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P01

電場を付与したマイクロチャネル上薄液膜蒸発を利用した高熱流束廃熱デバイスに関する研究

Study on High Heat Flux Thermal Management Devices Utilizing Thin Liquid Film Evaporation on Microchannels with Applied Electric Fields

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1. Introduction

Recently, in accordance with the rapid growth of the aviation industry, it is assumed that spacecraft will become more larger and more advanced, and aircraft are transitioning towards electrification, where traditional mechanical and hydraulic systems are replaced with electric and electronic components. This is due to the growing emphasis on reducing the environmental impact of aviation on a global scale, thus improving cost efficiency, reducing weight, and enhance system reliability. However, there are still several technological challenges associated with the growing trend in electrification of current engines. One of the concerns are regarding effective thermal management of the cooling system, where new solutions to dissipate higher heat loads released by the high-power electric components is required. Moreover, cooling extremely high heat densities with minimal refrigerant flow can be a challenge, especially in downsized engines where space is limited. Efficient thermal management becomes crucial to ensure that the engine components are adequately cooled without compromising performance, durability, or fuel efficiency.

Miniaturizing cooling systems while effectively managing high heat densities is indeed a complex challenge. As an example, microelectromechanical systems (MEMS) devices often generate heat due to their miniaturized size and high functionality, making effective thermal management crucial. Japan Society of Mechanical Engineers (JSME) have formulated a technology roadmap for high heat flux removal that outlined a framework for addressing the challenges posed by escalating heat densities in electronic devices and the necessity for efficient cooling solutions [1]. Based on the roadmap, this study is setting the goal of heat-reducible heat fluxes of $300\ [\mathrm{W/cm^2}]$ as a strategy to overcome the current cooling by means of MEMS of $100\ [\mathrm{W/cm^2}]$. In this study, we are exploring thin liquid film evaporative cooling system in microchannel as a potential solution for managing heat, which involves creating thin films of coolant that evaporates quickly to dissipate heat within a confined space. However, the evaporation rate of the liquid is extremely fast, and it is difficult to form and maintain a stable liquid film. This study suggests that thin liquid film is maintained stably by replenishing the liquid with the combination of capillary force acting on the microchannel and electrostatic force generated by the application of an electric field. Therefore, the final purpose of this study is to develop a compact cooling device by optimizing the efficiency of thin liquid film evaporative cooling systems in microchannel in an approach to address the challenges of cooling high heat densities within compact spaces and aiming the heat removal of $300\,[\mathrm{W/cm^2}]$. The establishment of this technology can contribute to advancements in thermal management technologies for which demand will increase in the future.

2. Overview of High Heat Flux Removal Device

2.1 Heat Transfer Characteristics in Thin Liquid Film Evaporation

In the context of high heat flux removal utilizing thin liquid film evaporation, the cooling system leverages the principle of evaporation to dissipate heat efficiently, making it a potential solution for managing heat in miniaturized systems. Thin liquid film evaporation cooling involves creating a thin layer of liquid coolant on a surface in contact with a heat source. Figure 1 shows the thinning of the liquid film on the right side. It is known that a three-phase interface is formed in this area, which involves the interaction of three phases: the liquid film, the solid substrate, and the vapor phase. Interfacial evaporation occurs at this interface, where heat is conducted from the high heat flux source through the liquid film to the liquid-vapor interface. The phase change associated with interfacial evaporation is key to reducing thermal resistance. As the liquid molecules transition to the vapor phase, they absorb latent heat, where considerable amount of energy is required to change the phase without a temperature change. This phase change absorbs a significant amount of heat, hence, effectively enhances the heat removal capacity of the system.

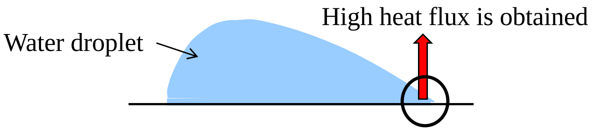

Figure 1. Thin liquid film evaporation.

2.2 Microchannel

Figure 2 shows a diagram of the microchannel, where it can be seen that it is constructed with micro-sized grooves that have uniform width and depth in the order of microns. This geometric consistency and appropriate wettability of the microchannel allows the liquid to spread evenly along the grooves, hence, ensuring that the liquid is confined within the microchannel, facilitating the formation of a thin and controlled liquid film. As shown in Figure 3, a three-phase interface can be formed on the walls of the microchannel when liquid is supplied. The controlled flow of liquid into the microchannel, coupled with the efficient evaporation process, results in a stable and continuous thin liquid film evaporation under minimum refrigerant flow rate within the microchannel.

