

Efficiency Improvement by Separation of Vapor and Liquid in Condenser Headers

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ABSTRACT

This paper introduces the concept of separation of two-phase flow in condenser as a way to improve condenser efficiency. The benefits of vapor-liquid refrigerant separation and the reason why it will improve the condenser performance are explained. Numerical studies are presented on the effects of separation on performance of an R134a microchannel condenser, with the comparison to experiment data. Model predicts that at the same mass flow rate, the exit temperature is lower by 2.2 K in the separation condenser compared with that in the baseline. Up to 9% more flow rate of condensate is also predicted by the model in the separation condenser. Experiment results confirm the same trend. In addition, the reason why a certain circuiting of passes with pre-assumed separation results in the header improves the condenser is investigated by the model and results are presented.

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INTRODUCTION

Numerous patents (Perkins and Marchese, 1974 [1]; Kim and Lee, 1983 [2]; Nobuta *et al.*, 2002 [3]) have indicated that separation of vapor-liquid two-phase flow has great applications in the field of heat exchangers. Despite different configurations for application, the authors want to use the more uniform properties of single phase flow by pre-separating the two-phase flow. Besides the patents for heat exchangers, separation of two-phase flow also has applications in other engineering fields such as oil field pipelines, refinery networks, gas distribution lines carrying small amounts of condensate, and so on. For instance, T-junction, as the simplistic component with the basic functionality, has drawn numerous research interests from scholars during the past three decades. Hwang *et al.* (1989) [4] built an analytic model for phase separation in impacting Tees and Wyes based on a dividing-streamline concept. Tuo and Hrnjak (2014) [5] presented the experiment results of separation performance of the vertical T-junction separator before evaporator in flash-gas bypass vapor compression systems.

This paper aims to discuss possible application of separation for enhancing the overall heat transfer performance of the microchannel condenser for mobile HVAC system. The method has separation in the header working together with separation pass geometry. The designing objective is to capitalize on the high HTC of vapor flow.

During a heat transfer process, liquid on the wall of condenser is detrimental while vapor on the wall of evaporator detrimental. If the unwanted phase were successfully removed, it may be one of the options to improve heat transfer and reduce pressure drop. For a refrigerant-side parallel-flow microchannel condenser, removing unwanted phase may refer to separating liquid from vapor during the

condensation process and then reassigning the flow passages for separated vapor and liquid, respectively. If two phase can be separated successfully in the header, the method may be realized without much additional manufacturing cost if any. Studies on the separation condenser only appear to be found in Oh *et al.* (2003) [6] and Won (2006) [7].

The configuration for separation in the header of the condenser was proposed by the patent of Oh *et al.* (2003) [6], shown by Figure 1. The authors claim that the gas-liquid separating condenser can enhance the sub-cooling rate in the pre-sub-cooling section dm4' as well as in the total sections. Subcooling was found inversely proportional to the ratio $A_{dm4'}/A_{TOTAL}$ (passage area of the pre-sub-cooling section dm4' to the total heat transfer area of the condenser) and $A_{dm4'}/A_{TOTAL}$ is suitable in a range of about 3% - 20%. The condenser can obtain suitable value of heat rejection in a range of 20% to 55% for the value of ratio A_{dm5}/A_{dm1} , wherein A_{dm5} is the area of the second sub-cooling section dm5 and A_{dm1} is the area of the super heat cooling/condensing section dm1.

Won (2006) [7] theoretically optimized the tube array (tube per pass) in the separation condenser shown as in Figure 1. Optimization was achieved on a condenser level by keeping refrigerant inlet and mass rate and air conditions as constants, while number of tube array was varied. Empirical modeling method was adopted. Through comparison, the best tube array was 14-6-3-5-3-4 (tubes per pass in the order dm1-dm2-dm3-dm4'-dm4-dm5). That array gave 7% higher heat release rate, much less pressure drop, and less charging amount in comparison to the baseline array, 17-5-3-3-2-5. Nevertheless, this optimization is restricted by the refrigerant and air inlet conditions pre-assumed by the author.

