

Periodic Reverse Flow and Boiling Fluctuations in a Microchannel Evaporator of an R134a Mobile Air-Conditioning System

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ABSTRACT

This paper presents experimental study of periodic reverse flow and induced boiling fluctuations in a microchannel evaporator and their impacts on performance of R134a mobile A/C system.

Simultaneous flow visualization and pressure measurements revealed that reverse flow due to confined bubble longitudinal expansion caused periodic oscillations of the evaporator inlet pressure and the pressure drop, and their oscillation magnitude and frequency increase with ambient air temperatures because of higher average refrigerant mass flux and heat flux. Three potential impacts of vapor reverse flow reversal on evaporator performance are identified: 1) mild liquid maldistribution; 2) increased the evaporator pressure drop; 3) reduced heat transfer coefficient.

Finally, to mitigate vapor reverse flow impacts, revised flash gas bypass (FGBR) method is proposed: vent and bypass backflow vapor trapped in the inlet header. Experimental results showed that system performances are further improved by an up to 5% higher capacity and an up to 3% higher COP.

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INTRODUCTION

Because of the superior performance over the conventional round tube plate-fin heat exchangers, compact cross-flow heat exchangers with parallel flat multi-port microchannel tubes have been widely used mobile air conditioning systems. However, one of the challenges using microchannel heat exchangers (MCHX) as evaporators is to distribute two-phase refrigerant evenly among parallel microchannel tubes, because vapor and liquid refrigerants have significantly different densities and inertia momentum. Studies performed in the past decades mainly focused on: 1) quantifying distribution of two phase flow in header-parallel tube structures (Tompkins et al., 2002; Bowers et al., 2006; Hwang et al., 2007; Zou and Hrnjak, 2010); 2) exploring methods to improve distribution either by creating homogenous two-phase flow (Fei et al. 2002; Jiang et al., 2010) or feeding liquid only into the evaporator (Beaver et al., 1999; Tuo et al., 2012a).

Due to increased heat flux densities and reduced channel size, flow boiling instability is a very noticeable problem in microscale heat exchangers. Extensive studies in open literature have identified several typical flow boiling instability modes and corresponding underlying mechanisms,

such as rapid bubble growth, parallel channel instabilities, and upstream compressible flow instability (Brutin et al., 2003; Wu and Cheng, 2003; Hetsroni et al., 2005; Kuo and Peles, 2008; Zhang et al., 2009). In microchannels, nucleation bubble can easily grow up the channel hydraulic diameter and quickly becomes confined by channel walls. The confined bubble then can only expand rapidly in the longitudinal direction along the channel. Such rapid bubble nucleation as well as expansion introduces a pressure spike in the flow which may overcome the inertia of the incoming liquid and the pressure in the inlet header, and cause bubble expanding upstream, i.e. a reverse flow (Kandlikar, 2006). Meanwhile, inlet header or plenum provides significant compressible volume upstream of the heated section, which is able to intermittently retain and discharge the reverse vapor flow, causing a dynamic interaction between the boiling channel and the header (Bergles and Kandlikar, 2005). Such dynamic interaction together with vapor reverse flow may even cause flow rate maldistribution among parallel channels (Balasubramanian and Kandlikar, 2005). The boiling boundary-interface between the single-phase liquid region and two-phase mixture region of all the channels oscillated back and forth differently between channel inlet and outlet (Qu and Mudawar, 2004).



However, most of previous work mainly focused on microchannels applied for microscale electronic cooling systems, and very few investigated vapor reversal and induced boiling instability in typical microchannel evaporators used in A/C or refrigeration systems. Most relevant work is that [Bowers et al. \(2012\)](#) reported reverse vapor flow in R410A microchannel evaporators for a residential A/C system. More importantly, no related work in literature is to study their impacts on refrigerant distribution in microchannel evaporators used in mobile air-conditioning system. Potential impacts, if any, may not be very significant, especially with quality maldistribution due to flashing vapor in direct expansion systems. However, they would be manifested in flash gas bypass A/C system, which eliminates quality maldistribution by bypassing flash vapor and feeding liquid only into the evaporator ([Tuo and Hrnjak, 2012b](#)). Therefore, this paper aims to characterize vapor reversal and flow boiling instability; 2) identify their potential impacts on performances of microchannel evaporators; 3) explore methods to mitigate these impacts.

