2016

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Alvarado, Jessica; Junge, Brent; and Kelecy, Andrea, "Experimental Study of Two-phase Seperators for Vapor Compression Systems in Household Appliances" (2016). *International Refrigeration and Air Conditioning Conference.* Paper 1681.
http://docs.lib.purdue.edu/iracc/1681

Experimental Study of Two-Phase Separators for Vapor Compression Systems in Household Appliances

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ABSTRACT

The objective of this study was to evaluate the design of liquid-vapor gravity separators for low mass flux systems (1.5 – 3.5lbm/ft^2 hr [7.3 -17.1 kg/m^2hr]). Two separator geometries with height to diameter aspect ratios of approximately 2 and 10 were evaluated to determine separation sensitivity to geometry. The results of the study show that both geometries perform similarly; the primary factor to influence separation in this study was the balance maintained between the inlet quality and top branch flow ratio. When inlet quality was greater than top branch flow ratio, no clear liquid-vapor interface was present; the mixture entering the separator was characteristic of misty flow and thus no liquid buildup was found within the separator. However, when inlet quality was less than the top branch flow ratio, the liquid-vapor interface was visible and a liquid build-up was observed within the separator vessel. The results indicate the feasibility of separating liquid effectively for low mass flux flow conditions and both separator geometries, as long as the top branch flow ratio is not less than the vapor quality entering the separator.

1. INTRODUCTION

The primary function of a separator is to direct a specific phase (liquid, vapor or solid) contained within a fluid to the appropriate step in a cycle in order to minimize losses or improve system efficiencies that otherwise could not be achieved. As energy regulations and the standard of living increase around the world, a strong demand for improved system efficiencies in refrigeration continue to grow.

Phase separators have been studied extensively by Milosev (2010), and Tuo and Hrnjak (2014) for ranges applicable to automotive air conditioning systems. The flow ranges are between 159-238 lbm/hr [72-108 kg/h], about 15 to 20 times greater than the ranges seen in refrigeration appliances. Their results show that vapor efficiency remains high with inlet quality lower than 0.3, in which vapor velocities remains low reducing any liquid entrainment through the vapor branch.

The implementation of a separator offers system efficiency benefits for vapor compression cycles; a typical cycle which uses a separator is called the "economizer"; the injection of vapor refrigerant typically refers to the introduction of vapor refrigerant to an intermediate stage of the compressor. In 1984, Umezu and Suma reported 15% energy savings using vapor injection, as compared with conventional systems.

Another system that takes advantage of the separator is the ejector system. A study by Domanski, P.A. (1995), compared the theoretical COP potential of the ejector cycle and found that it improves the COP for all the refrigerants evaluated due to an increase in capacity and a reduction of compression work. Experimental work by Pottker, Guo and Hrnjak (2010) demonstrated that a phase separator could improve EER by more than 5% for a vapor compression system working with an ejector. More recently Chaudhry, Zhuo, and Junge (2015) reached target efficiencies of 15% over a wide operating range in packed terminal air conditioners with the use of a separator in an ejector system.

A third application in vapor compression systems which utilize a separator is one that is comprised of a mixture of two or more refrigerants as the working fluid. This cycle is primarily beneficial due to lower average compression ratios, as well as better control of cabinet temperatures. Stoecker, 1978, tested a mixed refrigerant system using R-12 and R-114, with a 50% mixture and found an energy savings of 12% in a two-evaporator system. The implementation of a separator in the middle of the condenser separates the liquid and vapor phases. The vapor phase, rich in the low condensing temperature refrigerant is segregated in the separator vessel from the liquid phase, rich in the high condensing temperature refrigerant.

Implementing a separator in a vapor compression system for an appliance shows potential. The primary approach taken in this paper to evaluate separator designs for the implementation in home appliances was experimental. In home appliances, which operate at low mass flux, characterized by low vapor and liquid velocities, the use of separators can be beneficial for lower energy consumption and system efficiency improvements.

2. EXPERIMENTAL METHODS

Separator: Design and construction

The two separator vessels were constructed of clear PVC in order to visually record the flow at different test conditions. In Fig. 1 below, a schematic of Separator 1 is depicted, showing the inlet [1] and outlet branches [2 & 3] and the construction of the clear separator body. The dashed lines outline the portion of the separator that was visible during the film as the test system operated.

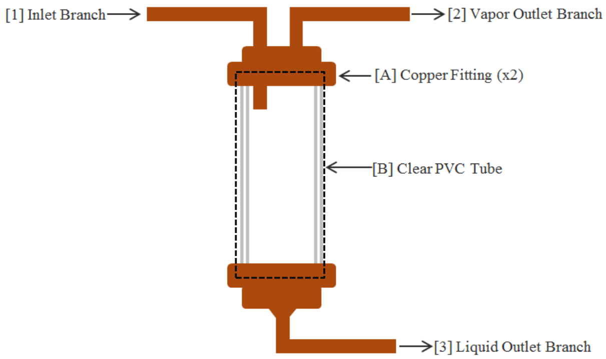


Figure 1: Visible portion of Separator 1

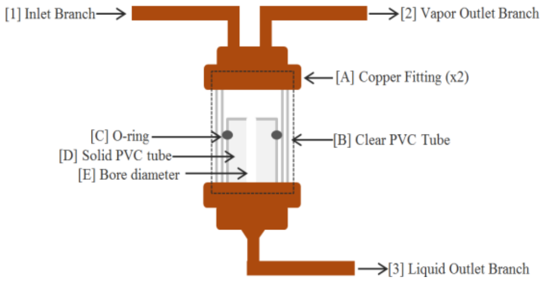


Figure 2: Visible portion of Separator 2

The total height of Separator 1 was 4.125 in [104.775 mm], and the separator body diameter was 0.423 in [10.7442 mm]; the aspect ratio α, which is defined as the ratio of the overall height to the inner wall body diameter, was 9.75 (approximately 10). The inlet branch diameter was 0.232 in [6.2 mm], and was the same for both Separator 1 and 2.

The visible portion of Separator 2 is indicated by the dashed lines in Fig. 2. The total height of Separator 2 was 1.75 in [44.45 mm], and the separator body diameter was 0.742 in [18.847 mm]; the aspect ratio was 2.4 (approximately 2). By reducing the overall length it was challenging to thread both ends without compromising the integrity of the seal of the PVC threads to the copper fitting. Therefore, in order to reduce the aspect ratio while maintaining a visual portion of the separator, without losing proper sealing needed during testing, a solid piece of PVC was machined [D] to fit inside the separator body and bored [E] to have the same diameter as the Liquid outlet branch [3]. An O-ring [C] was used to seal the volume within the separator body that would constitute to the equal volume of a separator of a, α, of 2.

Test Facility

The experimental setup is comprised of components typically sized for home appliance refrigerators. The schematic of the test facility in which the two separators were tested is shown in Fig. 3.

In this experimental system the purpose of Condenser 1 was to maintain the working fluid in the subcooled state. This permits a direct measurement of the pressure and temperature before the refrigerant enters the downstream heated coil section. With the known inlet enthalpy, the refrigerant quality leaving the heated coil section can be accurately calculated after measuring the heater input wattage and refrigerant mass flow. The fan on Condenser 1 is utilized to increase the heat transfer from the refrigerant to the ambient and to maintain pressure on the high side in steady state.

