Characteristics of pressure drop instability in microchannel cooling system

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Abstract – In this study, we analyze pressure drop oscillations occurring in a closed cycle refrigeration system interfaced with a microchannel evaporator. Specifically, we investigate how different system parameters affect the amplitude and frequency of oscillations in an unstable system. We do this by developing a dynamic model capable of predicting the system behavior. This study provides general guidelines to select the most appropriate operational parameters to stabilize the system.

1. Introduction

Microchannel cooling has been studied for a wide range of applications due to their superior thermal performance. However, microchannel evaporators are susceptible to flow instabilities, including pressure drop and thermal oscillations. Specifically, pressure drop oscillations (PDO) occur in the presence of compressible volume, when the channel pressure drop decreases with an increase of mass flow rate [1-3], which gives rise to severe structural vibrations and loss in thermal performance.

Several numerical and experimental studies have been carried out to determine mechanisms governing PDO and identify parameters affecting the frequency and amplitude of oscillations. For example, Stenning et al. found the amount of compressible volume to govern the period of oscillations [3]. Ding et al. found the amplitude of oscillations to decrease with flow rate, and increase with subcooling and heat input [4]. Kuang et al. found the oscillation period to vary non-monotonically with the upstream mass flow rate [5]. Kakac et al. found that the oscillation amplitude and period increases with the evaporator heat load and inlet sub-cooling [6]. Zhang et al. derived a mathematical expression for oscillation period using singular perturbation method [1]. A review of prior work indicates that computational studies of PDO have focused only on open systems, involving flow through a compressible volume and heat exchanger. On the other hand, experimental studies involving closed cycle systems have lacked a systematic analysis describing the influence of several key system operational parameters.

In this paper, we analyze PDO in a closed cycle refrigeration system interfaced with a microchannel evaporator. We conduct a parametric analysis to quantify the effect of expansion valve setting, compressor speed, compressible volume in the system, accumulator and evaporator heat loads on the frequency and amplitude of oscillations. With PDO characteristics predicted for different parameters, we expect the outcome of this study to guide the design and operation of closed cycle microchannel-embedded refrigeration systems for thermal management.

2. Microchannel-Embedded Refrigeration System

Fig. 1 shows the refrigeration cycle with microchannel evaporator using refrigerant R134a. In this system, the refrigerant enters the evaporator as two-phase mixture, undergoes flow boiling by absorbing heat \( Q_e \), and leaves as high quality mixture. The accumulator supplies vapor to the compressor and retains the liquid phase. Vapor supply from accumulator can be enhanced by supplying heat \( Q_a \) to the accumulator. The compressor increases the refrigerant pressure and supplies vapor to the condenser at high pressure. The flow rate through the compressor can be controlled by changing the compressor speed, \( \omega \). The refrigerant is then condensed in the condenser and supplied to the expansion valve as sub-cooled liquid. Pressure drop through the valve can be modulated electronically by controlling the expansion valve opening, \( A_v \).

3. Factors Affecting Pressure Drop Oscillation

For the system shown in Fig.1, the microchannel evaporator is designed to dissipate a maximum heat load, \( Q_e \), of 800 W. The pressure drop and heat transfer coefficient for the evaporator used in this study is shown pictorially in Fig. 2 [1,7].

Figure 1. Microchannel incorporated cooling system

![Microchannel incorporated cooling system](image)

Figure 2. Channel pressure drop and heat transfer coefficient

![Channel pressure drop and heat transfer coefficient](image)

Figure 3. Oscillation of evaporator mass flow rate and pressure

![Oscillation of evaporator mass flow rate and pressure](image)
settings result in an unstable system with oscillations in the evaporator mass flow rate and pressure. The system settings (\(Q_e\), \(\omega\), \(A_v\)) can be changed to stabilize the system, as described in [11]. In this study, we only investigate unstable system operation to compare parameters affecting the amplitude and frequency of PDO.

3.1 Effect of Individual System Parameters on PDO

We first examine the influence of several system parameters, including \(A_v\), \(Q_a\), \(\omega\), and \(Q_e\) and condenser volume, \(V_c\) on PDO by varying one parameter and keeping the others constant. For an unstable system, while all system states undergo oscillation, we focus only on the oscillations in the evaporator mass flow rate, \(m_{e0}\), to compare the relative effect of different system parameters.

