

An Infrared Thermography Based Method for Quantification of Liquid Refrigerant Distribution in Parallel Flow Microchannel Heat Exchanger

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ABSTRACT

This paper presents a method of utilizing infrared images to quantify the distribution of liquid refrigerant mass flow rate in microchannel heat exchangers, which are widely used in automobile air conditioning systems. In order to achieve quantification, a relationship is built between the liquid mass flow rate through each microchannel tube and the corresponding air side capacity calculated from the infrared measurement of the wall temperature. After being implemented in a heat exchanger model, the quantification method is validated against experimental data. This method can be used for several types of heat exchangers and it can be applied to various heat exchanger designs.

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INTRODUCTION

Microchannel heat exchangers have been widely used in air conditioning and refrigeration systems mainly due to their compactness and enhancement for heat transfer performance. However microchannel heat exchangers suffer from the problem of refrigerant maldistribution, especially for evaporator. The non-uniform distribution of two phase refrigerant in evaporator can significantly deteriorate the heat exchanger performance as well as system efficiency. Many simulation results shows that the capacity degradation due to refrigerant maldistribution ranges from 5% to 23% (Kulkarni *et al.*, 2004; Brix *et al.* 2009, 2010; Zou *et al.* 2012).

A good quantification of two phase refrigerant distribution is essential for evaluating maldistribution effect on heat exchanger and system performance. Many studies have been done to quantify refrigerant distribution using some intrusive techniques. The main idea is to measure the mass flow rate of liquid and vapor phase through each microchannel tube which branches from a realistic heat exchanger header. Vist (2003) investigated the distribution of two-phase CO₂ and R134a in horizontal heat exchanger headers for upward and downward flow configuration. Strong effect on distribution of vapor fraction at header inlet has been seen in the experiments: increasing vapor quality creates more uniform vapor distribution, while best liquid distribution is achieved at low vapor quality. An empirical model was developed to describe phase split in the header. Lee *et al.* (2004) examined the distribution of air-water two-phase annular flow in a vertical heat exchanger header. The effect of tube protrusion was examined and the most uniform distribution could be achieved by adjusting the depth of protrusion. Hwang *et al.* (2007) studied the distribution of R410A and R134a in horizontal heat exchanger headers. They concluded that the refrigerant distribution was largely affected by header inlet location and vapor mass flux. A set of

empirical correlations for refrigerant distribution were developed. Lee (2009) investigated the distribution of air-water two phase flow in a vertical header. The distribution at the front part of the header was found to be only affected by the upstream flow regime, while the distribution at the rear part of the header was mainly influenced by the downstream flow configuration due to flow recirculation. The existing T-junction phase split models were found to be working well for the front part of the header but not the rear part. Ahmad *et al.* studied the two phase HFE 7100 distribution in a horizontal header including both upward and downward flows. The effects of numerous operational and geometrical parameters on distribution were investigated and a map of flow regime in the header was developed. Kim *et al.* (2011) examined the effect of inlet location on two phase R134a distribution in a horizontal header. Parallel inlet configuration was found to have the worst performance, while normal and vertical inlet configuration yield similar refrigerant distribution. Empirical distribution correlations for all three inlet configurations were formulated, which were functions of Reynolds number of the upstream gas in the header. Zou and Hrnjak (2013a, 2013b) performed experimental studies for two phase R134a and R410A distribution in vertical heat exchanger headers. They found that the best distribution was achieved at high flux and low quality. Empirical distribution correlations were developed for both fluids. The intrusive method could provide accurate information of distribution which are the liquid and vapor mass flow rates through each microchannel tube, but none of the aforementioned experiment setups used real microchannel heat exchangers. Some of the experiments were conducted under adiabatic condition. Even for the diabatic cases, it was extremely hard to represent the heat load of each microchannel in a real heat exchanger; also some of the experimental facilities

didn't have outlet header, so the outlet header induced maldistribution, which was proved to be very important (Tuo and Hrnjak, 2013), was ignored.

Many attempts have been made to quantify two-phase refrigerant distribution through non-intrusive methods. Litch and Hrnjak (1999) related the air exit temperature of a microchannel condenser with the inside refrigerant distribution. Song *et al.* (2002) used the frosting pattern to identify maldistribution in an outdoor microchannel coil.