EXPERIMENT APPERATUS

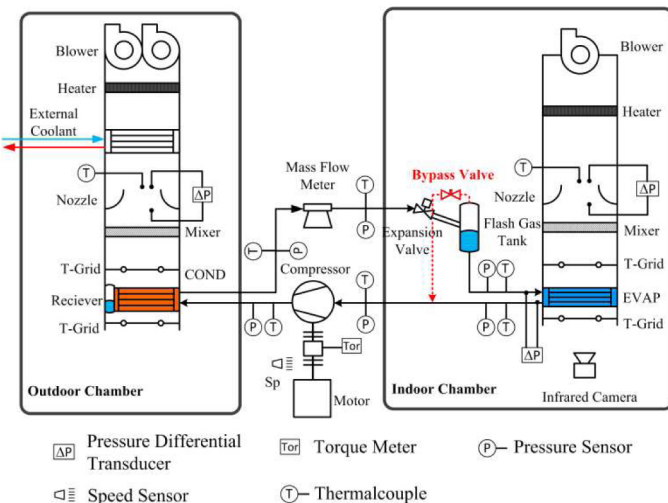


Figure 1. Schematic of test facility

[Fig. 1](#) shows a schematic diagram of the mobile air-conditioning system test facility. It consists of a fixed displacement variable speed compressor, a microchannel condenser with an integrated receiver, a microchannel evaporator, and a manually-controlled electric expansion valve. Detailed information for major components can be found in previous study ([Tuo and Hrnjak, 2012a](#)).

To visualize vapor reversal and oscillating flow regime inside the inlet header, the original aluminum headers are replaced by transparent ones made by PVC tubes as shown in [Fig. 2](#). The evaporator has a single-pass and single-slab design, consisting of totally 25 parallel microchannel tubes, each of which has 10 parallel rectangular ports with a hydraulic diameter of about 1 mm. [Fig. 2](#) also depicts the detailed layout of evaporator test section with flash gas

bypass approach. The system operates in a conventional direction expansion (DX) cycle when the bypass valve is fully closed. In this case, two-phase refrigerant generated during expansion process is directly fed into the microchannel evaporator. When the bypass valve is open, flash gas is separated and bypassed around the evaporator. The system operates in a flash gas bypass (FGB) cycle, feeding the evaporator with liquid only.

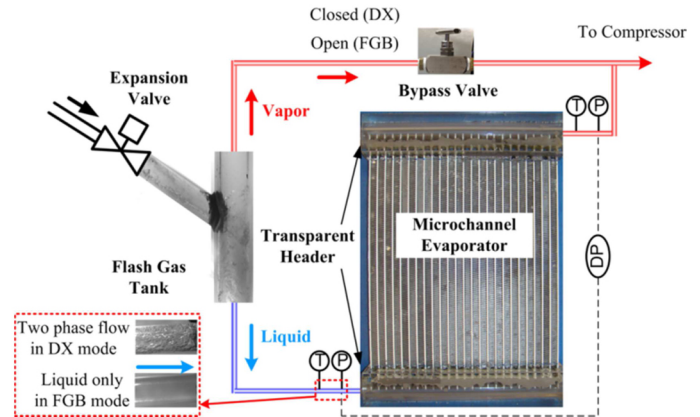


Figure 2. Detailed layout of evaporator section and flash gas bypass approach

A high-speed CCD camera was used to record the flow at a recording speed of 1000 fps. An infrared camera was used to measure the evaporator surface temperatures, which can provide indirect information related to distribution of refrigerant flow inside the parallel tubes. More importantly, a high-speed datalogger was employed to capture transient oscillations of evaporator inlet/outlet pressures and the pressure drop at a sampling rate of 100 Hz. [Table 1](#) lists the operating conditions. The uncertainties for pressure, temperature and mass flow rate measurements are about ± 3.56 kPa, ± 0.5 °C and $\pm 0.1\%$, respectively. The resulting uncertainty for the capacity measurement is about 3.3%.

Table 1. Operating conditions

Items	Unit	Condenser	Evaporator
Ambient temperature	°C	27 35 43	27 35 43
Air flow rate	m ³ /s	0.342	0.233
Relative humidity	—	—	Dry condition
Compressor speed	rpm	900 (idle condition)	

RESULTS AND DISCUSSIONS

1. Periodic Reverse Flow and Boiling Fluctuation in DX Cycle

[Fig. 3](#) shows the infrared image of evaporator surface temperatures and two-phase flow regime at the inlet header.

The large superheat zone on the left side indicates that tubes in zone 1 and especially zone 2 receive more vapor refrigerant than those at downstream, because as liquid-vapor mixture proceeds along the horizontal header, downward gravitational force separates vapor on the top and liquid on the bottom, causing a stratified liquid flow as indicated by recorded flow regimes. Thus, flow stratification at zone 2 increases the difficulty to feed bulk liquid refrigerant up to vertical tubes. Until at the rear part of the header, more liquid is fed into microchannel tubes.