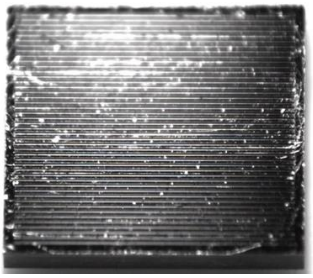

Figure 2. Microchannel.

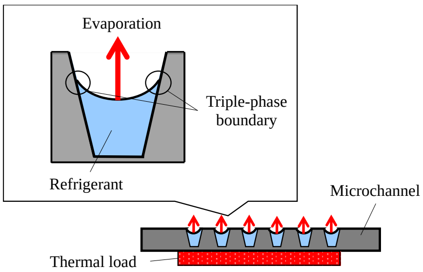

Figure 3. Structure of a microchannel and formation of three-phase interface.

2.3 Refrigerant Supply

Figure 4 provided illustrates the mechanism of the cooling system device used in this study, by which refrigerant is supplied from both ends of the microchannel through a pressure difference. As shown in Figure 5, the atmospheric pressure and the liquid pressure are equally balanced in the manifold. However, as the refrigerant moves from the source manifold into the microchannel, a pressure difference is generated between the atmospheric pressure and the liquid pressure within the grooves, which acts as a driving force that propels the refrigerant through the microchannel. As evaporation causes the liquid film to thin, capillary forces help replenish the liquid from the surrounding areas, ensuring a continuous supply to the evaporating region. Capillary action, driven by surface tension and the geometry of the microchannels, prevents the liquid from pooling and encourages it to spread uniformly.

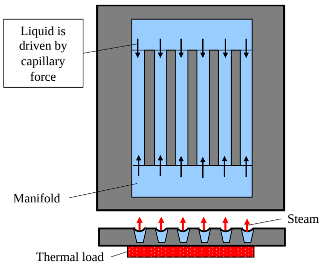

Figure 4. Schematic diagram of refrigerant supplied from both ends of a microchannel.

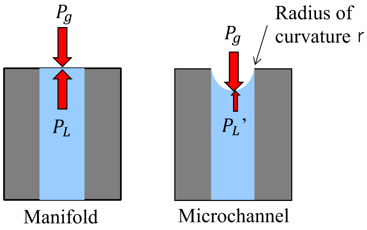

Figure 5. Gas-liquid pressure difference between manifold and microchannel.

2.4 Method of Applying Electric Field

In cases of extremely high heat fluxes, the three-phase interface can transition into boiling conditions, where rapid vapor generation occurs within the liquid film, hence, the capillary driving pressure can no longer counteract the losses incurred by liquid and vapor pressure. Boiling enhances the heat removal capacity but can also introduce risk like dry-out when the capillary limit is reached. This can lead to overheating and reduced cooling effectiveness. Therefore, in order to address these constraints, the Electrohydrodynamic (EHD) technique stands out for its ability to combine with the capillary structures like microgrooves [2].

The introduction of an electric field at narrow electrode spacing can enhance the drive of the movement of the liquid within the grooves of a microchannel cooling system as shown in Figure 6. This mechanism of induction in a microchannel with Electrohydrodynamic (EHD) effects involves the generation of electric fields within the microchannel when a voltage difference is applied. Then, the electric field exerts a force on charged particles present in the fluid, which results to Coulomb force, describing the interaction between charged particles. As the Coulomb force acts on the charged particle, it induces movement in the liquid [3].

To produce a Coulomb force within a liquid, it is necessary to establish a volumetric charge density or space charge. This objective can be accomplished through three primary approaches: conduction, injection, and induction. This study focuses on the induction method for achieving this phenomenon. Within the induction process, the space charge arises due to variations or breaks in electric conductivity. When an electric field is present, a volumetric charge density emerges within the zone of conductivity gradient. This induced charge density experiences attraction or repulsion, consequently initiating liquid movement [4]. Figure 7 shows the schematic diagram for the induction between two electrodes.

