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Control of flash gas bypass MAC system with emphasis on start-ups and transients

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ABSTRACT

Most of the previous research on flash gas bypass (FGB) focused on performance improvement in steady state and demonstrated that compared to direct expansion mode (DX), FGB mode have better performance. However, the control strategy of flash gas bypass system and dynamic behavior during start-ups and transients were not yet clearly defined and investigated. In this paper, a novel control strategy has been proposed for an automobile air conditioning system operating in flash gas bypass mode with R134a as the refrigerant. The proposed control strategy utilized an electronic expansion valve (EV) for the control of subcooling from condenser outlet and a bypass valve (BV) for superheat from compressor inlet. Both start-up and transient system behaviors were studied. The experimental results showed that the proposed cycle control strategy was found to be able to provide reliable control to the system. In addition, proper sizing of bypass valve and flash gas bypass tank have also been studied.

Régulation d'un système CMA avec bipasse de gaz à évaporation instantanée, en mettant l'accent sur le démarrage et les régimes transitoires

Mots clés : Bipasse de gaz à évaporation « instantanée » ; Stratégie de régulation ; Régimes transitoires ; Système de conditionnement d'air

1. Introduction

Microchannel heat exchangers (MCHX) are widely used in many applications, especially in evaporators and condensers for automobile air conditioning (MAC) systems. The main advantages for MCHX can be summarized as higher overall heat transfer coefficient, lower refrigerant inventory, more compactness, lower cost and weight. However, the parallel flow structure of MCHX will cause non-uniform distribution, also called maldistribution, since it is difficult to feed same quantity of refrigerant to each microchannel tube. The problem is more serious for the

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Nomenclature

BV	bypass valve
COP	coefficient of performance
DTsc	subcooling (°C)
DTsh	superheat (°C)
DX	direct expansion (°C)
EV	electric expansion valve
FGB	flash gas bypass
HX	heat exchanger
h	refrigerant enthalpy ($kJ \cdot kg^{-1}$)
IHX	internal heat exchanger ($kJ \cdot kg^{-1}$)
$\dot{m}$	mass flow rate ($g \cdot s^{-1}$)
MAC	automobile air conditioning
MCHX	microchannel heat exchanger
P	pressure (kPa)
PID	proportional integral derivative
Q	cooling capacity (kW)
t	time (s)
T	temperature (°C)
V_C	compressor speed (rpm)
W_C	compressor power (kW)
x	refrigerant quality

Subscripts

a	air side
c	condenser
cai	condenser air inlet
cao	condenser air outlet
cpri	compressor refrigerant inlet
cpro	compressor refrigerant outlet
cri	condenser refrigerant inlet
cro	condenser refrigerant outlet
e	evaporator
eai	evaporator air inlet
eao	evaporator air outlet
eri	evaporator refrigerant inlet
ero	evaporator refrigerant outlet
ihxrli	internal heat exchanger low-pressure side inlet
i	inlet
en	indoor nozzle
o	outlet
r	refrigerant side
xri	expansion valve refrigerant inlet
xro	expansion valve refrigerant outlet

evaporator because maldistribution will result in poor utilization of heat transfer area, thus decreasing the cooling capacity. There was numerous research in the last decade on how to quantify refrigerant maldistribution (Kim et al., 2011; Li and Hrnjak, 2015a; Vist and Pettersen, 2004; Zou and Hrnjak, 2013) and its effect on cooling capacity (Kulkarni et al., 2004; Li and Hrnjak, 2015b; Zou and Li, 2014).

To improve refrigerant distribution in MCHX, many attempts have been made by many scholars in open literature. One solution to this problem is flash gas bypass approach, which feeds only liquid to microchannel evaporators and bypasses the vapor refrigerant since vapor is the main reason to cause maldistribution among parallel tubes and it also has very small impact on cooling capacity. The FGB concept was first proposed and validated by Beaver et al. (1999). It was demonstrated that COP increased up to 20% by keeping the same capacity of an R744 residential A/C system compared to direct expansion. Later, Elbel and Hrnjak (2004) implemented FGB concept into transcritical R744 system and identified three detailed benefits: (1) reducing the refrigerant-side pressure drop of microchannel evaporator; (2) increasing the refrigerant-side heat transfer coefficient; (3) improving the refrigerant distribution in the evaporator inlet header. Most recently, Tuo and Hrnjak (2012) reported significant improvement of capacity and COP in automobile A/C systems using flash gas bypass. Same authors (2013) reported periodic reverse flow in a FGB system. Periodic oscillation of pressure at the evaporator inlet was discovered. Through visualization of the flow regime in the inlet header, they divided one oscillation cycle into three parts: (1) reverse vapor flow; (2) vapor re-entraining in forward flow; (3) liquid refilling in forward flow. The vapor re-entraining significantly deteriorated the refrigerant distribution. Tuo and Hrnjak (2014a, 2014b) and Li and Hrnjak (2016) visualized the flow regime in an electrically heated glass channel and an air heated aluminum channel. These authors confirmed the existence of flow reversal within microchannel heat exchangers. A theoretical model, which demonstrates the mechanism of flow reversal, can be found in Li and Hrnjak (2017).

Apart from flash gas bypass, subcooling control has been proven to be another way to improve the performance of vapor compression system. Pottker and Hrnjak (2015a, 2015b) demonstrated that COP has a maximum as condenser subcooling increases due to a trade-off effect by using cycle analysis and modeling of an air conditioning system. They also provided further experimental results which showed the same conclusion that COP undergoes a maximum as an effect of condenser subcooling. At a given condition, the system COP increased up to 9% for R134a at the optimal subcooling. Xu and Hrnjak (2014) continued the work, and they expanded the subcooling study to residential air-conditioning system with both numerical and experimental investigations and they found that under a specified condition, the maximum COP improvement achieved was up to 33% and the maximum cooling capacity gain is 14.7%.

Based on the previous studies, it has been demonstrated that both flash gas bypass and subcooling control could improve system performance. However, few studies focus on investigating applicable control strategies and understanding system performance under dynamic and transient working conditions. In flash gas bypass system, it is crucial to maintain a certain liquid level inside FGB tank and make sure only liquid is fed into evaporator which requires proper sizing of FGB tank as well as functional control strategy. At the same time, to prevent liquid from flooding into compressor during start-ups, a reliable and effective control strategy