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VARIABLE THERMAL INTERFACES BASED ON DISCRETE LIQUID DROPLETS

[1*]Zhunusov Zh.A., [2]Arbi Y.

[1]Karaganda Industrial University, Temirtau, Kazakhstan
[2]Padang State University, Indonesia
**Corresponding author e-mail: zharaskanzhunusov@gmail.com*

Author information:
Zhunusov Zh.A. - Karaganda Industrial University, Temirtau, Kazakhstan. E-mail: zharaskanzhunusov@gmail.com
Arbi Yaumal - Department of Civil Engineering, Faculty of Engineering, Padang State University (Universitas Negeri Padang), Indonesia. E-mail: yaumalarbi@ft.unp.ac.id

Abstract. We propose a variable thermal interface based on an array of discrete liquid droplets initially confined on hydrophilic islands in the substrate. The droplets are reversibly morphologically transferred to a continuous liquid film when mechanically compressed by the opposite substrate to create a heat-conducting pathway with low thermal resistance. We study the criterion of reversible transition in terms of hydrophilic sample size and liquid volume. The dependence of fluid morphology and rupture distance on the diameter and distribution share of hydrophilic Islands, fluid volume, as well as load pressure, is also characterized from a theoretical and experimental point of view. The thermal resistance in this state is characterized experimentally for ionic liquids, which are promising for practical use due to the insignificant vapor pressure. A service life test unit has been designed to assess the reliability of the interface under continuous switching conditions at relatively high switching frequencies.
Keywords: variable thermal interface, reversibility, liquid morphology, thermal resistance, reliability.

ДИСКРЕТТІ СҰЙЫҚТЫҚ ТАМШЫЛАРЫНА НЕГІЗДЕЛГЕН АЙНЫМАЛЫ ЖЫЛУ ИНТЕРФЕЙСТЕРІ

[1*]Жүнісов Ж.А., [2]Arbi Y.

[1]Қарағанды Индустриялық Университеті, Теміртау, Қазақстан
[2]Паданг мемлекеттік университеті, Индонезия
**Корреспондент автор e-mail: zharaskanzhunusov@gmail.com*

Авторлар туралы ақпарат:
Жүнісов Ж.А. - Қарағанды Индустриялық Университеті, Теміртау, Қазақстан. E-mail: zharaskanzhunusov@gmail.com
Arbi Yaumal - Паданг мемлекеттік университетінің (Universitas Negeri Padang), Құрылыс инженериясы кафедрасы, Индонезия. E-mail: yaumalarbi@ft.unp.ac.id

Аңдатпа. Біз бастапқыда субстраттағы гидрофильді аралдармен шектелген дискретті сұйықтық тамшыларының массивіне негізделген айнымалы жылу интерфейсін ұсынамыз. Тамшылар қайтымды морфологиялық жолмен қарама-қарсы субстратпен механикалық сығымдалған кезде үздіксіз сұйық қабықшаға ауысады, жылу өткізгіштігі төмен жылу өткізгіш жол жасайды. Біз гидрофильді үлгінің мөлшері мен сұйықтық көлемі бойынша қайтымды ауысу критерийін зерттейміз. Сұйықтық морфологиясы мен жарылу қашықтығының гидрофильді Аралдардың диаметрі мен Аудан үлесіне, сұйықтық көлеміне, сондай-ақ жүктеме қысымына тәуелділігі теориялық және эксперименттік тұрғыдан да сипатталады. Күйдегі жылу кедергісі будың шамалы қысымына байланысты практикалық қолдануға перспективалы иондық сұйықтықтар үшін эксперименталды түрде сипатталады. Салыстырмалы түрде жоғары коммутациялық жиіліктерде үздіксіз коммутация жағдайында интерфейстің сенімділігін бағалау үшін қызмет ету мерзімін тексеру блогы жасалған.
Түйінді сөздер: ауыспалы жылу интерфейсі, қайтымдылық, сұйықтық морфологиясы, жылу кедергісі, сенімділік.