This combination of capillary and electrostatic forces will enhance the cooling process and mitigate the challenges associated with the risk of dry-out, thus contribute to achieving the heat removal of $300\ [W/cm^2]$ aimed. By altering the electric field's properties dynamically, we can control the liquid's behavior, allowing for responsive adjustments in the cooling process. The positioning of electrodes that generate the electric field needs to be optimized for effective liquid manipulation. In this study, the cooling system device is constructed with the approach of electrodes configuration parallel to the microchannel. Due to the increased electric field strength resulting from the narrow electrode spacing, lower voltage levels are sufficient to induce significant wetting behavior changes. Using lower voltages translates to lower energy consumption while achieving the desired cooling efficiency of the microchannel.

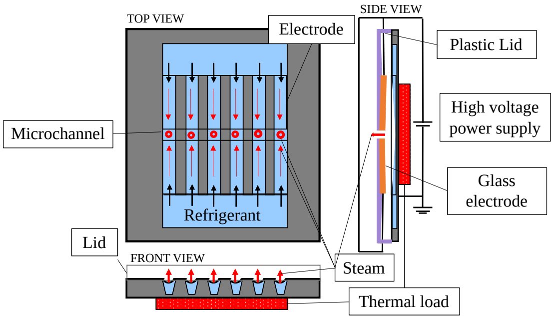

Figure 6. Overall view of the cooling system device.

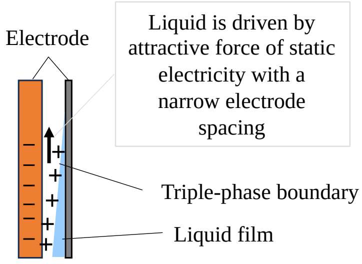

Figure 7. Induction between two electrodes.

3. Experiment on Visualization of Capillary & Electric Force

3.1 Experimental theory

The primary objective of this experiment is to visually and quantitatively study the interplay between capillary and electric forces with liquids within microchannels. In previous study, experiments were conducted using microchannels fabricated from silicon wafers with good wettability. It was confirmed that water was driven into the microchannels both at room temperature and when the microchannels were heated, hence demonstrating the ability of capillary forces to draw liquid into the microchannels. The penetration of water into the microchannels was observed to occur faster at higher temperatures. This aligns with expectations, as increased temperature generally enhances capillary action due to reduced surface tension. But due to risk of dry-out as mentioned, electric field is introduced into the system. Since extremely high voltages are involved, it is crucial first to visualize and comprehend how liquids are driven within microchannels under the influence of voltage. Developing techniques to visualize this behavior and analyzing the flow patterns at different voltages will provide essential insights into the interactions between voltage, electrostatic forces, and capillary action that could contribute to the optimization design of microchannels cooling systems.

3.2 Visualization of Capillary and Electric Force Experimental Setup

The configuration of electrodes in a microchannel cooling system can significantly influence the behavior of liquids within the grooves and subsequently impact heat transfer and cooling efficiency. Parallel electrode placement which involves positioning the electrodes alongside the microchannel walls with the electric field lines running parallel to the liquid flow direction, can indeed introduce certain challenges and complexities. Factors such as electrode surface irregularities, variations in spacing, and the nature of the liquid affecting the wetting behavior requires advanced fabrication techniques in achieving consistent results. Contrarily, perpendicular electrode placement which involves positioning the electrodes perpendicular to the microchannel walls, intersecting the flow direction allows simplifying electrode fabrication and placement. In this study, prior to parallel electrode placement experiment, perpendicular electrode placement experiment is conducted. This sequence provides a baseline for reference and comprehension of the potential challenges and complexities associated with parallel electrodes configuration.

The visualization of capillary and electric force for perpendicular electrode configuration experimental setup is shown schematically in Figure 8. The experimental setup consists of tested microchannel, copper electrodes, DC voltage supply, PTFE board, petri dish, and clamps. Distilled water was used in the experiments as tested liquid due to its well-defined properties and minimal impurities. It has low conductivity, making it sensitive to electric fields and providing a clear response to voltage variations. The microchannel is made out of borosilicate glass, with the dimensions shown in Figure 9. The experiment involves gradually supplying voltage to the electrodes with electrode spacing of 40mm. These electrodes generate electric fields across the microchannel. As the voltage is applied, the electric field interacts with the liquid, influencing the movement of the liquid from the petri dish into the grooves. The rise of the liquid in the grooves in response to the electric field is documented using images and videos.