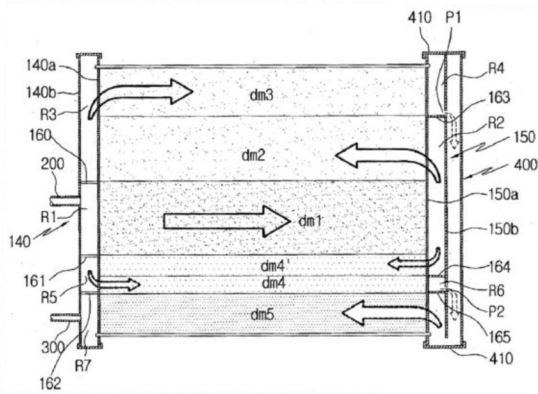


Figure 1. Flow of refrigerant in the multi-stage gas and liquid phase separation condenser (Oh *et al.*, 2003, [6])

This paper provides experimental and modeling results for quantifying the effect of liquid-vapor phase separation on condenser performance in the geometry represented by Figure 1. Also, although Oh *et al.* and Won had experimental and modeling results to verify the better performance of separation condenser, they have uniformly assumed a perfect separation of gas from liquid in second header, tank 150 defined by baffle 163 and baffle 164. However, it is unlikely that pure gas enters section dm2 while pure liquid enters section dm4'. Usually upward moving gas flow will entrain liquid droplets/ligaments in it and liquid flow will mix with gas-phase bubbles. This paper studies benefits brought by separation by taking the separation results happening in the second header into account.

DESCRIPTION OF THE SEPARATION CONCEPT

Different from a traditional multi-pass condenser starting from the top ending at the bottom, the separation condenser is designed to have vapor-liquid phase separation in the vertical second header by placing the inlet at the midpoint of the condenser height as shown in Figure 1. After de-superheating in the 1st pass, vapor flow will be condensed to a certain quality, depending on different operating conditions, at the end of the 1st pass, e.g. inlet of the second header. Relatively active vapor phase is expected to move upward owing to buoyancy based on the density difference between vapor phase and liquid phase. Meanwhile, liquid phase moves downward along gravity direction based on larger density and high viscosity. This separation between vapor and liquid is based purely on property difference, which will provide no additional cost for manufacturing.

Figure 2 is showing several potential design options of condensers with separation circuiting, all for single-slab, parallel-tube and cross-flow condensers. Upper pass is named vapor pass because it is expected to receive vapor-rich flow, while lower pass is named liquid pass because it is expected to receive liquid-rich flow. The most simplistic designing circuiting would be Figure 2(a), with only 2 passes. According to customs in manufacturing industries, a 3rd pass can be added after the receiver working as a designated subcooling pass, as shown in Figure 2(b). However, the drawback of the 2-pass design is the difficulty to keep mass flux of 2nd vapor pass at the same level with that in the 2nd pass of the traditional condenser, so prototype separation condensers

usually adopt a 3-pass design shown as Figure 2(c), in which 2nd pass is further divided into 2 pass to increase the mass flux in vapor passes. A subcooling pass can also be added at the end after the integrated receiver as presented in Figure 2(d).

In general, separation condensers can be either microchannel condensers or round-tube finned condensers. The optimization of tube number in each pass needs further investigation in order to work with corresponding separation results in the 2nd header. Even though separation happens in the aid of vertical configuration of the header and separation mechanism is based on gravitational force, it does not exclude the possibility that headers can have low-cost special liquid-vapor separators (as in Wurz and Zimmermann, 1989 [8] or Nobuta *et al.*, 2002 [3]) installed inside for better separation performance after cost design analysis.

A valid question would then be how much separation between the two phases really exists in the header of a microchannel condenser. Li and Hrnjak (2016) [9] built an intermediate header of the same geometry and simulated two-phase flow injection into the header. They found perfect separation at the lower end of the tested mass flux ($80 \text{ kg/m}^2 \text{ s}$) while the inlet quality is also at the lower end. Vapor-liquid separation is essentially one type of maldistribution. Indeed, maldistribution/separation of two-phase flow has been observed in this type of vertical parallel-flow manifold (Cho and Cho, 2004 [10]; Dschida and Hrnjak, 2013 [11]; Zou and Hrnjak, 2013 [12]). Although it has been studied mostly for evaporator application, refrigerant flow is condensed into two phase in a condenser prior to entering the second header and remains two-phase in downstream. It is inevitable to have maldistribution in this intermediate header as long as two-phase refrigerant exists.

While maldistribution exists as a problem, it provides a possibility for creating vapor-liquid separation. Meanwhile, two-phase distribution can also be improved by first separating the liquid and vapor then sending them to separated passes, since single-phase flow after separation has more uniform properties than a two-phase flow.

THEORETICAL RATIONALE

The theoretical rationale behind the advantages of a condenser with vapor-liquid separation is following. For a condensation process of a refrigerant, heat transfer coefficient usually decreases monotonically with quality. Figure 3 is showing the trend of R134a predicted by the model of Cavallini *et al.* (2006) [13]. At the same mass flux, the high-quality (0.9-1) two-phase refrigerant has 5-7 times higher heat transfer coefficient than a low-quality (0-0.1) two-phase refrigerant, depending on the specific refrigerant. This provides the opportunity to increase the heat exchanger performance by separating vapor from the liquid and using the high heat transfer coefficient of vapor, in the meanwhile, maintaining or even decreasing the heat transfer coefficient of liquid a bit after separation. In principle it is possible to separate liquid from vapor and take it to the outlet of the condenser but that is another approach that is under investigate. If the mass flux of vapor can be kept close to the non-separated refrigerant and the deterioration of heat transfer on the liquid side is compensated, this method should enhance the overall heat transfer of the condenser.

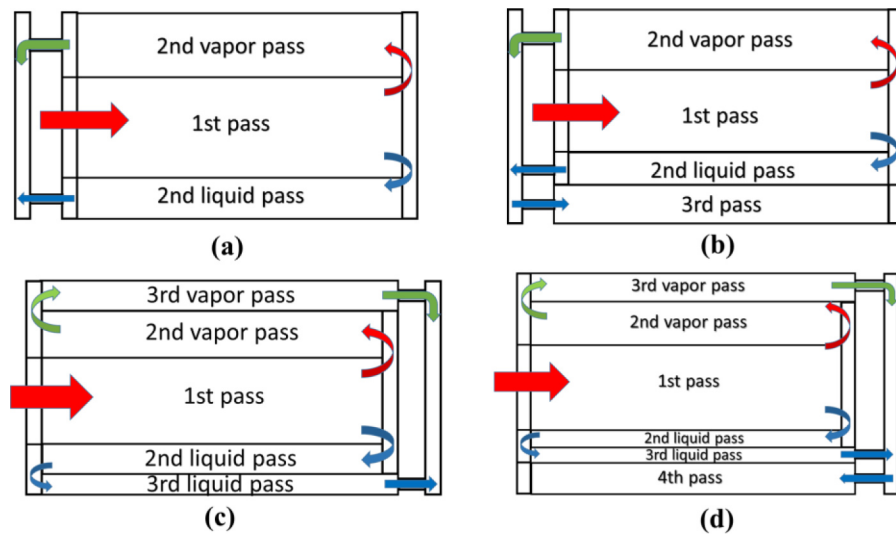


Figure 2. Geometries of separation condensers

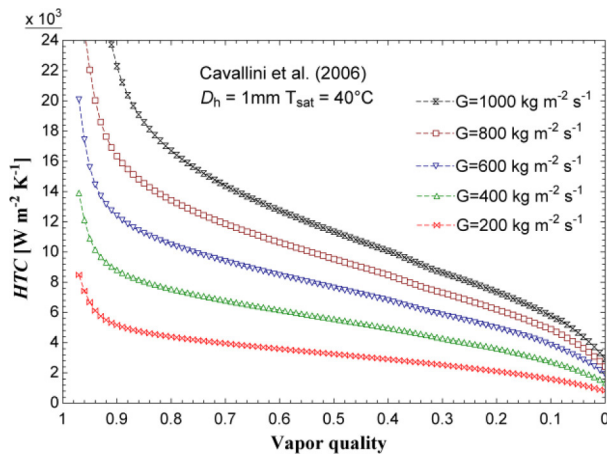
Figure 3. R134a HTC inside tubes of 1 mm hydraulic diameter, predicted by model of Cavallini *et al.* (2006)