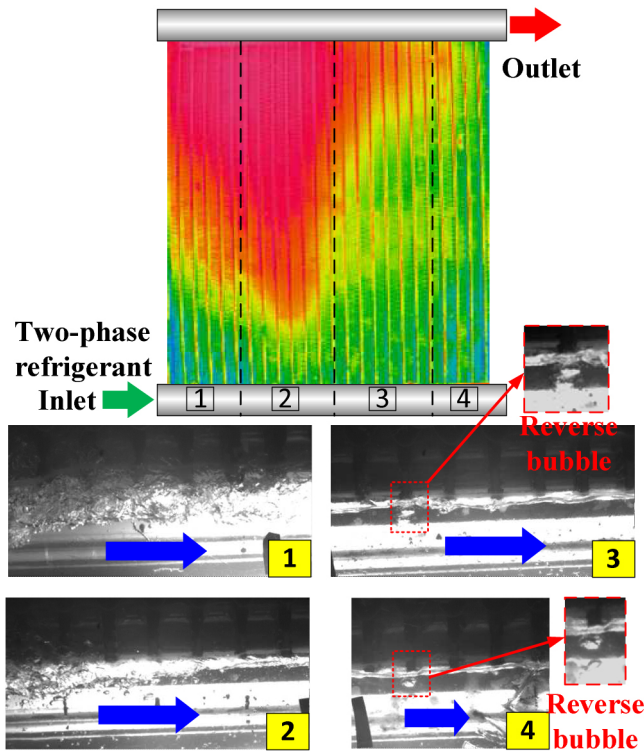


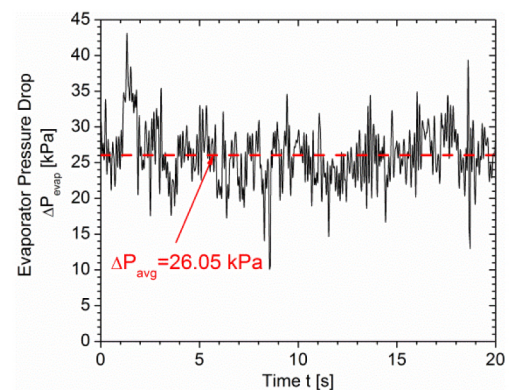
Figure 3. Flow regime at the inlet header in DX cycle under 35 °C conditions

The reverse bubbles are observed, being discharged from microchannel tubes against the bulk flow direction, especially from those located at zones 3 and 4 where the liquid surface is as high as the tube inlets. Whereas, at the front part of the header, i.e. zones 1 and 2, backflow vapor is less “visible” without forming bubbles because it directly merges into vapor pocket on the top.

Fig. 4 shows the temporal variation of the evaporator inlet/outlet pressures and pressure drop in DX cycle. In order to characterize oscillation, Fast Fourier Transform (FFT) analysis is used to convert time-dependent data (Fig.4 (1a) and (2a)) into corresponding frequency domain data (Fig.4 (1b) and (2b)), in which dominant frequency, if any, and amplitude could be identified. In Fig. 4(1a), the pressure drop oscillates considerably but in somewhat random fashion with a temporal average of about 26 kPa. Such fluctuation is mainly caused by the nucleation bubble dynamics and instances of vapour blockage during confined bubble growth

in the channels. Whereas, its random behavior may be attributed to the complicated interaction among hundreds of parallel channels through the inlet header, since this evaporator contains totally 25 parallel tubes, and 250 parallel microchannels. The pressure drop measured between inlet and outlet is dynamic superimposition of all pressure drops across individual channel with each other. Considering that severe quality maldistribution results in uneven vapor and liquid mass flux and heat flux in each individual channel (see infrared image in Fig. 3), the overall pressure drop is expected to be chaotic.

The frequency of the pressure drop is plotted against the amplitude in Fig. 4(1b). The spectrum shows two dominant frequency bands around 0.5 Hz and 0.83 Hz, indicating two corresponding oscillation periods of about 20 s and 1.2 s. Particularly, the shorter one or the faster oscillation mode is very similar to that of the vapor backflow observed through the high speed images, which well confirms that reverse flow due to bi-directional bubble expansion disturbed the upward main flow and the overall pressure drop. For pressure oscillations, the outlet pressure is relatively constant with a small oscillation of about ± 5 kPa around the average; whereas the inlet pressure fluctuates significantly with a peak-to-peak value up to 20 kPa. FFT analysis reveals that: 1) P_{out} only has a low frequency band around 0.02 Hz, confirming its steady behavior in time domain; 2) P_{in} has an extremely similar dominant frequency band peaking at 0.82 Hz. Such coincidence reveals that ΔP oscillation originates from P_{in} and the latter is the consequence of periodic vapor reverse flow and compressible volume instability. The volume of the inlet header is sufficient to intermittently retain the reverse vapor flow discharged from tubes.



(1a). temporal oscillation of pressure drop

Figure 4. Variation of pressure drop and pressures in DX cycle under 35 °C conditions