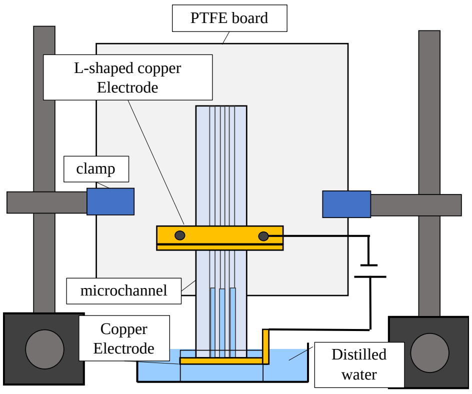

Figure 8. Diagram of the visualization of capillary and electric force experiment.

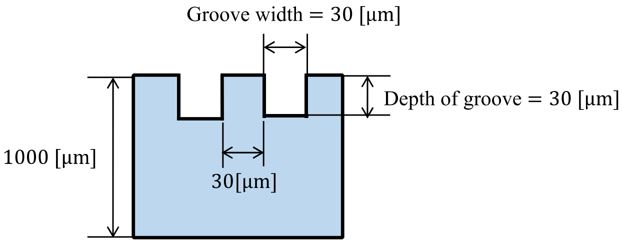

Figure 9. Dimension of the microchannel.

4. Result

The recorded visual data is analyzed to quantify the rise of the liquid in the grooves under different voltage conditions. Figure 10 shows the experimental data of the capillary and electric force experiment recorded. During the experiment, it is observed that the rise of the liquid across multiple grooves in the microchannel is non-uniform. The recorded experimental values focus on the grooves with the most significant differences from the initial condition (voltage 0 [V]), which prioritizes areas where the electric and capillary forces had a more substantial impact. This allows for the extraction of valuable data even when uniformity is challenging to achieve.

The graph shows the non-uniformity in the rise of liquid across multiple grooves in the microchannel during the experiment. The data of the 2nd row and 3rd row from the left side of the microchannel is both taken to compare the difference in the behavior of the liquid.

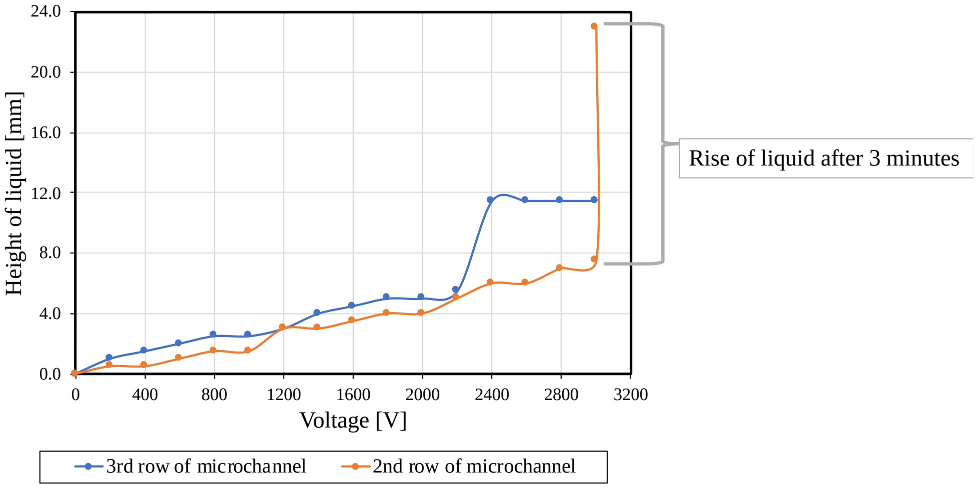

Figure 10. Experiment values of the capillary and electric force experiment.

5. Conclusion

In conclusion, the study findings shed light on the crucial role of voltage in influencing the behavior of the liquid within the microchannel. The observed rise in liquid height as voltage increases underscores the substantial impact of the electric field. With the combination of capillary force, it is evident that the application of voltage is a key factor in inducing and controlling fluid movement through Electrohydrodynamic (EHD) effects in microgrooves.

However, it is important to acknowledge the presence of non-uniformity in the absolute height of the liquid across the multiple grooves in the microchannel. While the voltage-induced response is clear, the variations in liquid height might stem from factors beyond direct control. Subtle microscopic variations in grooves and minor inconsistencies in electrode effects could contribute to this non-uniform behavior. As such, future research efforts could focus on minimizing these sources of non-uniformity to enhance the precision and predictability of the induced fluid movement.

In essence, this study advances our understanding of fluid manipulation within microchannels through EHD effects, emphasizing the significance of voltage while acknowledging the complexities associated with achieving absolute uniformity in liquid behavior. These insights pave way for further investigations aimed at refining techniques for precise fluid control in microfluidic applications and cooling system.

6. References

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