ИЗМЕНЯЕМЫЕ ТЕПЛОВЫЕ ИНТЕРФЕЙСЫ НА ОСНОВЕ ДИСКРЕТНЫХ КАПЕЛЬ ЖИДКОСТИ

[1*]***Жунусов Ж.А.***, [2]**Arbi Y.**

[1]*Карагандинский индустриальный университет, Темиртау, Казахстан*
[2]*Государственный университет Паданга, Индонезия*
**Автор-корреспондент e-mail: zharaskanzhunusov@gmail.com*

Информация об авторах:
Ж.А. Жунусов - Карагандинский индустриальный университет, Темиртау, Казахстан. *E-mail: zharaskanzhunusov@gmail.com*
Arbi Yaumal - Кафедра гражданского строительства, Государственный университет Паданга (Universitas Negeri Padang), Индонезия. Электронная почта: yaumalarbi@ft.unp.ac.id

Аннотация. Мы предлагаем изменяемый термоинтерфейс, основанный на наборе отдельных капель жидкости, изначально удерживаемых на гидрофильных островках в подложке. Капли обратимым образом преобразуются в сплошную пленку жидкости при механическом сжатии противоположной подложкой для создания теплопроводящего канала с низким тепловым сопротивлением. Мы изучаем критерий обратимого перехода с точки зрения размера гидрофильного образца и объема жидкости. Зависимость морфологии жидкости и расстояния разрыва от диаметра и доли участков гидрофильных островков, объема жидкости, а также давления нагрузки также охарактеризованы с теоретической и экспериментальной точек зрения. Термическое сопротивление в этом состоянии экспериментально охарактеризовано для ионных жидкостей, которые перспективны для практического использования из-за незначительного давления паров. Для оценки надежности интерфейса в условиях непрерывного переключения при относительно высоких частотах переключения была разработана установка для проверки срока службы.
Ключевые слова: изменяемый тепловой интерфейс, обратимость, морфология жидкости, термостойкость, надежность.

MAIN PROVISION

A novel variable thermal interface based on discrete liquid droplets confined on hydrophilic islands is proposed and experimentally validated. The study establishes the conditions for a reversible droplet-to-film transition and demonstrates how hydrophilic island geometry, liquid volume, and applied load influence thermal performance. The proposed interface exhibits low thermal resistance and reliable switching stability, highlighting its potential for practical thermal management applications.

INTRODUCTION

Interchangeable thermal interfaces allow controlled modulation of the thermal conductivity between the devices of interest and their heat sinks/sources. They are key components of Micro Devices and systems that require reconfigurable heat transfer pathways to control and control low-power heat. Potential applications [1, 2, 3, 4] include microbolometers with locally adjustable dynamic ranges, pulsed thermoelectric cooling, solid-state electrocaloric refrigerators requiring a fast thermal cycle of the working environment, pyroelectric waste heat collection, and satellite heat management.

It is well proven that thermal transfer through solid-solid contacts is often limited to surface dead ends that reduce specific contact areas. Previous experimental studies have shown that even for rough silicon surfaces on a nanometer scale (<10-4 m2·K·w), a significant load pressure (Order 1 MPA) is required to achieve a small thermal contact resistance (<10-4 m2·K·W) [1]. This may be due to trapped gas layers, which strongly inhibit thermal conductivity. Dense arrays of vertically aligned carbon nanotubes [5] or nanofibers

[6] have received much attention for potential heat transfer applications. A relatively large load pressure, however, was often necessary to achieve a small thermal resistance, as only a small part of the tubes communicated
with the opposite surface. In addition, the strong adhesion between carbon nanotubes and the opposite surface [7] during close contact and the resulting delamination defects render them unsuitable as alternating thermal interfaces.

The previous study showed an appropriate thermal switch consisting of an array of discrete Mercury droplets [2]. Since the thermal conductivity of mercury is relatively high, the thermal resistance in each drop can be very low (~4 × 10-6 M2·K·W). However, Mercury poses a threat to health and the environment. Some alternative room-temperature liquid metals can bypass this problem, but they oxidize quickly in the surrounding air, making their practical use difficult.

Recent studies have repeatedly demonstrated the potential of an alternative liquid-mediated thermal interface that can provide thermal contact resistance comparable to direct solid-state contacts at a small load pressure [8, 9, 10, 11]. The main idea was to use the predominance of surface tension over gravity and other volumetric forces in micromasses to reversibly change the morphology of parallel columns of dielectric fluid bounded by microchannels. In its out-of-state state, the two interface-defining surfaces are separated from each other by an air or vacuum gap. The fluid is bounded by an array of discrete microchannels separated from each other by hydrophobic regions. The two surfaces are then in contact to compress and deform the liquid columns until a continuous liquid layer is formed. Two pages are pulled apart to disable the interface. The continuous liquid layer is then first transformed into an array of liquid bridges covering the gap, which then break off to break the thermal bond between the two surfaces.

The channel-based liquid thermal interface has the advantages that it can be easily made using standard microfabrication methods, and each channel can be easily filled with a specific amount of liquid to control the final distance.

The main disadvantage of this design, however, is associated with its requirement for a long mechanical stroke. The distance required for the rupture of liquid Bridges is equal to the length of the microchannels, or usually ~1 mm. This can be a problem in applications that require microactuators in a limited starting range or a fast thermal cycle.

Research gap. Although previous variable thermal interfaces based on liquid columns and microchannels have demonstrated promising thermal performance, their relatively large rupture distance limits their application in compact microsystems requiring short actuation strokes and high switching frequencies. Therefore, there remains a need for a reversible thermal interface capable of maintaining low thermal resistance while reducing the required mechanical displacement.

This work informs our theoretical and experimental work on an alternative design that replaces microchannels with arrays of discrete chemical-expression hydrophilic islands to reduce or otherwise control the breaking distance of a liquid bridge. As an illustration, Figure 1 shows the difference in the break distance between the two constructions. For one fluid volume in question, the interface with circular islands has a break distance of less than 300 microns [Figure 1(a)], while the interface with parallel microchannels is more than 700 microns [Figure 1(B)].

Novelty statement. The novelty of this work lies in introducing discrete hydrophilic islands as an alternative to conventional microchannels for reversible liquid-mediated thermal interfaces. This design reduces the rupture distance while maintaining low thermal resistance and reliable switching behavior.

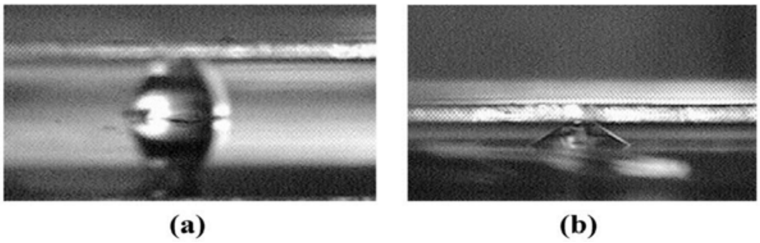

Figure 1 - Comparison of the breaking distances of liquid bridges defined by (a) microchannels and (b) discrete hydrophilic samples

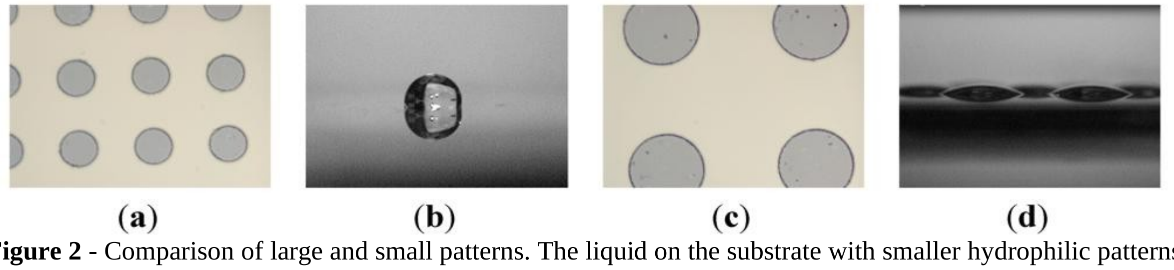

Figure 2 - Comparison of large and small patterns. The liquid on the substrate with smaller hydrophilic patterns (a) forms a single drop after breaking, but on the substrate with larger hydrophilic patterns (c) it forms discrete droplets (d)

METODOLOGY

One of the most important design issues for interchangeable thermal interfaces is their reversibility. That is, the continuous liquid shell resulting from the deformation and fusion of an array of discrete liquid droplets must return to the original state of discrete droplets when the two surfaces are separated from each other.

As a model system, we consider a set of circular hydrophilic patches on a nonhydrophobic surface. The two main design parameters are: (1) sample size, characterized by diameter d, and (2) the territorial portion of the pattern, defined as the proportion of surface area occupied by hydrophilic Islands F. when d or f is too small, the continuous liquid film formed in the addition state can become one large liquid drop instead of several discrete droplet arrays, as shown in Figure 2.

To establish numerical reversibility criteria, we compare the interface energy of the Es of a single-drop State and the EM of a discrete multi-drop State. Assuming that the effect of gravity is negligible, we can bring liquid drops closer as cut balls. The interfacial energy can then be written as:

Here r is the radius of the wetting zone of a single droplet determined by the total volume (equation (3)), the apparent contact angle of a discrete droplet in each hydrophilic sample, g is the required minimum gap (i.e., the target minimum thickness of a continuous liquid layer), and V is the total volume of the liquid.

$$E_s = \left[2\pi r^2 \frac{1-\cos\theta_2}{\sin^2\theta_2} - \cos\theta_1 \cdot \pi r^2 \cdot f - \cos\theta_2 \cdot \pi r^2 \cdot (1-f)\right] \cdot \gamma_{lv} \quad (1)$$

$$E_m = f\left[2\,\frac{1-\cos\alpha}{\sin^2\alpha} - \cos\theta_1\right] \cdot \gamma_{lv} \cdot \frac{V}{g} \quad (2)$$

$$V = \frac{\pi r^3}{3}\frac{(1-\cos\theta_2)^2}{\sin^3\theta_2}(2+\cos\theta_2) \quad (3)$$

Figure 3 shows the interfacial energy calculated for two states f = 0.2, V = 0.7 µL and g = 20 µm. We consider a situation where the contact angle in the hydrophilic pattern is θ1 = 24.4° (experimentally measured for Silicon after plasma etching of hydrophobic coating) and θ2 in the hydrophobic zone (e.g. Teflon® coating) is 120°. It is believed that the liquid-vapor surface tension γlv = 73 mn/M is comparable to water.

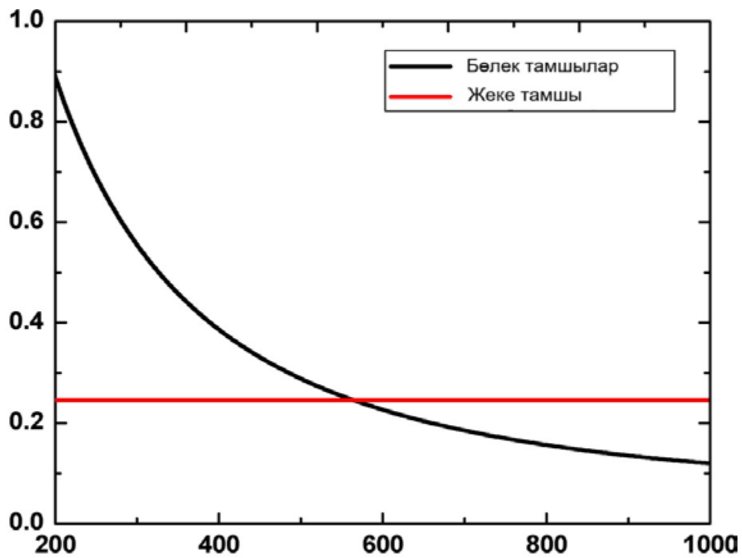

Figure 3 - Interface energy versus sample size of one drop State and multi-drop State

RESEARCH RESULTS

When the sample size is below about 560 microns, the discrete multi-drop State has a higher energy and is therefore less energetically favorable than the single-drop State. That is, instead of forming several discrete droplets, a continuous liquid layer can turn into one large liquid drop when two surfaces are separated from each other. To achieve reversibility, the sample size must exceed this value.

Figure 4 (A) shows the difference in the interfacial energies of the two states for different values of the areal part of the expression F. X-segments of about 500 to 700 microns correspond to the minimum sample size required for a discrete multi-drop state to be energetically acceptable. This minimum sample size decreases as f increases. In other words, smaller samples can achieve reversibility in higher sample fractions, since neighboring hydrophilic samples are located close to each other. When the sample size is very large, the interfacial energy difference decreases as the pattern density increases. The liquid droplets in these large specimens tend to merge to form one large drop. As shown in Figure 4 (b), smaller visible angles are needed to prevent neighboring liquid droplets from merging in higher sample fractions.

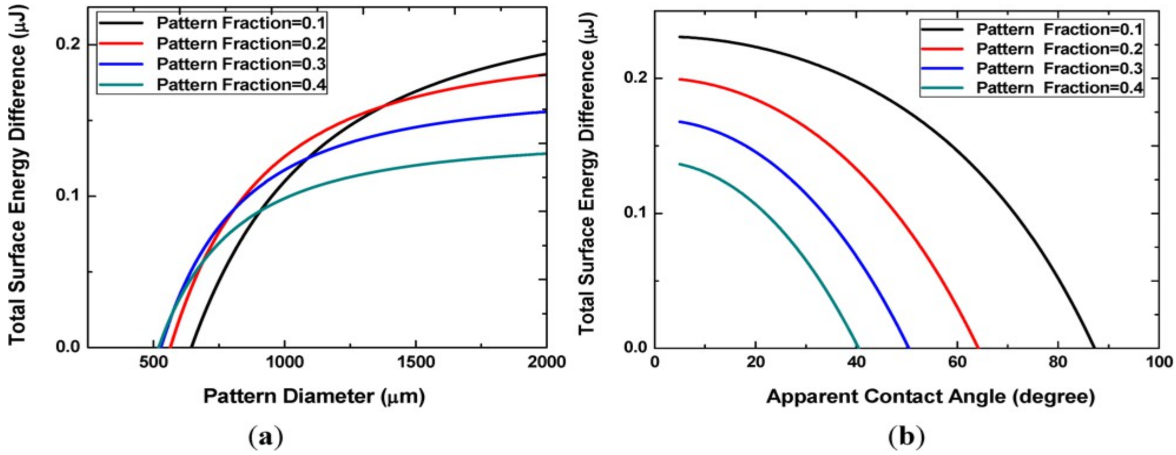

Figure 4 -the difference in interface energy (B) with different sample sizes and densities (a) or different visible angles of discrete droplets

DISCUSSION

The present study demonstrates that the reversibility of the proposed variable thermal interface is primarily governed by the geometric characteristics of the hydrophilic islands and the liquid volume. The theoretical energy analysis and experimental observations consistently indicate that an appropriate combination of these parameters enables a stable reversible transition between discrete droplets and a continuous liquid film.

The analysis further shows that increasing the hydrophilic pattern fraction reduces the minimum island diameter required for reversible operation. This behavior can be explained by the reduced spacing between neighboring hydrophilic islands, which facilitates liquid redistribution while maintaining the stability of discrete droplets after separation. These findings provide practical design guidelines for optimizing reversible thermal interfaces. Recent studies have likewise emphasized that interfacial wettability and liquid morphology are critical factors governing heat-transfer performance and the efficiency of advanced thermal interface materials [12].

Compared with previously reported microchannel-based thermal interfaces, the proposed design offers a substantially shorter liquid bridge rupture distance while preserving low thermal resistance. The experimental evaluation using ionic liquids further confirms their suitability as working fluids because of their negligible vapor pressure and stable thermal characteristics. This observation is consistent with recent reviews highlighting the growing importance of ionic liquids for thermal management applications owing to their high thermal stability and favorable physicochemical properties [13].

The proposed variable thermal interface contributes to the ongoing development of advanced thermal management technologies for engineering applications. Recent studies have emphasized the importance of advanced high-temperature materials and numerical modeling for improving the thermal performance and reliability of heat-transfer systems [14, 15]. In this context, the present work demonstrates that controlling the geometry of hydrophilic islands and liquid morphology provides an effective approach for achieving reversible thermal switching with low thermal resistance, thereby extending the potential applications of adaptive thermal interface technologies.

Although the present study demonstrates the feasibility of the proposed concept, further investigations are required to evaluate long-term durability under different operating temperatures, alternative ionic liquid formulations, and extended switching cycles. Such studies would further support the practical implementation of the proposed thermal interface in advanced thermal management systems.

CONCLUSION

This study demonstrates the feasibility of a reversible thermal interface based on discrete liquid droplets confined on hydrophilic islands. The proposed design provides low thermal resistance while significantly reducing the required rupture distance compared with conventional microchannel-based interfaces. These findings indicate considerable potential for compact thermal switching devices used in MEMS, electronics cooling, and adaptive thermal management systems. Future work should focus on long-term durability, optimization of surface geometry, and performance evaluation under varying thermal loads.

This work establishes the concept of alternating thermal interfaces based on an array of discrete liquid droplets initially confined on hydrophilic islands in a hydrophobic substrate. The droplets are reversibly morphologically transferred to a continuous liquid film when mechanically compressed by the opposite substrate to create a heat-conducting pathway with low thermal resistance. We study the criterion of reversible transition in terms of hydrophilic sample size and liquid volume. The dependence of fluid morphology and rupture distance on the diameter and distribution share of hydrophilic Islands, fluid volume, as well as load pressure are also characterized from a theoretical and experimental point of view. The thermal resistance in this state is characterized experimentally for ionic liquids, which are promising for practical use due to the insignificant vapor pressure. To assess the reliability of the interface in the case of continuous switching at relatively high switching frequencies, a service life test unit is designed.

Author Contribution Statement (CRediT Taxonomy): **Zh.A. Zhunusov**: Conceptualization (lead), Methodology, Investigation, Formal analysis, Validation, Supervision, Writing – Original Draft. **Arbi Y**.: Data curation, Visualization, Writing – Review & Editing. Both authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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