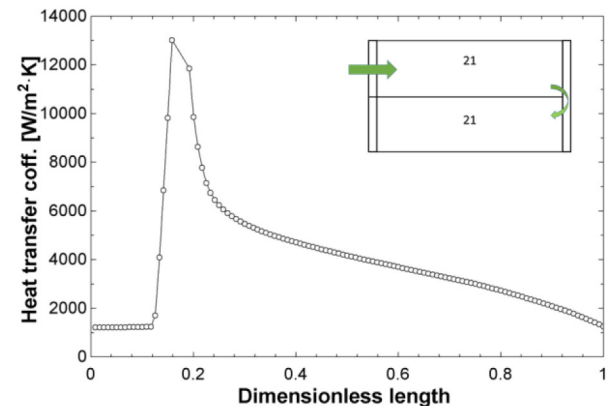
Figure 4 presents the potential of heat transfer coefficient enhancement of the separation condenser. The heat transfer coefficient profile along the flow path for a constant mass flux in a traditional condenser is shown in Figure 4(a). When it is converted to a separation condenser in Figure 4(b), vapor pass is divided into the 2nd vapor pass and the 3rd vapor pass to maintain a close mass flux with that in the 2nd pass in Figure 4(a). While the total tube number remains constant, the heat transfer coefficient of the 2nd vapor pass and 3rd vapor pass is largely increased compared with that at the same dimensionless location in Figure 4(a). This comparison shows the potential of usage of separation to increase heat transfer performance.

MODEL DESCRIPTION

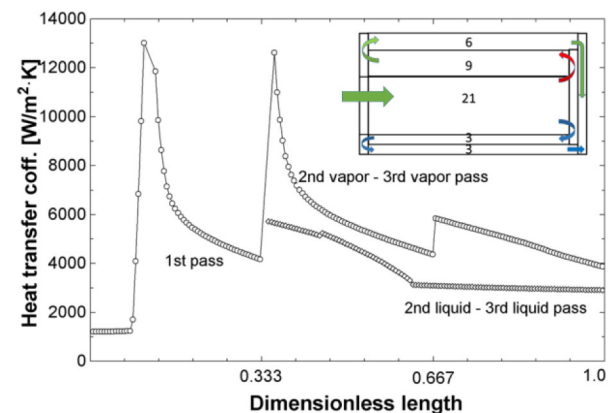
Methodology and Empirical Correlations

Tuo *et al.* (2012) [14] proposed a discretized parallel microchannel evaporator model with experimental validation. The method is applied here to multi-pass microchannel condenser. An empirical steady-state model is developed based on ϵ -NTU method. Finite

volume method is applied as the discretization scheme to evaluate the impact of separation on the performance of a multi-pass microchannel condenser.



a.



b.

Figure 4. Potential of heat transfer enhancement of the separation condenser

In the model for the baseline condenser, finite volume method is conducted in a normal way that the outputs from the current element serve as the inputs into the next element. The model collects the outputs of each element and sums the capacity and pressure drop in

each element to provide the total values for the condenser. In the model for the separation condenser as shown in Figure 5(a), the model reaches convergence when the pressure drop of upper flow path and the lower flow path between the header (P_{header}) and the receiver (P_{out}) have a difference within 0.01 kPa. This is met by varying mass flow rates through two separated flow path for certain separation performance in the second header.

Figure 5(b) shows nomenclature of the quantification phase separation in the separation header. x_v and x_l denote the quality at the vapor exit and the quality at the liquid exit, respectively. They are calculated as

$$x_v = \frac{\dot{m}_{v,v}}{\dot{m}_{v,v} + \dot{m}_{l,v}} \quad (1)$$

$$x_l = \frac{\dot{m}_{v,l}}{\dot{m}_{v,l} + \dot{m}_{l,l}} \quad (2)$$

where $\dot{m}_{v,v}$ and $\dot{m}_{l,v}$ are the vapor mass flow rate and liquid mass flow rate, respectively, at the vapor exit; $\dot{m}_{v,l}$ and $\dot{m}_{l,l}$ are the vapor mass flow rate and liquid mass flow rate, respectively, at the liquid exit.