Infrared (IR) thermography has also been used by many researchers to examine refrigerant distribution, but only qualitative information was obtained. (Litch and Hrnjak, 1999; Dschida and Hrnjak, 2008; Qi *et al.*, 2009; Shi *et al.*, 2011; Tuo and Hrnjak, 2012). Bower *et al.* (2010) proposed a distribution rating parameter which is based on the uniformity of the surface temperature of the heat exchanger. Some quantification of distribution could be acquired from the IR image by using this parameter. Bowers *et al.*'s method has been adopted by many authors (Tuo and Hrnjak, 2012; Li and Hrnjak, 2013).

Non-intrusive method has the advantage of saving time and cost over the intrusive method, but typically uncertain quantitative information about refrigerant distribution is obtained. In this study, an IR thermography based method is proposed to quantitatively estimate liquid refrigerant distribution in parallel flow microchannel heat exchangers. This method is validated against experimental results in conjunction with the heat exchanger model.

METHOD DEVELOPMENT

Heat Transfer Basis for the Quantification Method

Latent heat of the liquid refrigerant is the major part of the cooling capacity of an evaporator, so distribution of liquid is more important than vapor. The refrigerant inside of tubes could be either two phase or superheat vapor as shown in Figure 1.

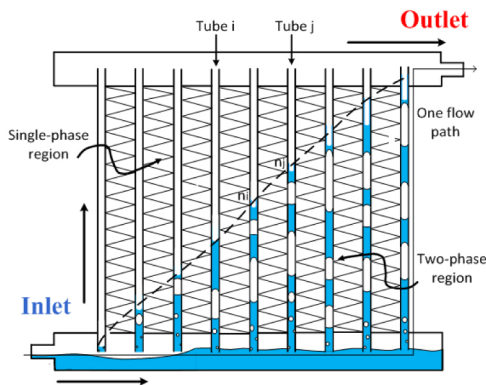


Figure 1. Snapshot of a simplified situation in parallel flow heat exchanger

From the modeling perspective (finite volume approach), a heat exchanger has several parallel microchannel tubes and each tube is divided into elements. The following assumptions are made to simplify the model without losing generality: 1) Uniform temperature and velocity profile of the incoming air; 2) Uniform distribution of refrigerant among parallel ports within the same tube; 3) Uniform wall temperature within each element; 4) No conduction through the fins or wall along tube direction.

For each element in the two-phase region, because of the uniform wall temperature, the energy balance on the air side can be calculated using the ε -NTU method:

$$Q_{air,element,tp} = \varepsilon C_{min} (T_{air,in} - T_{wall,element}) \quad (1)$$

$$C_{min} = c_{p,air} \dot{m}_{air} \quad (2)$$

$$\varepsilon = 1 - \exp(-NTU) \quad (3)$$

$$NTU = \frac{h_{air} A_{air}}{C_{min}} \quad (4)$$

Assuming uniform temperature and velocity profile of the incoming air, A_{air} , $T_{air,in}$, $\dot{m}_{air}$, $c_{p,air}$ and h_{air} stays constant for each element, ε and C_{min} is also constant.

In the two-phase region, the refrigerant-side capacity is the latent heat of the liquid refrigerant, so in each element, the following energy balance equation can be formed:

$$Q_{ref,element,tp} = \Delta \dot{m}_{ref,liq,element} i_{fg} \quad (5)$$

For each microchannel tube, refrigerant side capacity in the two phase region is calculated by summing up the capacity of each element together:

$$Q_{ref,tube,tp} = i_{fg} \sum_1^n \Delta \dot{m}_{ref,liq,element} = i_{fg} \dot{m}_{ref,liq,tube} \quad (6)$$

(n is the last element of the two phase region)

Based on energy balance between refrigerant-side and air-side,

$$Q_{ref,tube,tp} = \sum_1^n Q_{air,element} = \varepsilon C_{min} \sum_1^n (T_{air,in} - T_{wall,element}) \quad (7)$$

the ratio of liquid refrigerant mass flow rate through any two microchannel tubes can be calculated as following:

$$\frac{(\dot{m}_{ref,liq,tube})_i}{(\dot{m}_{ref,liq,tube})_j} = \frac{\left(\sum_1^{n_i} (T_{air,in} - T_{wall,element}) \right)_i}{\left(\sum_1^{n_j} (T_{air,in} - T_{wall,element}) \right)_j} \quad (8)$$

Given the above ratio, liquid refrigerant distribution among parallel microchannel tubes can be fully described by the following equation: