input of heat-flux in delaying dryout of heat exchangers.
Acknowledgements: NASA- NNX17AL27G

Thermal management challenges on integrated electric powertrain-drivers, difficulties and demonstrators

Bo Li, Xuehui Wang, Yuying Yan
Faculty of Engineering, University of Nottingham, Nottingham, UK

A helicopter view of current thermal challenges on transport electrification is introduced in order to underpin the research developments and trends of recent cooling techniques. Major thermal issues of high power density machines were raised including the difficulties of understanding of thermal path and multiphysic interactions in power electronic semiconductors, non-isotropic electromagnetic materials and thermal insulation materials. The review listed several typical integrated machines with integrated cooling techniques such as liquid cooling jacket, impingement/spray cooling and immersion cooling. To facilitate the development of integrated electric machine, the phase change cooling method is reviewed and a recent research project is introduced to explain the efforts of integration based on a mechanic-electric-thermal holistic approach. In addition, a brief introduction of the emerging new cooling techniques is presented and the keys to a successful integration is concluded.
Key unsolved questions: Periodic thermal behaviour (Pulse) of power electronic is usually hHz or Khz, which means the transient time is in μs range, this great difficulties on heat transfer simulation regarding the BCs, intervals, and convergence. Any other smart ways to get away with it but capture the accurate thermal response of each thermal shock? For example, nucleate boiling on a heated surface with a superfast periodic BCs (μs)? * PE engineers need that 100% accurate thermal impedance and it is nearly impossible to measure it directly in real world.

An application of machine learning in flow regime identification

Wil Jones
Flow Capture AS, Skedsmokorset, Norway and University of Edinburgh, Edinburgh, UK

The complex nature of multiphase flow makes fully understanding their behavior very challenging even to this day. This means that for the purpose of industrial designs, generalizations of multiphase flow phenomena need to be made, this is typically done in the form of flow regime identification. Many sources have reported that the traditional process of identifying flow regimes is long winded and involves laborious quantities of hand calculations. In this talk I will be presenting two new and robust techniques for identifying multiphase flow regimes using machine intelligence and image recognition. Firstly, numerical flow-regime data was compiled on air-water two phase flow, this data was then fed through a kNN machine learning algorithm and an artificial neural network in order to construct two flow regime maps. The resulting flow regime maps were compared to analyze the strengths and weaknesses of each machine learning method. Secondly, a convolutional neural network was applied to classify two phase flow images into an initial pre-defined set of flow regimes. By training the machine to learn how to identify x-ray projections of two-phase air-water pipe flows, the machine was able to predict these two-phase flow regimes to a high degree of accuracy and with rapid a run time. This same technique was applied to two more image sets; a set of holdup plots and a set of coupled images which incorporated both the x-ray images along with their corresponding holdup plots, resulting in a total of three sets of neural networks to identify flow regimes via image recognition. Each of these image recognition tasks and outcomes were compared to better understand the prospect of applying convolutional neural networks to industrial multiphase flow problems.

Questions:

1) Would applying a weighted kNN increase the performance of the kNN classifier for the numerical data problem?
2) Is there another technique of coupling the x-ray and holdup images?
3) Noise analysis was completed by changing pixel resolution in preprocessing and completing error analysis, would it make sense to pursue future work into correlating noise with attributes within the different flow regime images?
4) Would another type of classifier or different neural network architecture be more suitable to tackle either the numerical or image recognition problem?
5) Would suitable future work entail applying these techniques in vertical two-phase flows, three-phase flows and transient flows to see if the techniques are equally applicable throughout various multiphase flow cases?

Acknowledgment: I would like to express my gratitude to both Dr Prashant Valluri and Dr Bin Hu for providing me the opportunity to conduct this research as part of my final year studies towards a master's degree in chemical engineering from the University of Edinburgh.

Drag reduction on free-falling Leidenfrost droplet

Muhammad Sofwan Mohamad[1,2], Coinneach Mackenzie Dover, Rachid Bennacer[3] and Khellil Sefiane

1. Institute for Multiscale Thermofluids, School of Engineering, University of Edinburgh, Edinburgh, UK
2. School of Mechatronic Engineering, Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia
3. ENS-Cachan, LMT, CNRS, Université Paris Saclay, Paris, France

Drag reduction is highly desired in various applications such as ships and underwater vehicles to reduce power consumption and minimize impact on environment. In recent years, the use of air/ gas lubrication to reduce hydrodynamic drag has been a topic of intense research interest. One possible method to create the lubricating layer is by utilizing Leidenfrost effect. In this study, The ability of Leidenfrost effect to reduce drag coefficient of a free-falling liquid droplet in an immiscible viscous liquid is experimentally examined. Liquid gallium was used to create the droplet and FC-72 was used as the continuous phase. In the experiments, the initial temperature of liquid gallium was varied in the range of 40ºC to 170ºC, while the temperature of FC-72 was kept constant at 50ºC for all cases. High speed imaging system was used to record the motion of the free-falling droplet in FC-72. The fully-developed Leidenfrost regime was stabled at droplet temperature of 130ºC indicated by the vapour layer stream moving upward on the droplet surface. A 57% drag reduction is observed for the 170ºC droplet compared to the 40ºC droplet. This research extends previous studies on the drag reduction efficiency of gas layers sustained on solid (rigid) spheres falling in liquid by the Leidenfrost effect. The understanding gained from this research will hopefully contribute to the current effort in developing and applying air/ gas lubrication based technologies for sustained drag reduction.

High-resolution measurement of fundamental heat transfer process in pool nucleate boiling

Tomohide Yabuki

Department of Mechanical and Control Engineering, Kyushu Institute of Technology, Fukuoka, Japan

The development of high-resolution diagnostics enables direct access to the micro-scale fundamental heat transfer phenomena in the nucleate boiling, such as evaporation and dry-out of the microlayer, rewetting of the dry-patch, convection induced by bubble motion and the heat transfer at the three phase contact line. Our group has been utilizing MEMS thermal sensor having multiple micro thin film temperature sensors and high-speed IR thermography for the microscale observation of fundamental processes. The findings obtained through the fast local thermal measurement leads to better understanding of the boiling mechanisms. Also the precise measured local wall temperature is useful as the benchmark data for direct numerical simulations of nucleate boiling. This talk will focus on (1) contribution of each fundamental heat transfer process to overall wall heat transfer, and (2) heat and mass transfer characteristics of the microlayer (thin liquid film) with dependence on fluid properties.