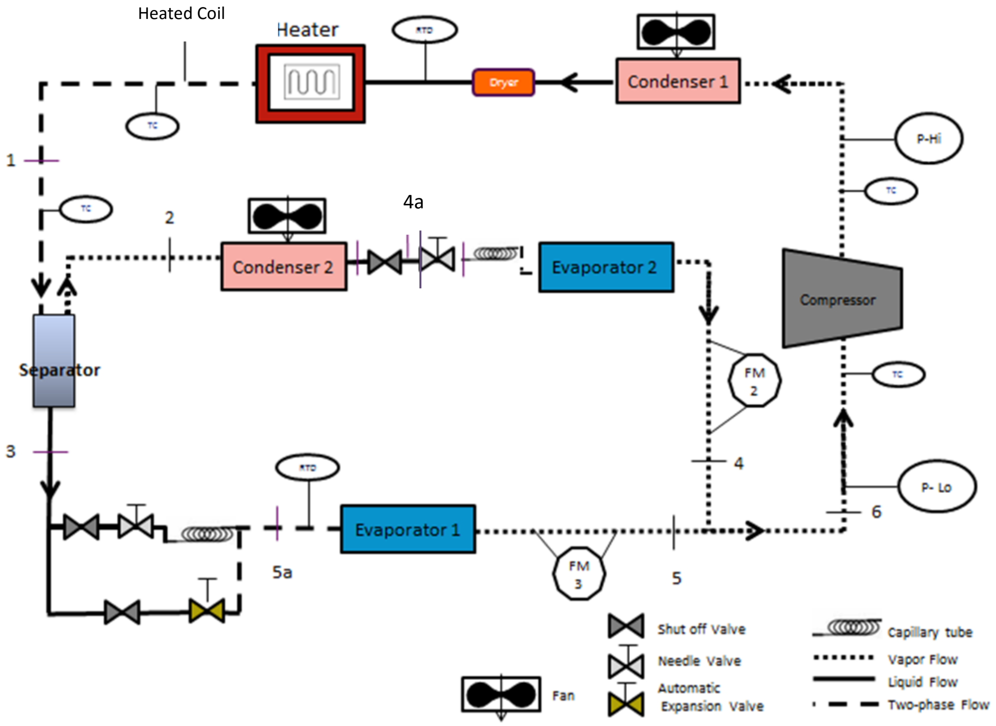


Figure 3: Two-phase Separator Test facility

The two-phase mixture enters the separator from the inlet top branch (state point 1); when the phases are segregated completely, ideally, 100% of the vapor will exit through the outlet top branch (state point 2) and 100% of the liquid exits through the bottom branch (state point 3). This can only occur if the top branch flow ratio (defined by Eq. [1]) is held equal to the inlet vapor quality, x_1, for an adiabatic separator. The mass that exits the top branch (state point 2) should be comprised of vapor which will then proceed to be condensed into liquid in Condenser 2. The fluid once fully condensed continues through the variable expansion device, which consists of a needle valve upstream of a capillary tube. Similarly, the mass that exits through the bottom branch (state point 3) undergoes expansion through a second needle valve and capillary tube. The needle valve is used to adjust the restriction of the liquid branch. Through the use of both needle valves, the top branch flow ratio (TBFR) was controlled. It is defined as:

$$\gamma = \frac{mass\ exiting\ vapor\ branch}{total\ mass\ flow\ entering\ separator} = \frac{\dot{m}_v}{\dot{m}_T} \qquad \textbf{[1]}$$

Finally, the fluid at state point 4a and 5a is at a low temperature and pressure, and gains heat from the ambient, fully evaporating any remaining liquid. At point 4 and 5 the fluid exits the evaporator as either saturated or superheated vapor, and can be measured by Flow Meters 2 and 3, which are used to determine the overall mass flow in the system. The flow from 4 and 5 will combine (state point 6) and enter the suction side of the compressor to undergo the cycle again.

Control of Vapor Quality

To vary the inlet quality to the separator, a heater was used to add heat to the refrigerant fluid entering the heated coil section, before the refrigerant entered the separator. To implement the heating, a silicon-extruded electrical resistance heater was mounted around a copper coiled section (see Fig. 4).

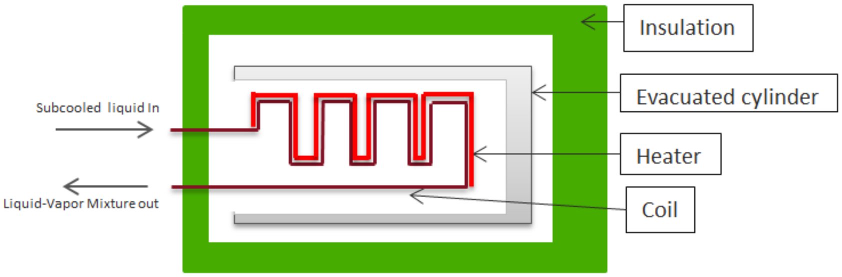


Figure 4: Heater Coiled Section for Vapor quality control

Care was taken when controlling subcooling at the outlet of the condenser since at saturated liquid conditions any small amount of heat addition can result in significant change in phase. To adjust to a specific quality reliably during experimentation, subcooling was monitored to 5˚F of subcooling to ensure the refrigerant was fully liquid. After controlling to five degrees of subcooling, heat was added to the 1.5ft [.457 mm] long heated coil section; care was taken to prevent any heat loss to the ambient by placing the coiled section inside an evacuated cylinder; the cylinder and the coiled section were insulated further from the ambient by being placed within a polyurethane foam insulated box (as shown in Fig 4).

Currently, no instrumentation exists which makes a direct measurement of quality. Therefore, quality was determined by the first law energy balance of the heat transferred to the refrigerant by the heater (see Fig.5).

The input energy from the heater is given by:

$$\dot{q}_{htr} = I^2 R \qquad [2]$$

The heat transferred to the refrigerant is given by:

$$\dot{q}_r = \dot{m}_T (h_o - h_i) \qquad [3]$$

$$\dot{q}_{htr} - \dot{q}_r = 0 \qquad [4]$$

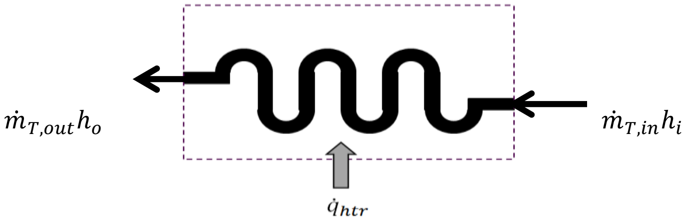


Figure 5: Refrigerant side balance on Copper Coil Control Volume.

When rate of input energy, $\dot{q}_{htr}$, from the heater is a measured variable, h_o can be determined if the inlet state point, h_i, is known; this method was used to determine the required energy transferred from the heater to achieve a specific quality. The refrigerant enthalpy exiting the heater coil and entering the separator is calculated by the equation [5]:

$$h_o = \frac{\dot{q}_{htr}}{\dot{m}_T} + h_i \qquad [5]$$

The inlet state condition, h_i, is derived from refrigerant tables using the measured values of temperature (RTD) and pressure (P-Hi) measurements before the Heater coil section. The inlet quality,x_i, is thus calculated by:

$$\boldsymbol{x_i = \frac{h_o - h_f}{h_v - h_f}} \qquad \textbf{[6]}$$

The temperature measurements of the refrigerant downstream and upstream of the heater coil section were taken with RTDs in direct contact with the stream.

The accuracy in the measurement of quality depends highly on the energy balance between the heater coil and the refrigerant-side. Guaranteeing the energy balance error is less than 5% when measuring a quality of 1 ensures that the instrumentation and setup are capable and can be used to accurately calculate separator inlet qualities less than 1. The measured energy balance in the trials tested was on average 4%.

Qualitative visual observations

The separator body was constructed from clear PVC tubing to visualize entrainment phenomena and identify vapor bubbles and liquid droplets in the range from $3x10^{-4}$ – 0.03937 in [100 – 10000 µm]. Flow visualizations within the body of the separator were recorded using video equipment. Any vapor bubbles or droplets less than 100 microns are out of the range of the smallest detectable size by the human eye and would constitute 0.001% of the liquid build up. Therefore, it was assumed that the quality through the liquid branch was zero if no vapor bubbles were visible in the liquid build up within the separator body which was visible during experimentation. However, when no liquid buildup was detected within the separator body, the quality through the liquid branch could no longer be assumed to be zero. An important aside is that although the assumption is made that liquid quality through the liquid branch is zero whenever a liquid plug was present, the similar assumption that vapor quality is 1 through the vapor branch is not made when there is no liquid build up. When there is no liquid build up, the flow inside the separator is characteristic of misty flow, and droplets less than 100 µm could be dragged through the vapor branch, therefore making it difficult to estimate the liquid branch quality. Furthermore, under these conditions, without any visualization of the vapor branch, no estimate of the quality through this branch could be used to validate in the quality in the liquid branch under these conditions.