The quality x_v is first assumed for every simulation case with a certain inlet condition ($\dot{m}_{\text{in}}, x_{\text{in}}$) for the header. Different x_v represents different separation result in the header. When $x_v > x_{\text{in}}$, phase separation happens.

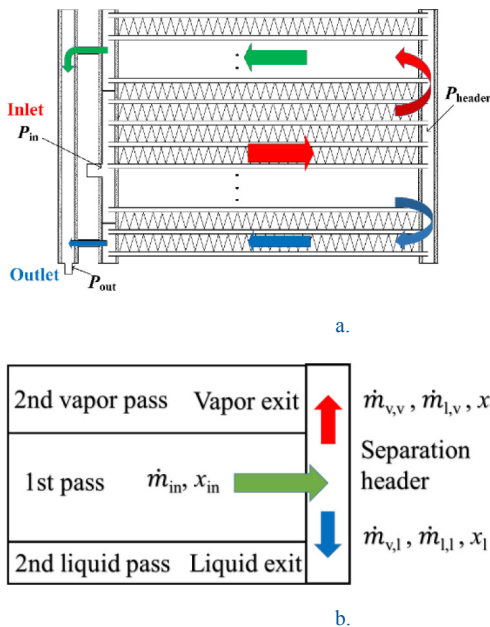


Figure 5. (a) Schematic of a two-pass separation microchannel condenser; (b) Zoom in of the separation header

Figure 5(b) also contains the variables needed to quantify separation in a separation condenser. Two separation efficiencies have been defined for liquid and for vapor. Vapor separation efficiency is

evaluated as the ratio of the separated vapor which flows through the designated vapor outlet divided by the total amount of vapor entering the header, as shown by Eqn. (3). Liquid separation efficiency is calculated as the ratio of separated liquid which flows through the designated liquid outlet of the header divided by the amount of liquid supplied to the inlet, as shown by Eqn. (4).

$$\eta_v = \frac{\dot{m}_{v,v}}{\dot{m}_{v,v} + \dot{m}_{v,l}} \quad (3)$$

$$\eta_l = \frac{\dot{m}_{l,l}}{\dot{m}_{l,l} + \dot{m}_{l,v}} \quad (4)$$

Assuming distribution has less of effect in condenser than in evaporator (Pöttker and Hrnjak, 2012 [15]) and our focus is on phase separation, distribution issue is not taken into account in the model. Following assumptions are made to simplify the model: (1) Refrigerant distribution is uniform among microchannel tubes in each pass; (2) at each port in the same tube, refrigerant mass flow rate is the same; (3) no heat is conducted along the tube nor between tubes through fins; (4) all headers are adiabatic; (5) incoming air has uniform temperature and velocity profile.

Correlations for heat transfer and pressure drop are used in this model are listed in Table 1. The heat transfer correlation for the condensing superheated region can be referred to Kondo and Hrnjak (2011) [22]. In the model, the superheated routine outputs an inner wall temperature. This inner wall temperature is checked to see if it is below the fluid's saturation temperature. If the inner wall temperature is below the saturation temperature while the bulk temperature is still above, the previous calculation for the element is disregarded and the inner wall temperature is used to iterate through correlations in the condensing superheated zone.

Table 1. Summary of selected heat transfer and pressure drop correlations

Item	Correlation
Air side	
Heat transfer coefficient	Chang and Wang (1997) [16]
Pressure drop	Chang and Wang (1996) [17]
Refrigerant side – Single phase region	
Heat transfer coefficient	Gnielinski (1976) [18]
Frictional pressure drop	Churchill (1977) [19]
Refrigerant side – Two phase region	
Heat transfer coefficient	Cavallini <i>et al.</i> (2006) [13]
Frictional pressure drop (in microchannel)	Cavallini <i>et al.</i> (2006) [13]
Deceleration pressure drop (in microchannel)	Cavallini <i>et al.</i> (2009) [20]
Pressure drop (in header)	Friedel (1979) [21]
Refrigerant side – Condensing superheated region	
Heat transfer coefficient	Kondo and Hrnjak (2011) [22]