Effects of surface porosity and wettability on saturated boiling of ethanol

Biao Shen[1], Takeshi Hamazaki[2], Naoki Iwaki[2], Sumitomo Hidaka[2], Koji Takahashi[1,3], Yasuyuki Takata[1,2], Junji Nunomura[4], Akihiro Fukatsu[4], and Yoichiro Betsuki[4]

1. International Institute for Carbon-Neutral Energy Research, Kyushu University, Fukuoka, Japan
2. Department of Mechanical Engineering, Kyushu University
3. Department of Aerodynamics and Astrodynamics, Kyushu University
4. UACJ Corporation, Tokyo, Japan

Effective thermal management of high-performance electronic systems relies on boiling heat transfer, which often employs low-boiling-point fluids such as ethanol. Conventional boiling surface design for ethanol entails complex shape modifications. In this study, we explore the possibility of enhancing ethanol boiling using both porous texturing and wettability patterning. The experimental results show that boiling could be enhanced significantly (more than 100%) compared with the Rohsenow correlation on a surface coated with porous structure. However, the onset of nucleate boiling (ONB) was found to vary wildly dependent on the initial wetting state of the surface. Deposition of a biphilic pattern (consisting of amphiphobic coating of fluoropolymer modified halloysite nanotubes) on top of the microporous textured surface led to an over-40-Kelvin shift in ONB while retaining nearly all the gains in boiling performance, as Fig. 1 shows.

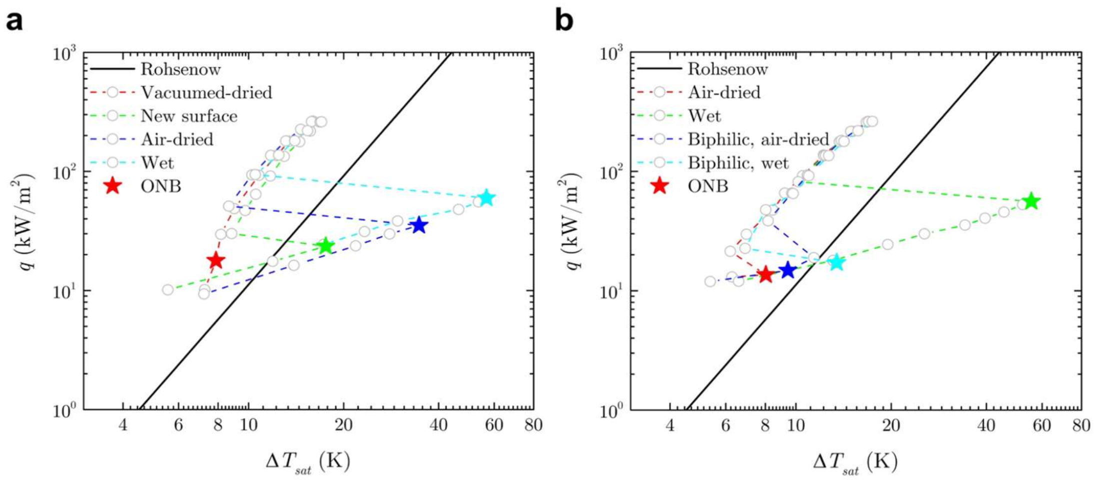


Fig. 1 Boiling curves for (a) the sulfuric acid anodized surface and (b) phosphoric acid anodized surface.

Key unresolved questions: How does one describe the physical mechanism behind the dramatic reduction of ONB on the wettability-modified porous surface? Is it possible to accurately predict ONB based on parameters such as surface topography and wettability?

The influence of laminar flow conditions on the onset of flow boiling in a horizontal tube

Marilize Everts and Josua P Meyer
University of Pretoria, Pretoria, South Africa

When heat is applied to a tube surface, the fluid near the surface (which has a higher temperature and thus lower density) circulates upward along the tube surface. Continuity then requires the fluid in the centre of the tube (which has a lower temperature and higher density) to flow downward. This leads to a secondary fluid motion, which is symmetrical about a vertical plane, and is also known as free convection effects. Combining the secondary fluid motion with the axial fluid velocity, leads to three-dimensional streamlines with a spiralling character [1]. Although free convection effects are always present when a temperature difference exist inside a tube, it might not always be significant compared to the axial fluid velocity. The flow regime maps of Metais and Eckert [2], for a constant surface temperature boundary condition, and Everts and Meyer [3], for a constant heat flux boundary condition, can be used to determine whether free convection effects are negligible (forced convection) or significant (mixed convection). Mixed convection conditions can increase the heat transfer to a fluid in laminar flow through a horizontal tube by a factor of three or four [4] and significantly decrease the thermal entrance length, therefore it has a significantly influence on the flow characteristics. Although it is known that when increasing the free convection effects, the laminar heat transfer coefficients will increase and the thermal entrance length will decrease, it is not known what will happen with the local heat transfer coefficients at the onset of flow boiling and how this will affect the flow downstream of the tube. The purpose of this study is to investigate the influence of laminar flow conditions (forced or mixed convection conditions and developing and fully developed flow) on the onset of flow boiling, as well as the flow boiling characteristics, in a smooth horizontal tube. Experiments will be conducted in a smooth horizontal tube heated at very high heat fluxes, in order to obtain flow boiling along the tube length from four different flow conditions: (1) forced convection developing flow, (2) forced convection fully developed flow, (3) mixed convection developing flow, (4) mixed convection fully developed flow.

References:

[1] Newell, P.H., Jr. and A.E. Bergles, *Analysis of combined free and forced convection for fully developed laminar flow in horizontal tubes*. Journal of Heat Transfer, 1970. **92**(1): p. 83-94.

[2] Metais, B. and E. Eckert, *Forced, mixed, and free convection regimes*. Journal of Heat Transfer, 1964. **86**(2): p. 295-296.

[3] Everts, M. and J.P. Meyer, *Flow regime maps for smooth horizontal tubes at a constant heat flux*. International Journal of Heat and Mass Transfer, 2018. **117**: p. 1274-1290.

[4] Oliver, D., *The effect of natural convection on viscous-flow heat transfer in horizontal tubes*. Chemical Engineering Science, 1962. **17**(5): p. 335-350.

Advanced instrumentation and diagnostics for two-phase flow mechanisms research

Jungho Kim

Department of Mechanical Engineering, University of Maryland, College Park, MD, US

Numerical simulations can provide insight into the physics of phase change and is slowly becoming a cost effective way to design new systems involving boiling and condensation in HVAC and power systems, cryogenics, and water recovery among others. However, the models that feed into the numerics should be validated and experiments and simulations should ideally be tightly coupled, with experiments providing the needed boundary and initial conditions required for simulations, and simulations providing insight into experimental results. Advanced diagnostic techniques are needed to verify phase change heat transfer mechanisms for models and theory. Ideally, full field measurements of the velocity and temperature within the fluid (both vapor and liquid) along with wall temperature distributions would be measured. Some techniques to measure the temperature/heat flux distributions at the solid fluid interface have recently been developed using various techniques, but measurements *within the fluid* have proved to be very difficult especially at higher heat fluxes due to the merging and departing bubbles that limit optical access. High resolution tomographic techniques based on electrical conductivity, electrical capacitance, nuclear spin, neutron absorption, etc. may provide access such data. Techniques to measure the thickness of thin films that occur in the annular regime in flow boiling or condensation are generally based on optical or ultrasonic techniques are available, but these are not reliable when used to measure highly turbulent, wavy films. More robust techniques to measure film thicknesses are needed. The use of advanced instrumentation and data acquisition systems to obtain full field data for pool and flow boiling processes, and improved modeling that will be developed from such data, will have a game-changing impact on this field. This research will provide a valuable dataset for model development and will significantly improve our understanding of boiling physics. Future experiments should provide spatially and temporally resolved wall heat flux measurement whenever possible. Techniques that can access velocity and temperature within the bulk fluid should be developed and demonstrated.

Dropwise condensation on structured surfaces

Daniel Orejon[1,2], Yasuyuki Takata[2,3]

1. Institute for Multiscale Thermofluids, School of Engineering, University of Edinburgh, Edinburgh, UK
2. International Institute for Carbon-Neutral Energy Research (WPI-I²CNER), Kyushu University, Fukuoka, Japan
3. Thermofluid Physics Laboratory, Department of Mechanical Engineering, Kyushu University

The occurrence of condensation phase change in a dropwise fashion has potential applications in thermal management and cooling of electronics. On a smooth hydrophobic surface, the better heat transfer performance of dropwise condensation when compared to filmwise condensation has been reported [Rose, *Proc. Inst. Mech. Eng. A* 216, **2002**]. More recently, superhydrophobic surfaces have been demonstrated to provide enhanced heat transfer when compared to smooth hydrophobic ones as a consequence of the efficient removal of smaller sized droplets characteristic of high heat transfer [Miljkovic *et al.*. *Nano Lett.* 13, **2013**].

Recent work on condensation phase change on micro- and nano-structured coated and un-coated superhydrophobic surfaces is introduced. The presence and absence of micro- and nano-structures on the coalescence and droplet shedding performance via gravitational effects or droplet-jumping are discussed and demonstrated in terms of a surface energy analysis.

Nonetheless, to date most experimental work has been carried out at moderate sub-cooling conditions, since increasing sub-cooling leads to the nucleation and growth of droplets in between the micro- and/or nano-structures in partial Wenzel state (high adhesion) eventually leading to the flooding of the surface. Then, different studies aiming to minimise water vapour diffusion and nucleation of droplets within the nano-structures are reviewed and discussion on the effective design of structured surfaces withstanding high sub-cooling conditions by novel fabrication techniques is posed to ThermaSmart partners.

Simulation studies on droplet nucleation and thin film heat/mass transfer

Hongtao GAO*, Dong NIU, Wei LV, Fei MAO, Jiaju HONG

Naval Architecture & Ocean Engineering College, Dalian Maritime University, Dalian, China

This presentation includes three parts: droplet nucleation and growth on high-precision surface; effect of models of smooth laminar and wave laminar on falling film absorption; heat and mass transfer in membrane-based absorber microchannels.

Droplet nucleation and growth have a significant influence on the dropwise condensation heat transfer. Controlling the droplet nucleation and growth with a high-precision surface to realize the dropwise condensation heat transfer enhancement is a promising way. Molecular dynamics simulation is employed to investigate the effects of heat flux, surface wettability. Simulation results indicate that the high heat flux can lead to the droplet nucleation and growth inside the rough structure and finally the Wenzel droplet will form due to the coalescence between the inside droplet and the initial existing droplet. However, for the surface with lager contact angle, the droplet in Wenzel state will transit to Cassie state due to the droplet coalescence. The droplet nucleation radius is introduced to quantitatively determine the droplet nucleation state (inside or outside the nanostructures) and whether the dropletcould achieve the state transition from Wenzel to Cassie or not in the growth process.

Falling film absorption is one of the most common forms of mass and heat transfer in absorption system. Based on the analysis of the mass and heat transfer characteristics of LiBr solution in the falling film absorption process, the physical and mathematical models of smooth laminar and wave laminar falling film absorption are established by using the finite element method. Simulation results show that when there is an isolated wave passing through the liquid film surface, the mass transfer flux will fluctuate, and then become stable. The mass transfer flux of wave laminar flow is larger than that of smooth laminar flow.

The use of microporous hydrophobic membranes in absorbers and generators in absorption systems can limit the solution interface and will fundamentally address the application limitations of conventional absorption systems. A two-dimensional CFD model of plate and frame type membrane-based absorber is established to simulate the phenomena of water vapor transport across membrane and heat and mass transfer in the absorber.

Of course there are some questions in our simulation, such as: 1) Limited by molecular simulation method itself, the simulation scale maintained at nanoscale. Is the vapour property in the nanoscale consistent with the macroscale? 2) The size and the arrangement of the rough structure can represent the random nanostructure or not? 3) In what condition will the surface wave of liquid film improve the mass transfer and heat transfer?

Numerical simulation of nucleation and droplet growth of carbon dioxide in supersonic flows

Chuang Wen[1], Yan Yang[1], Hongbing Ding[2], Yuying Yan[1, *]

1. Faculty of Engineering, University of Nottingham, University Park, Nottingham, UK
2. Tianjin Key Laboratory of Process Measurement and Control, School of Electrical and Information Engineering, Tianjin University, Tianjin, China

*Corresponding author: Yuying.Yan@nottingham.ac.uk

The mitigation of CO_2 emissions is an effective measure to solve the global warming issue. The present study proposed and developed a computational fluid dynamics (CFD) model to predict the CO_2 condensing flow in a supersonic nozzle. For the prediction of the non-equilibrium condensation of CO_2 in supersonic flows, the comparison between the ideal gas law and Redlich – Kwong EOS shows that the ideal gas assumption significantly under-predicts the mass flow rate of the CO_2 through the Laval nozzle with the relative error up to 25% at the inlet pressure of 50 bar. The expansion characteristics of the CO_2 in supersonic flows is over-predicted by the ideal gas assumption, i.e. Mach number of 1.94 at nozzle outlet by ideal gas law compared to 1.77 by Redlich – Kwong real gas model. Furthermore, the ideal gas assumption computes a later onset of the non-equilibrium condensation of CO_2 in supersonic flows compared to the real gas model. The Redlich – Kwong EOS predicts higher mass generation both for the nucleation process and droplet process than the ideal gas assumption. There are 9 orders of magnitudes between the mass generation due to the nucleation process and the droplet growth process, which indicates that the droplet growth process contributes significantly to the mass transfer during the CO_2 condensation in supersonic flows. The ideal gas model under-predicts the CO_2 condensation with a liquid fraction of approximately 15% of the total mass, while the Redlich-Kwong EOS predicts a liquid fraction up to 28% of the total mass. The key unsolved questions include the roles of the viscous heating and boundary layers in the condensation process in supersonic flows and are expected to be carried out in future.

Thermodynamic analysis for a pulsating heat pipe

Xiangzhi Zhang[1] and Yuying Yan[1,2]

1. Research Centre for Fluids and Thermal Engineering, University of Nottingham Ningbo China, Ningbo China
2. Fluids and Thermal Engineering Research Group, Faculty of Engineering, University of Nottingham, Nottingham, UK

E-mail: (XZ) xiangzhi.zhang2@nottingham.edu.ch (YY) yuying.yan@nottingham.ac.uk

Pulsating heat pipes (PHP), or oscillating heat pipes (OHPs) are passive heat transfer devices where the heat can be carried at a much higher velocity compared with general heat transfer devices, such as metal fins, which makes PHPs efficient cooling tools in thermal management systems. In thermodynamics, the exergy is described as the maximum theoretically available energy to do work with respect to a given state via a reversible process, while the entransy is a novel physical quantity that characterize the potential of heat transfer. In the present study, we have discussed the exergy and entransy dissipation during the processes of heat transfer, phase change and liquid slug friction, along with numerical simulations of a pulsating heat pipe, in order to investigate the effects of temperature fluctuations, vapor pressure, sensible/latent heat on heat transfer performance and thermodynamic efficiency. The results show that several parameters have impacts on the heat transfer performance of a pulsating heat pipe, and the initial temperature is a factor that significantly affect the exergy and entransy dissipation among the parameters. Afterwards, a potential approach is to explore the correlation between the periodic oscillations of multiphase flow state and energy migration with thermodynamic quantities, but there remain several questions to be solved, including the thermodynamical description of oscillation starting and the randomness involved in an operation period.

Keywords: pulsating heat pipe, exergy, entransy, dissipation

Experimental investigation on the surfactant influence on the heat transfer performance of pulsating heat pipe

Xuehui Wang[1,2], Yuying Yan[1], Xiaohong Han[2], Guangming Chen[2]

1. Fluids and Thermal Engineering Research Group, Faculty of Engineering, University of Nottingham, Nottingham, UK
2. Institute of refrigeration and Cryogenics, Zhejiang University, Hangzhou, China

In this presentation, the effect of surfactant solutions on the startup characteristics, heat transfer performance and dry-out heat flux of the PHP were investigated experimentally. The surfactant was sodium stearate, and three different concentration solutions (10 ppm, 20 ppm and 40 ppm) were prepared. The operational characteristics of the PHP with deionized water and surfactant solutions were tested when the charge ratio and the heat flux were (30.9%~67.9%) and (637~19427) W/m^2, respectively. The experimental results indicated that for the PHP with surfactant solutions, it could start at a lower heat flux. The temperature also oscillated at a lower level at the same time. The thermal resistance of the PHP could be greatly decreased by using surfactant solutions as the working fluid. When the concentration of the solution was 20 ppm, the PHP had the lowest thermal resistance in the tested conditions. The results also suggested that the PHP with surfactant solutions presented higher dry-out heat fluxes, and showed relatively stable temperature oscillation characteristics.

Based on the experimental results abovementioned, the author would like to be open-minded to discuss the following questions. First, whether the initial distribution of the vapor and liquid phase affects the heat transfer performance of the flow boiling/two phase convection boiling in microchannel? Second, we would like to explore the theoretical models to predict the influence of the surfactant on the heat transfer performance of PHP.

Effects of operating conditions on refrigeration performance of reciprocating room temperature active magnetic regenerator

Georges El Achkar[1*], Bin Liu[1], Rachid Bennacer[1,2]

1. Tianjin Key Laboratory of Refrigeration Technology, Tianjin University of Commerce, Tianjin, China
2. LMT/ENS-Cachan/CNRS, Paris-Saclay University, Cachan, France

*Corresponding author: georges.elachkar@tjcu.edu.cn

The growing need for cooling of microprocessors and high-power electronic devices requires an increasing use of two-phase thermal systems, such as heat pumps, capillary pumped loops or loop heat pipes. Nevertheless, these thermal systems have the disadvantage of operating with refrigerants, which often have a negative impact on the ozone layer and/or a significant contribution to the greenhouse effect. The quality of the new environmentally friendly refrigerants will probably be to the detriment of the energy performance or the stability of these thermal systems. It is therefore important to search for new cold production solutions ensuring low environmental impact and high energy efficiency and stability.
In this context, the magnetic refrigeration technology, based on the magnetocaloric effect (MCE) of magnetocaloric materials (MCMs), appears as a potentially viable solution. The theoretical optimal coefficient of performance (COP) of this technology is of the same order as that of two-phase thermal systems. In addition, this technology operates with water at low pressure and frequency, which is convenient for the environment, the security, the maintenance cost, the noise and the lifetime. However, this technology involves rare earth MCMs, which are less available and very expensive, and its initial cost is higher than that of two-phase thermal systems.
In this work, an experimental study was conducted on the refrigeration performance of a reciprocating room temperature active magnetic regenerator (AMR), with gadolinium and water used as MCM and working fluid, respectively. A test rig allowing the control of the AMR operating conditions was designed and realized. The effects of the magnet moving speed (0.04-0.16 m/s), water pumping time (0.4-0.8 s) and room temperature (14.5-18.1 °C) on the AMR cold end temperature were determined. An optimal working point was found for a magnet moving speed of 0.16 m/s, a water pumping time of 0.7 s and a room temperature of 18.1 °C, with a lowest cold end temperature reached of 5.2 °C.

On the evaporation of multiple sessile droplets

Stephen K. Wilson
Department of Mathematics and Statistics, University of Strathclyde, Glasgow, UK
E-mail: s.k.wilson@strath.ac.uk

As well as being of fundamental scientific interest in their own right, evaporating sessile droplets arise is a wide range of practical applications, including printing and heat transfer. As a result, there has been an explosion of theoretical and experimental work on droplet evaporation in recent years, including theoretical work at the University of Strathclyde, much of it collaboration with Professor Khellil Sefiane and his research group in Edinburgh (see, for example, references [1]-[7]). In common with most of the research in this area, this work concerns single droplets. However, in practice, droplets rarely occur in isolation, and so there is considerable interest in understanding (and possibly harnessing) the interaction between multiple evaporating droplets. In this talk I shall describe our recent advances in this area. In particular, I shall describe our recent theoretical work on the evaporation of a pair of thin droplets in two dimensions and on the evaporation of multiple thin droplets in three dimensions.

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New perspectives in modelling heat transfer and multiphase flow

Lennon Ó Náraigh[1] and Daniel R. Jansen van Vuuren[1,2]

1. School of Mathematics and Statistics, University College Dublin, Dublin, Ireland
2. School of Engineering, University of Pretoria, Pretoria, South Africa

In this work we bring new methodologies to bear on two familiar problems in Heat Transfer and Multiphase flow. In the first case, we outline how linear stability analysis can be used to predict the onset of Marangoni convection in a sessile droplet heated by a hotspot. This is preliminary work and some questions about boundary conditions need to be clarified before the full linear stability analysis can be conducted. In the second case, we outline how an existing highly parallel in-house CFD solver (TPLS) can be modified to allow for the interaction between the fluid and solid bodies and, at the same time, for heat and mass transfer. This opens up the possibility to look at classical problems in Fluid Dynamics, but with a twist – for instance, how the presence of particles in a Rayleigh-Bénard cell can enhance the heat transfer achievable from natural convection.

Experimental investigation on the behavior of ferromagnetic fluid droplet in a magnetic field

Li Wang

Fluids and Thermal Engineering Research Group, Faculty of Engineering, University of Nottingham, Nottingham, UK

In recent years, the application of droplet in aerospace have received increasing attention. In this experimental study, in order to simulate the behavior of droplet in a non-gravity environment, ferromagnetic fluid has been adopted to balance the gravity with its magnetic force in a magnetic field. The process of droplet being lifted from the surface against gravity will be studied, and the surface wettability, as well as droplet density and viscosity will be studied as factors. High-Speed camera will be used to record the process of droplet lifting, and contact angle will be calculated using MATLAB. It’s expected that the droplet will be more likely to be lifted as a whole part on a hydrophobic surface, and with bigger liquid viscosity. Contradictorily, the droplet is more likely to break into multiple parts in this process. A problem remaining is that as the droplet is dark and opaque, is very hard to measure the streamline inside the droplet. LBM Simulation works also carried to get numerical results of the streamline and temperature distribution. Pseudo-potential method is adopted, and simulations of droplet evaporate & condensation has been done.

Mechanisms of vapor absorption into hygroscopic ionic solution droplets

Zhenying Wang[1,2], George Karapetsas[3], Prashant Valluri[4], Khellil Sefiane[2,4], Yasuyuki Takata[1,2]

1. Department of Mechanical Engineering, Kyushu University, Fukuoka, Japan
2. International Institute for Carbon-Neutral Energy Research (WPI-I²CNER), Kyushu University
3. Department of Chemical Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece
4. School of Engineering, University of Edinburgh, Edinburgh, UK

Ionic solution with hygroscopic properties has been widely applied in various dehumidification and heat recovery systems. This talk focuses on the physical mechanisms of vapor absorption into single hygroscopic ionic solution droplets. With the assistance of high-speed optical imaging, infrared thermography and micro PIV, we experimentally reveal the droplet dynamics, the heat and mass transfer processes, and the thermal and solutal Marangoni effects of single hygroscopic droplet undergoing vapor absorption. The influences of substrate wettability and environmental conditions are analyzed, and the evolution of driving forces for vapor diffusion is evaluated along with time. An innovative mathematical model is developed for sessile hygroscopic solution droplets based on the lubrication approximation. This model fully reveals the complex multi-physical processes, and indicates the distribution of different interfacial parameters and evolution of flow fields within the droplet. The droplet kinetics is further explained by decomposing the capillary effect, the solutal Marangoni effect and the thermal Marangoni effect. This work provides a good example of collaborative research with the support of ThermaSMART project, which combines the experimental advantage of Kyushu University and the modeling advantage at University of Edinburgh. Further collaborations will continue regarding the interface instability with the mathematical model and the dendritic structures that form from evaporating hygroscopic ionic solution droplets.

Molecular-scale modelling of droplet evaporation in phase-change: A coupled Monte Carlo – kinetic Monte Carlo (KMC^2) scheme

Panagiotis E. Theodorakis[1], Soheil Arbabi[1], Yongjie Wang[1], Bin Liu[2], Georges El Achkar[2]

1. Institute of Physics, Polish Academy of Sciences, Warsaw, Poland
2. Tianjin Key Laboratory of Refrigeration Technology, Tianjin University of Commerce, Tianjin, China

High-power electronic devices require functionality at top processing speed and durability. In this context, phase-change cooling has been identified as the technology of the future, which overcomes many of the shortcomings of air-cooling technology. The ambition of our work is to understand the complexities of phase-change technology right from the evaporation at the solid substrate at a molecular-scale resolution, in this way reaching beyond the current state-of-the-art understanding of evaporation phenomena in phase-change cooling technology. To achieve this, we are developing a coupled Monte Carlo – Kinetic Monte Carlo (KMC^2) scheme, which constitutes a simple and accurate way of simulating evaporation phenomena at the molecular level. The computational scheme combines the advantages of an off-lattice Monte Carlo molecular model and a Kinetic Monte Carlo scheme that allows to exchange molecules between the liquid and the vapour phase. The method also offers the possibility of simulating evaporation of liquid mixtures with or without additives (e.g. nanoparticles, surfactants) based on force-fields that can take into account the chemical identity of the species, in this way establishing a closer connection with relevant experiments. Our case study is a sessile liquid droplet, which will be simulated by using the KMC^2 method to obtain molecular-scale information on the evaporation process, such as evaporation rate or patterns. On this path, we discuss challenges and new routes towards addressing various issues facing molecular modelling in the case of evaporation phenomena in the context of phase change technology.

Influence of capillary origami of elastic membranes on the evaporation of sessile drops

Yuhong Chen[1], Daniel Orejon[1], Prashant Valluri[1], Vasileios Koutsos[2], Khellil Sefiane[1]

1. Institute for Multiscale Thermofluids, University of Edinburgh, Edinburgh, UK
2. Institute for Material Process, University of Edinburgh, Edinburgh, UK

Drops drying on elastic substrates are common in our daily life and in nature, such as from perspiration on human skin and raindrops on tree leaves. Particularly, when the elastic substrate is thin enough, it can fold around the evaporative drop. This is known as ‘capillary origami’ governed by the competition between the decrease of surface energy of the drop and the increase of elastic bending energy of the membrane. In present work, we carried out evaporation experiments of pure water and ethanol drops on square PDMS membranes, respectively. These membranes were fabricated to various thicknesses, which give rise to different folding extent. Specifically, the different extent of folding for water drops is as follows: thick membranes do not fold whereas thin membranes partially fold and very thin membranes completely fold. In cases of ethanol drops, membranes either do not fold (thin) or fold completely (very thin). The different folding states between water and ethanol drops can be attributed to the different surface tension of the two liquids. The PDMS membrane is hydrophobic for water drops while behaves other than omniphobic for ethanol drops. The folding extent is measured by the distance between the endpoints of the membrane extracted from side-view imaging. Results indicate that the folding of membranes reduces the average evaporation rate of drying drops therefore lengthening the drop lifetime, irrespective of liquid wettability. Furthermore, we try to explain such a dependence in detail by relating the evaporation rate of drops to the surface area of evaporation (the liquid-gas interface area). However, the latter is difficult to calculate when capillary origami happens. A model combining both drop evaporation and thin tube evaporation for the complete folding cases is considered but needs more discussion on its validity. Upon understanding how the folding of elastic membranes influences drop evaporation, we may go further with drops containing particles. By evaporating a drop with particles in suspension on such folding membranes, the coupling of membrane folding and particle deposition may lead to the formation of well-arranged predetermined 3D structures. This opens new questions to be addressed as how the thickness of the membrane, type of suspension (type liquid, particles and concentration), and the isolation of the deposits from the membrane can be effectively carried out for specific purposes.

In-situ observation of water inside hydrophilic and hydrophobic CNTs

Yoko Tomo
Department of Mechanical Engineering, Kyushu University, Fukuoka, Japan

Water under nanoscale confinement differs from the bulk water in physical properties, interfacial morphology and dynamic behavior owing to the strong atomic and molecular interactions in a nanoscale space. We observed water inside hydrophilic and hydrophobic CNTs using the transmission electron microscopy (TEM). Water was stable inside both hydrophilic and hydrophobic CNTs exposed to a high vacuum environment in TEM. However, the interfacial morphology of water depends on the wettability of CNTs. Suspended ultrathin water films, nanobubbles on the wall and the zig-zag shaped liquid-gas interface were observed depending on the wettability. We consider that this different morphology of water was due to the strong atomic and molecular interactions and pinning effects on the wall. These experimental results give new insights into interfacial phenomena and wettability at nanoscale.

Development of a two-phase compressible Euler numerical solver with applications to shock wave interactions with gas bubbles

Stephen J. Shaw
Xi'an Jiaotong - Liverpool University, Suzhou, China

An overview of the development of a compressible Euler numerical solver for two phase gas/gas or gas/water flows in conservative form which permits the study of multiple gas bubble interactions with a shock wave, is presented. In each phase the respective hyperbolic equations are solved using finite difference methods to approximate both the spatial fluxes and temporal derivatives. The interface between the two phases is captured using a level set function and accurate, thermodynamically correct, boundary conditions are imposed using the ghost fluid method, together with the isobaric fix technique. Outstanding issues to be discussed include the improvement in the accuracy of the imposed interface boundary conditions and the improvement of mass conservation. However, the most significant issue is the occurrence of a numerical instability inside the bubble as finer mesh resolutions are employed and is illustrated in the figure below, for a strong shock wave impact.

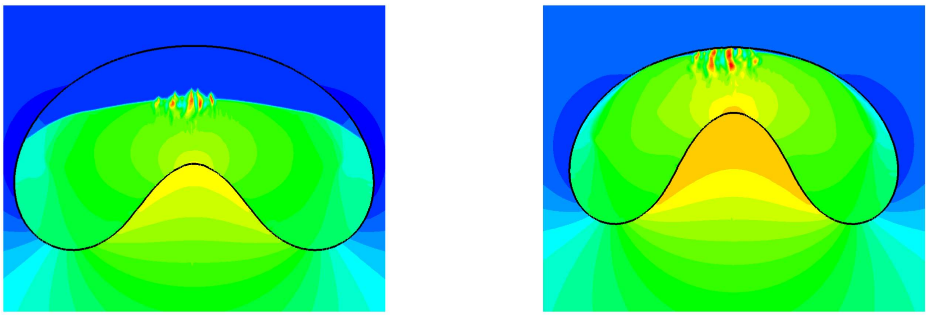

Figure 1: y-velocity contours of a 2D (disc) air bubbles of initial radius 3 mm in water impacted by a 0.4 GPa shock wave.

Asymmetric droplet breakup by bifurcation in multiple- layer microsystem

Yong Ren[1,2*], Yue Chan[3]

1. Department of Mechanical, Materials and Manufacturing Engineering, University of Nottingham Ningbo China, Ningbo, China
2. Research Group for Fluids and Thermal Engineering, University of Nottingham Ningbo China, Ningbo, China
3. Institute for Advanced Study, Shenzhen University, Shenzhen, China

*Corresponding author: yong.ren@nottingham.edu.cn

Microchannel with bifurcation design is one of the most common geometrically mediated strategies for droplet fission in lab-on-a-chip system, leading to a number of biomedical applications. One may expect symmetric breakup of a mother droplet when single layer is used. This talk will focus on asymmetric droplet breakup dynamics when applying two-layer microfluidic multiphase system which features with overlapping of two layers of microchannel followed by constriction in cross-section shrinking towards singularity. Open question remains to be answered for addressing the droplet breakup dynamics when a microsystem with more than two layer structure is used.

Numerical two-phase flows study in channels with variable cross-section

Gustavo R. Anjos[1], Jose Pontes[2], Norberto Mangiavacchi[2], Rachel Lucena[2], Leandro Marques[2], Luis Carnevale[2]

1. COPPE, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil
2. GESAR, State University of Rio de Janeiro, Rio de Janeiro, Brazil

Bubbles and drops dynamics through capillaries of variable cross-section still remains of considerable importance in two-phase flows and is an interesting alternative to standard straight channels used in cooling of electronics. The aim of this work is to investigate two-phase flows found in the cooling of new generation of computer processor units in the scope of the ThermaSMART - Marie-Curie/RISE Consortium. We seek to study numerically the effects of domain boundaries to the bubble dynamics, including change in the film thickness, bubble shape and vortex shedding in channels with variable cross-section using a moving mesh/boundary domain scheme, which dramatically shortens the domain length. Such a scheme moves the computational boundary nodes according to the bubble's center of mass relative to the variable cross-section of a given problem. The new methodology proposed to simulate two-phase flows in variable cross-sectioned channels shows good accuracy to describe interface forces and bubble dynamics in different complex geometries with moving boundaries.

Chaotic orbits of tumbling ellipsoids in viscous and inviscid fluids

Erich Essmann[1], Prashant Valluri[1], Stephane Popinet[2], Rama Govindarajan[3]

1. School of Engineering, University of Edinburgh, Edinburgh, UK
2. Institut Jean le Rond d'Alembert, Sorbonne Universite, Paris, France
3. International Centre for Theoretical Science, Tata Institute of Fundamental Research, Bangalore, India

It was shown that the equations of motions of an immersed tri-axial ellipsoid become non-integrable under certain inviscid conditions, (Kozlov and Onishchenko, 1982). Non-integrability is a necessary condition for chaotic dynamics. We used analytical and numerical methods to determine occurrence and conditions of chaotic orbits in viscous and inviscid environments for both tri-axial and prolate ellipsoids. Our numerical work uses Gerris (Popinet et al, 2003) augmented with a fully-coupled solver for fluid-solid interaction with 6 degrees-of-freedom (6DOF). For inviscid conditions, our numerical results agree with the solution of Kirchhoff's equations. Using recurrence quantification (Marwan et al, 2007) methods, we also characterise chaos and identify regime shifts from being periodic to chaotic. For inviscid systems, we observe chaotic behaviour only in the tri-axial systems and that chaos is a strong function of density ratio and the initial energy ratio. In viscous systems, we have noted evidence of chaotic orbits for symmetric ellipsoids. Due to vortex shedding behaviour in this context breaking the symmetry of the system. We show how chaos can be exploited under viscous environments to promote mixing.

Crystallisation-induced flows in evaporating aqueous saline drops

Marina Efstratiou, John Christy*, Khellil Sefiane
School of Engineering, University of Edinburgh, Edinburgh, UK

When an aqueous saline droplet is left to dry on a hydrophilic glass slide, a ring of spaced crystals is formed. Although there have been speculations on the mechanisms of salt crystal deposition, no experimental work has linked the flows arising in these droplets with the final pattern formation. In our work, we have performed micro-PIV (Particle Image Velocimetry) to examine the link between the flow and the final deposit formation. We report for the first time the existence of a nucleation-driven flow within the droplets which is responsible for the formation of the ring of spaced crystals on the initial periphery of the drop. Two evaporation stages were observed. During the first stage (I), prior to nucleation, a generally outward flow is observed driven by evaporative flux. At the end of this stage, believed to correspond to supersaturation of the salt solution at the contact line, the internal flow decreases significantly. The second stage (II) is governed by the appearance of strong flow jets and vortices within the fluid, due to crystal nucleation and growth. This flow regime appears to be driven by concentration gradients occurring due to crystal nucleation and, demonstrates for the first time how crystal nucleation affects the induced internal flow.

* Presenting author

Evaporative parameters, controlling particle formation in evaporating microdroplets

Justice Archer[1], Florence Gregson[1], Jim Walker[1], Panagiotis Theodorakis[2] and Jonathan Reid[1]

1. School of Chemistry, University of Bristol, Bristol, UK
2. Institute of Physics, Polish Academy of Sciences, Warsaw, Poland

E-mail: justice.archer@bristol.ac.uk

The evaporation of aerocolloidal microdroplets to form solid microparticles is an important process in many industrial applications, especially spray-drying, where rapid evaporation is employed to form solid microparticles for pharmaceuticals, combustion, food and cosmetic products. The evaporation dynamics, and ultimately the morphology and surface structure of the dried microparticle formed, can be highly condition dependent. In particular, the evaporation kinetics is both influenced by the droplet surface recesion rate driven by the mass and heat transfers at the droplet surface as well as the rheological properties of the dispersing solvent and the diffusional mixing rate of the suspended particles. In this talk, I will present recent experimental measaurements based on a single-particle levitation instrument: the electrodynamic balance[1] (EDB) on the drying kinetics of micron-sized droplets for a range of Péclet numbers through variable evaporative parameters (relative humidity, temperature, initial droplet composition and size). The aim is to provide a quantitative data that can be used to scale up industrial processes and applications. Additonally, I will present a complementary droplet-chain technique[2] used to reproduce the droplet drying kinetics for collecting final dried microparticles for offline analysis with scanning electron microscopy (SEM).

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Thermocapillary migration of a self-rewetting liquid droplet

Hongyu Zhao, Daniel Orejon, Khellil Sefiane,

School of Engineering, University of Edinburgh, Edinburgh, UK

The occurrence and accurate transport of microliter droplets without the need for mechanical components are of great importance for microfluidic, medical and biological applications as well as for other analytical purposes. A droplet of a pure liquid deposited on a non-uniformly heated solid surface is driven from the hot to the cool region due to the spatial variations of the liquid-vapour surface tension along the droplet interface. This phenomenon is called thermocapillary migration [1]. Typically, the surface tension of a liquid decreases monotonically with the increase in temperature, however, such dependence of the surface tension on temperature is non-monotonic for self-rewetting fluids [2], which exhibit a minimum of surface tension. This property leads to an interesting phenomenon during the thermocapillary motion.

As a common kind of self-rewetting fluid, n-Butanol aqueous solution has been used in our experiments. In addition, for comparison purpose, other ordinary liquids, such as pure water, butanol, and ethanol aqueous solutions, are presented. To minimize the hysteresis and the friction from the surface, slippery liquid-infused porous surfaces (SLIPSs) were fabricated and used in our experiments. Instead of the unidirectional motion expected for the ordinary liquid droplets, an oscillatory motion under a thermal gradient was observed for the self-rewetting droplets for the first time. Further, the influence of temperature and viscosity of the impregnated liquid on the SLIPS underneath the droplets were investigated.

However, the mechanism remains unknown and a model is required to explain the phenomenon. Besides, it was observed that the thermal gradient on SLIPS may cause the migration of oil and that the oil may also cloak the droplet influencing on the droplet motion. Both migration and cloaking of the oil may lead to oil depletion with the consequent loss on slippery proprieties. In order to achieve a better understanding of the mechanism behind the motion and on the stability of the oil and slippery characteristics, further tests on different SLIPS types, measurements of the surface tension with different temperatures and concentrations, and analysis to explain the oscillation still need to be done.

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The distribution of droplet deposition patterns affected by thermal strategies

Zeyu Liu[1], Yuying Yan[1,3]*, Xinyong Chen[2], Li Wang[1], Xin Wang[1]

1. Fluids & Thermal Engineering Research Group, Faculty of Engineering, University of Nottingham, Nottingham, UK
2. School of Pharmacy, Faculty of Science, University of Nottingham, Nottingham, UK
3. Fluids & Thermal Engineering Research Centre, University of Nottingham Ningbo, Ningbo, China

Controlling deposition patterns can be applied on different applications, like ink-jet printing, liquid biopsy, medical science, and etc. Many scholars have studied different strategies to control deposition patterns, but most patterns are controlled by adjusting droplet characteristics. In this work, saline deposition patterns have been experimentally conducted with different substrate temperatures. The experimental results presented that deposited patterns transited with temperature increasing. Low substrate temperature suppresses the inward transport at the liquid-air interface; in terms of ambient temperature, particles inside tend to the edge for compensation of evaporation loss. At high temperature, dual ring structure formed due to the contribution of both Marangoni flow and radially outward transport. Meanwhile, localized heating is also applied from apex and edge of the droplet. the experimental results showed that the deposits of both heating modes accumulate in the heated area, which possibly because of Marangoni effect. Additionally, micro-beads with the diameter of 3μm are also applied to track particles motions with different temperatures and temperature directions. Experimental results show that thermal strategy is a potential method in controlling the distribution of droplet deposition patterns.

Key unsolved issues:

1. How to track the trajectory of particles in the target solution?
2. How to ensure the stability of colloid?

About ThermaSMART

Project ThermaSMART is an international and intersectoral network of organisations working on a joint research programme in the area of phase-change cooling of microprocessors and high-power electronic devices.

ThermaSMART aims to gain a competitive advantage through the exposure of secondees to new research environments both in academia and industry which will enable exchange of crucial skills and knowledge and empower their career prospects in this increasingly important area.

Our partners span across 5 continents: Europe, Asia, Africa, North America and South America. Our project will promote international and inter-sector collaboration through research and innovation staff exchanges, and sharing of knowledge and ideas from research to market (and vice-versa).

ThermaSMART also offers a unique opportunity to train 41 early stage researchers (over 285 exchange months) in state-of-the-art experimental and modelling techniques for phase-change and microfabrication both in participating Universities and industries.

In addition to regular consortium meetings, technical workshops and research publications, we will hold summer schools at Maryland, Kyushu, Toronto and Edinburgh, alongside several exchange programmes to sustain a long-term interaction between the partners.

For more information, visit https://thermasmart.eng.ed.ac.uk/

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