The video camera used in this test facility was Microsoft Lifecam, with 720p HD sensor which captures up to 30 frames per second. The video recordings were made once a test case achieved steady state. Reaching stable conditions was critical to confirm that the inlet quality was effectively controlled. To ensure that recordings were observed after reaching steady state, a stability criterion was established; evaluating the pressure conditions and ensuring that a variation in the measured values was no greater than 2%, the system was considered to have stabilized and the video recordings were initiated.

3. RESULTS

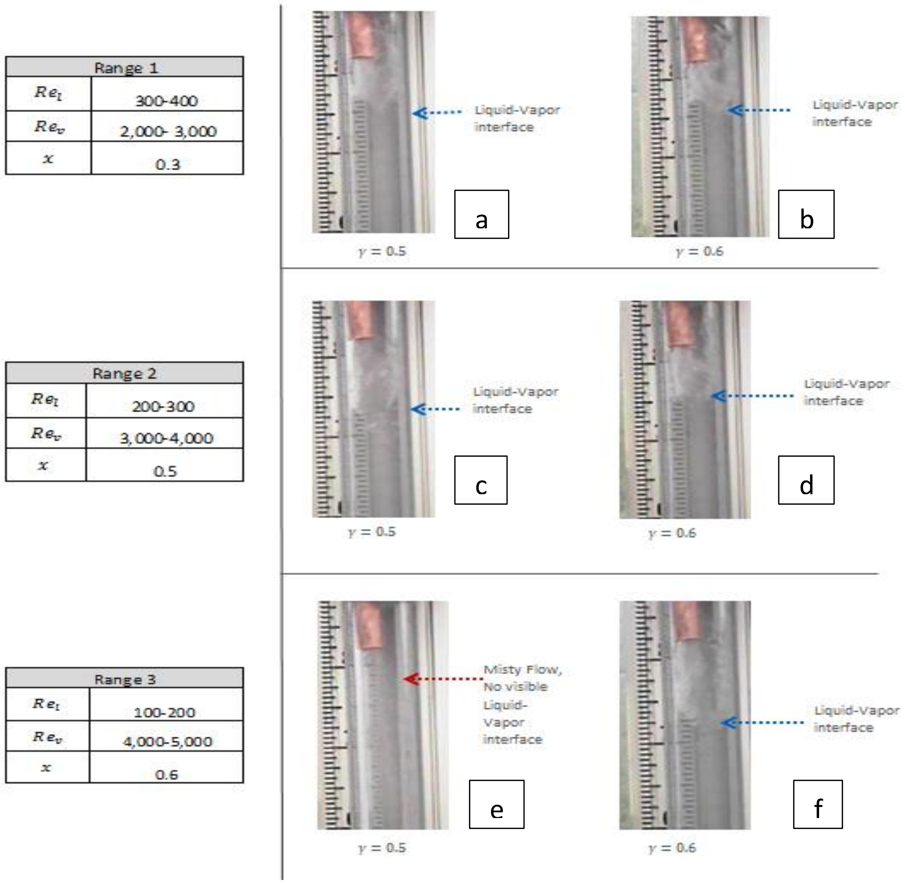
For the scope of this project, the ranges of working conditions that were experimentally investigated were those for small scale residential appliances. The working fluid was R-134a. The visual recordings were made of the two separator vessels. The results presented in this section pertain to the still images captured from the video recordings of various test cases at 30 minutes after stability for Separator 1 and 2.

Separator 1

In Fig. 6, flow visualizations within Separator 1at the higher mass flow rate and low operating pressure conditions are shown. The tables on the far left column indicate the liquid and vapor Reynolds ranges based on the superficial velocities given inlet vapor quality. The images of a, c, and e show the visualization of the flow inside of the separator when γ is maintained at 0.5; Likewise, images of b, d and f pertain to γ maintained at 0.6. The liquid-vapor interface is indicated by a blue dashed arrow. At the liquid-vapor interface, no significant liquid-vapor shearing was observed.

In all cases, a clear liquid-vapor interface was observed except in the case e. In case e, where a liquid-vapor interface is not present, misty flow is visible. This occurs because the inlet quality exceeds the top branch flow ratio and therefore some vapor is forced out through the liquid branch.

As inlet vapor quality increases, the height of the vapor-liquid interface decreases relative to the bottom of the separator. For cases a and b, inlet quality is maintained at 0.3, and the liquid-vapor interface is approximately 1.75 in [44.45 mm] (as measured from the bottom of the separator). As quality increases to 0.5 (cases c and d), the height reduces to 1.25-1.50 in [31.75- 38.1 mm], and finally at a quality of 0.6 in, where the liquid-vapor interface is visible(case d), the height reduces to 1.00- 1.25 in [25.4-31.75].



Range 1	
Re_l	300-400
Re_v	2,000- 3,000
x	0.3

Range 2	
Re_l	200-300
Re_v	3,000-4,000
x	0.5

Range 3	
Re_l	100-200
Re_v	4,000-5,000
x	0.6

Figure 6: Separator 1, P = 115 Psia [800 kPa], $\dot{m}_T$ = 12 lbm/hr [5.44 kg/hr]

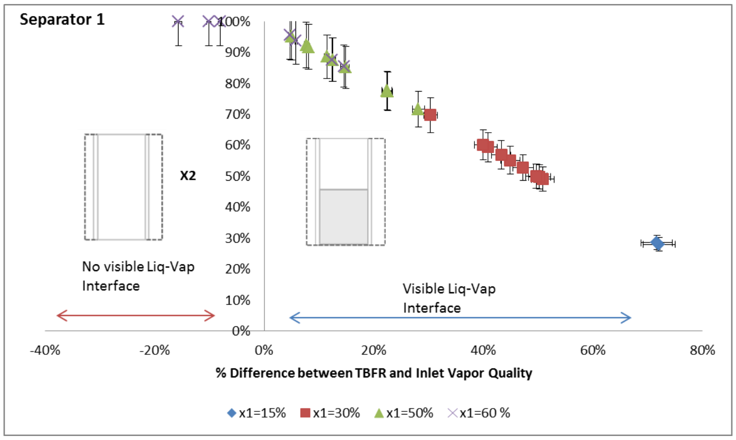


Figure 7: Separator 1, Outlet Vapor Branch Quality vs. Percent difference between Top Branch Flow Ratio and Inlet Vapor Quality

In Fig. 7, the vapor quality at the outlet vapor branch, x_2, is presented as a function of the percent difference between Top Branch Flow Ratio and inlet vapor quality, which is defined as

$$\frac{\gamma-x_1}{\gamma}x100 \qquad [7]$$

The purple indicators denote an inlet quality of 60%, green 50%, red 30% and blue 15%.

A positive [+] percent difference indicates that top branch flow ratio is greater than inlet quality; in such cases, this physically means that liquid is being force out of the vapor branch. Also, the mass flow exiting through the vapor branch is greater than through the liquid branch in these cases, and the inlet quality entering the separator is 50% or lower. Visually, a liquid plug was present which provided a liquid seal through which vapor bubbles did not penetrate and exit through the liquid branch.

A negative [-] percent difference indicates that the inlet quality is greater than the Top Branch Flow ratio. From the graph, one can see that in the cases where inlet quality is 60%, operating at a top branch flow ratio of 50%, the percent difference is negative; these points pertain to the cases where no clear liquid-vapor interface was identified and misty flow was apparent at the exit of the inlet branch of the separator. In such cases where a liquid build up is not visible the assumption that the vapor quality through the liquid branch is zero is not accurate since vapor is being forced through the liquid branch. For these cases, the vapor branch quality, x_2, was capped at 100%, but it was not possible to determine the actual value.

Separator 2

The visualization of the inlet flow characteristics is limited due to the smaller volume of Separator 2. However, identifying a liquid plug or the presence of vapor bubbles in that plug was still possible. In Fig. 8, the conditions that are presented are at a top branch flow ratio of 0.6. The results shown are of conditions operated at a low mass flow rate and a low operating pressure. In all three cases, a liquid plug was present and no vapor bubbles penetrated through the liquid plug or exited through the liquid branch.

Range 1	
Re_l	200-300
Re_v	500- 1,500
x	0.3

Range 2	
Re_l	150-250
Re_v	1,500-2,500
x	0.5

Range 3	
Re_l	100-200
Re_v	2,500-3,500
x	0.6

Figure 8: Separator 2, P = 115 Psia [800 kPa] $\dot{m}_T$ = 6 lbm/hr [2.7 kg/hr]

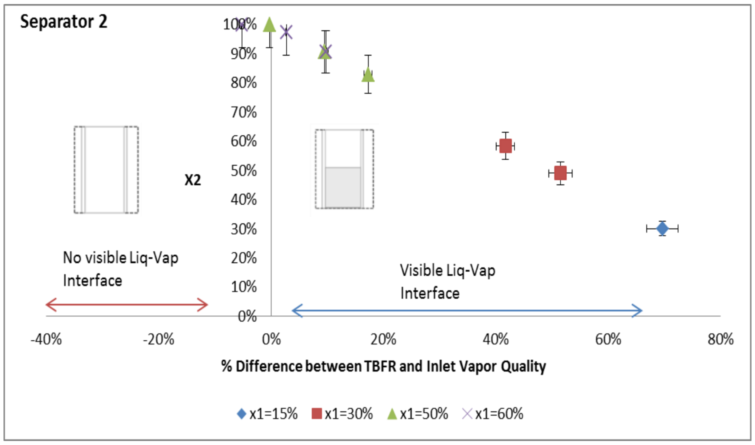


Figure 9: Separator 2, Outlet Vapor Branch Quality vs Percent difference between Top Branch Flow Ratio and Inlet Vapor Quality

In Fig. 9, the vapor branch quality, x_2, is presented as a function of the percent difference between Top Branch Flow Ratio and inlet vapor quality for Separator 2. Similar to Fig. 8, a positive percent difference indicates that Top Branch flow ratio is greater than inlet quality; in those cases visual confirmation of a liquid plug was present, which provided a liquid seal which prevented vapor bubbles from penetrating and exiting through the liquid branch. A negative percent difference indicates that the inlet quality was greater than the Top Branch Flow ratio. Because the effect of inlet pressure and total mass flow did not show high a correlation to $\dot{x}_2$, fewer points were tested to verify the performance of Separator 2. One case was observed to have no visible liquid-vapor interface, and the percent different between top branch flow ratio and inlet quality was -5%.

4. DISCUSSION AND CONCLUSIONS

The results of this study show that liquid-vapor separation is effective for the two separators tested. When reducing the aspect ratio by a factor of 5, separation performance still remained sensitive only to the balance between inlet quality and top branch flow ratio for these operational ranges. Visual observations indicate that separation is primarily driven by gravitational forces; liquid settles at the bottom while vapor bubbles that were dispersed in the liquid plug tended to coalesce and stay towards the top of the separator. No excessive entrainment or high vapor shearing through the liquid build up was apparent in the lower mass flow ranges. Even at higher mass flow ranges investigated in this study vapor shearing through the liquid build up did not disturb the liquid seal, and at qualities between 30-50 %, preventing vapor bubbles from exiting through the liquid branch. For Separator 2, it was not possible to see the incoming fluid characteristics as well as with separator 1, but no vapor bubbles were present in the liquid plug which was a physical indication that the quality at the liquid branch remained at 0, and that the vapor quality at the outlet liquid branch could be estimated appropriately, as similarly done for separator 1.

Another important finding from this study was that the control and balance of the top branch flow ratio to the inlet quality was necessary to maintain a liquid plug which enables the evaluation of vapor quality at the vapor branch outlet. The greatest vapor quality attainable through the vapor branch is obtained when inlet quality and top branch flow ratio are equally balanced for these operational ranges. When inlet quality and top branch flow ratio are not equally balanced, two outcomes resulted:

1) $x_1 > \gamma$: No clear liquid-vapor interface was present thus no liquid buildup was found within the separator.

2) $x_1 < \gamma$: The liquid-vapor interface was visible and a liquid buildup was observed within the separator vessel.

Effective liquid-vapor separation can be achieved when the top branch flow ratio is set equal to the inlet vapor quality for operating conditions that are pertinent to domestic refrigerators, in which low mass fluxes on the order of 6 to 12 lbm/hr[2.7-5 kg/hr] are typical. In the current study valves that are downstream of the vapor and liquid branches were adjusted to increase the pressure drop and adjust the top branch flow ratio. The implications of the study suggest that to implement the separator designs from this study would require some additional work to size the capillary tubes in order to adjust the top branch flow ratio appropriately for a particular system. In order to obtain a liquid branch free of vapor bubbles and a vapor branch free of liquid droplets, the inlet quality and top branch flow ratio must be equal; therefore, both inlet quality and top branch flow ratio need to be known prior to operation.

