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# An experimental study of the fluid flow and heat transfer characteristics in micro-condensers with slug-bubbly flow

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**Abstract**

Experiments were conducted to study the condensation flow pattern in silicon micro-condensers using water as the medium. Slug-bubbly flow was found to be one of the dominant flows in the micro-condenser and it was a major factor in determining the heat transfer and pressure drop properties of the fluid inside the micro-condenser. The transition from the slug-bubbly flow to a mixed flow pattern was studied. A correlation was obtained to predict when the transition of the flow pattern would occur. Only slug-bubbly flow existed under low steam mass flow rate and high heat transfer rate conditions. As the steam mass flow rate increased or the heat transfer rate dropped, the mixed flow pattern would then appear. In the slug-bubbly flow regime, the heat transfer coefficient and pressure drop in the micro-condensers were investigated in detail. It was found that micro-condensers with smaller channels could exhibit higher heat transfer coefficients with the same Reynolds number. The condensation heat transfer coefficient was higher than that in the tubes with the diameter of centimeter. Pressure drops in the micro-condensers with smaller channels were higher due to the increased transition loss. At the same time, the pressure drop in the micro-condenser was found to be lower than what could be predicted using the macro-scale correlation. Increasing the heat flux would create a longer bubble–film region and fewer unit cells in the micro-condenser resulting in an increased heat transfer coefficient and a decreased pressure drop.


*Keywords:* Cooling; Component; Electronic; Experiment; Flow; Heat transfer; Pressure drop; Microchannel; Condenser

# Etude expérimentale sur l'écoulement du fluide et les caractéristiques de tansfert de chaleur dans les microcondenseurs à écoulement turbulent intermittent

*Mots clés :* Réfrigération ; Composant ; Électronique ; Expérimentation ; Écoulement ; Transfert de chaleur ; Chute de pression ; Micro-canal ; Condenseur

## 1. Introduction

With the fast development of microelectromechanical system (MEMS) technologies, there has been an increasing

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**Nomenclature**

| | |
|---|---|
| $A$ | cross-section area ($m^2$) |
| $d$ | hydraulic diameter (m) |
| $(dp/dx)_{b/f}$ | pressure drop at the bubble–film region (Pa) |
| $G$ | steam mass flow rate ($g\ min^{-1}$) |
| $\dot{m}$ | mass flux of the steam ($kg\ m^{-2}\ s^{-1}$) |
| $q$ | heat flux ($W\ m^{-2}$) |
| $Q$ | heat transfer rate (W) |
| $R_{bubble}$ | radius of the bubble (m) |
| $R_{channel}$ | hydraulic radius of the microchannel (m) |
| $Re$ | Reynolds number of the liquid ($Re = \dot{m}d/\mu_L$) |
| $U_{film}$ | velocity of the film ($m\ s^{-1}$) |
| $x$ | quality |
| $\mu_L$ | viscosity of the liquid ($kg\ m^{-1}\ s^{-1}$) |

interest in developing micro-refrigeration systems in recent years for various new applications. The potential applications of micro-refrigeration systems may include distributed cooling systems in buildings, portable cooling systems for workers in hazardous environments, micro-cooling systems for micro-electronic devices, etc., where traditional refrigeration systems may not be applicable. Besides the new applications, fabricating refrigeration systems by microfabrication technologies also has other advantages including batch fabrication, improved performance, cost effectiveness, compactness, lightness, etc. To date, some researchers have carried out studies on micro-refrigeration systems [1–6] as summarized in ref. [7]. To develop a micro-refrigeration system, it is important to develop all the necessary components successfully at the micro-scale with a comprehensive understanding of the fundamental mechanisms involved in heat transfer and fluid transport.

The micro-condenser is one of the key components needed to develop micro-refrigeration systems. To explore the mechanisms and performance of the micro-condenser, some research work has been conducted in recent years as was illustrated in refs. [8–14]. All these studies offered important insights on the condensation process at the miniature/micro-scale. However, compared with macro-scale condensers, the studies on micro-condensers are far from being mature. Thome [15] and Munkejord et al. [2] noted that the studies of two-phase heat transfer on the micro-scale are still in the very initial development phase. Quite a lot of research works are needed to understand the whole picture. A review of previous studies on the condensation process at the micro-scale showed that:

- Most of the studies were on annular flow, e.g., Zhao and Liao [11], Wang and Rose [13]. Heat transfer and pressure drops in other condensation flow regimes, such as intermittent flow and droplet flow, were relatively less studied. However, such flow regimes may be the dominant flow patterns in micro-condensers under certain conditions.
- Some flow regime maps for small round tubes were established. However, these flow maps were primarily based on experiments on the isothermal air–water mixture. The phase change during condensation was not considered. Garimella and coworkers [10] developed a flow map to predict the intermittent flow and annular flow during condensation. However, their work was based on a process under which the quality changed very little. In condensers used in cooling applications, a large change in the quality is expected. Thus, flow pattern transition under the condition of large quality change should be studied.
- Among the previous studies, not many were conducted on microchannels, which were generally defined as channels with a hydraulic diameter from 10 to 200 μm [16].
- Most of the studies were conducted on channels with hydrophilic surfaces. In micro-devices, silicon is the most commonly used material. Silicon wafers are hydrophobic [14]. As the surface tension plays a much more important role in microchannels than in large tubes in the flow and heat transfer properties, a study of the condensation process in microchannels with hydrophobic surfaces is important with silicon-based micro-condensers. To date, very little research has been conducted on this aspect. Wu and Cheng [12], and Chen and Cheng [14] carried out studies on flow condensation in micro-silicon channels. In these works, the flow patterns were the main focus. The condensation heat transfer coefficient and the pressure drop in microchannels have not been well studied yet.

Motivated by obtaining an in-depth understanding of micro-condensers, a series of experiments was carried out in this study to investigate the flow pattern and the pressure drop and heat transfer properties. It was found that slug-bubbly flow was one of the dominant flow patterns in silicon-based micro-condensers, which mainly influenced the pressure drop and heat transfer properties under high heat transfer rate and/or low steam mass flow rate conditions. A correlation was developed to predict the existence of the slug-bubbly flow and the mixed flow patterns. In the slug-bubbly flow regime, the heat transfer coefficient and pressure drop of the micro-condensers with different channel diameters were studied.

## 2. Experimental setup

Micro-condensers were fabricated on ⟨100⟩ silicon wafers as schematically shown in Fig. 1 by microlithography