Fig. 4 shows the amplitude and frequency of PDO as a function of (a) \(A_v\), (b) \(Q_a\), (c) \(\omega\), (d) \(Q_e\), and (e) \(V_c\).

![Figure 4. Oscillation amplitude (left) and frequency (right) in terms of (a) expansion valve setting, (b) accumulator heat load, (c) compressor speed, (d) evaporator heat load, (e) condenser volume.](image)

Decreasing \(A_v\) reduces amplitude but increases the frequency of oscillation. This is primarily due to the change in the overall demand pressure curve (Fig. 2), which influences the operating point and decreases the allowable amplitude of oscillations. When \(A_v\) is small enough, PDO can be eliminated to stabilize the system. Since \(Q_a\) and \(\omega\) have negligible effect on the demand pressure drop, they do not affect the amplitude of oscillation, as shown in Fig. 4 (b) and (c), respectively. However, oscillation frequency is sensitive to the evaporator mass flow rate, which is a function of both \(Q_a\) and \(\omega\). Note that the oscillation frequency is not a monotonic function of \(Q_a\). In addition, increasing \(\omega\) does not necessarily correspond to an increase in the mass flow rate for stabilizing the system. In this case, the compressor efficiency decreases with increase in \(\omega\). The mechanism of \(Q_e\), affecting oscillation is similar to \(A_v\), since both parameters change the shape of the demand pressure drop curve, thus changing both oscillation frequency and amplitude. Fig. 2 shows that the negative slope region of the demand pressure drop curve becomes steeper and wider when \(Q_e\) increases. This makes the oscillation amplitude larger and the frequency smaller. In this system (Fig. 1), the condenser consists of the compressible volume, \(V_c\), which is a necessary condition for PDO. As indicated in prior studies, the size of compressible volume could affect PDO characteristics. Fig. 4 (e) shows that an increase in \(V_c\) decreases the frequency but does not affect the amplitude of oscillations. A larger \(V_c\) serves as a buffer to delay the period of oscillation but not suppress the amplitude of oscillation.

3.2 Effect of Different Parameter Combinations on PDO

Since \(\omega\), \(A_v\) and \(Q_e\) are controllable parameters, this section presents the combined effect of these parameters on PDO. As shown in Fig. 5, \(\Delta m_e\) and \(f\) denote the amplitude and frequency of oscillations in the mass flow rate through the evaporator. Fig. 5 shows the combined effects of \(A_v\), \(\omega\) and \(Q_a\) on PDO for a fixed \(Q_e = 300W\) and \(V_c = 0.002 m^3\). For instance, by increasing both \(A_v\) and \(Q_a\), the amplitude of oscillation increases while the frequency decreases. However, when both \(A_v\) and \(Q_a\) are increased, the amplitude of oscillation decreases while the frequency increases.

![Figure 5. Oscillation amplitude and frequency as a function of \(A_v\), \(\omega\) and \(Q_a\).](image)

A similar trend is observed when \(A_v\) and \(\omega\) are varied simultaneously. The change in PDO characteristics due to simultaneous change in multiple parameters indicate that this approach may be more effective than changing individual parameters.

Our analysis shows that PDO occurring in a closed cycle microchannel cooling system can exhibit a wide range of oscillatory behavior. To mitigate PDO, the system operational parameters have to be selected carefully to avoid thermal or structural failure due to large oscillation amplitudes or unmanageable frequencies. In the event of large PDO, our study provides general guidelines to modulate operational parameters to stabilize the system.

4. Conclusion

This study considers pressure drop oscillations in a closed cycle refrigeration system interfaced with a microchannel evaporator. The effect of different system parameters on the oscillation frequency and amplitude were analyzed in detail. Our results show that the accumulator heat load, compressor speed and compressible volume have negligible effect on the amplitude, but strongly influence the frequency of oscillation. On the other hand, both frequency and amplitude of oscillations are very sensitive to the expansion valve setting and the evaporator heat load.

References