In a Flash Gas Bypass (e.g. Economizer system) and Mixed Refrigeration system a separator is generally installed before the evaporator, which is intended to have a higher liquid load to direct to the evaporator for increased capacity and redirecting the flow of gas on the high side of the system can be beneficial in overall system efficiency. In such systems the effects of re-entrainment of liquid in the vapor branch are not detrimental. However, in systems such as the Ejector Refrigeration or systems which include oil separators which are directly routed to the suction side of the compressor, any liquid present in the vapor branch can be detrimental to the reliability and performance of components and overall system. This study confirmed that liquid separation is readily achieved for a range of separator geometries, suggesting that these separators would be effective for Flash Gas Bypass and Mixed Refrigeration systems. However, since it was not possible to confirm that liquid was not entrained in the vapor branch during this study, further study would be needed before confirming the use of these separators for systems such as the Ejector Refrigerator.

NOMENCLATURE

x	Quality	(-)
γ	Top branch flow ratio	(-)
α	Aspect ratio	(-)
h	Enthalpy	(Btu/lbm)- (J/kg)
$\dot{m}$	Mass flow	(lbm/hr) – (kg/hr)
P	High side Pressure	(Psia) – (kPa)

$\dot{q}_{htr}$	Energy from Heater	(Btu/hr) – W
$\dot{q}_{r}$	Energy transferred to refrigerant	(Btu/hr) – W
Re	Reynolds Number	

Subscript

i	Inlet
o	Outlet
l	liquid
f	fluid
v	vapor
T	Total
1	Inlet Branch
2	Vapor Branch
3	Liquid Branch

REFERENCES

Chaudhry, G., Zhuo, J., & Junge, B. (2015). Ejector Refrigeration for Packaged Terminal Air Conditioners. Bangalore - Louisville: GE Global Research & Appliances.

Domanski, P. A. (1995). Theoretical Evaluation of the Vapor Compression Cycle with a Liquid-line/suction-line Heat Exchanger, Economizer, and Ejector. National Institute of Standards and Technology.

Milosevic, A. S. (2010). Flash Gas Bypass Concept utilizing Low Pressure Refrigerants. Urbana-Champaign: PhD thesis University of Illinois at Urbana-Champaign.

Pottker, G., Guo, B., & Hrnjak, P. S. (2010). Experimental Investigation of an R410A Vapor Compression System Working with an Ejector. International Refrigeration and Air Conditioning Conference.

Stoecker, W. F. (1978). Improving the Energy Effectiveness of Domestic Refrigerators by the Application of Refrigerant Mixtures. Urbana: U.S. Department of Energy.

Tuo, H., & Hrnjak, P. (2014). Vapor Liquid Separation in a Vertical Impact T-junction for Vapor Compression Systems with Flash gas Bypass. Internation Journal of Refrigeration, 40: 189- 200.

Tuo, H., Bielskus, A., & Hrnjak, P. (2011). Effect of Flash Gas Bypass on the Performance of R134a Mobile Air-Conditioning System with Microchannel Evaporator. SEA International, 231-239.

Umezu, K., & Suma, S. (1984). Heat Pump Room Air-Conditioner Using Variable Capacity Compressor. ASHREA Transactions, 335-349.

Xu , X., Hwang, Y., & Radermacher, R. (2011). Refrigerant Injection for Heat Pump/Air Conditioning Systems: Literature Review and Challenges Discussions. International Journal of Refrigeration, 402-415.

Xu, X. (2012). Investigation of Vapor Injection Heat Pump System with a Flash Tank Utilizing R410A and Low-GWP refrigerant R32. College Park: University of Maryland.

ACKNOWLEDGEMENT

I would like to acknowledge Carlos Herrera for his mentorship and guidance in experimental portion of the project. Additionally, I would like to acknowledge the late Michael Kempiak for his vision, mentorship, and dedication in this project.