

A Review of the Effects of Changes in the Void Fraction of the Superheated Region on the TEV Operation and Evaporator Stability

Ramos, Raimundo A.

B.S. of Mechanical Engineering Candidate
Mechanical Engineering Department
Federal University of the Valley of San Francisco
José de SáManiçoba Ave
Petrolina - PE, 56304-917, Brazil

De Castro, José

Doctor of Agricultural Engineering
Mechanical Engineering Department
Federal University of the Valley of San Francisco
José de SáManiçoba Ave
Petrolina - PE, 56304-917, Brazil

Abstract

A level of superheat is necessary to ensure proper operation of vapor-compression refrigeration systems. An overly superheated vapor prior to entering the compressor can render the system inefficient, while inadequate superheat can result in evaporator instability and compressor damage. The void fraction present in the suction line is directly related to evaporator stability and the hunting phenomenon in the thermostatic expansion valve (TEV). This article aims at reviewing superheated region-related researches in the field of refrigeration as they relate to the operation of the TEV and the stability of the evaporator. In a first part, literature review will explain the causes of the void fraction in the superheated region and the second part describes the effects of the lubricant oil on the void fraction. The third part of this article is a review of the effects of the superheated region on the TEV and on evaporator stability.

Keywords: superheat, void fraction, maldistribution, lubricant oil, hunting, instability

1. Introduction

In the refrigeration and air-conditioning vapor compression, systems superheating is the result of additional heat transfer from the environment to the system after the evaporation of the fluid inside the evaporator and through the suction pipes prior to entering the compressor. Depending on how the theoretical vapor-compression refrigeration system is defined, the analysis of the cycle does not account for such heat transfer, as it is assumed to exist no heat transfer in the pipes, and no additional heat is transferred after the fluid has been completely evaporated inside the evaporator. Superheating plays an important role in the vapor-compression refrigeration cycle. It ensures that no liquid goes into the compressor, thus, protecting the compressor from damage. All refrigeration systems today are designed to account for some degree of superheat. However, high degrees of superheating can render the system inefficient in its operation. Therefore, maintaining the superheating of a system to a minimum can potentially decrease the size of the evaporator. (Solberg et al. 2000)

Maintaining the superheat levels at a minimum is a challenge directly related to the means by which it is measured in a system. Most air-conditioning systems with a control signal today uses superheat as the variable to which the system will make changes in order to operate within its threshold of normal operation. This makes the measurement of superheat an important aspect of the operation and efficiency of the vapor-compression refrigeration cycle. The objective of this paper is to review the effects of the superheated region in the TEV and the stability of the evaporator. The first section will consider the void fraction in the suction pipe and its causes and the second section considers the effects of the oil-refrigerant mixture in the superheated region.

The third and final section will review the impact of the superheated region on the expansion device and on evaporator instability.

2. Void Fraction in the Superheated Region

Books of thermodynamics fundamentals consider the superheated vapor in the superheated region to be 100% vapor with some fraction of lubricant oil, both in equilibrium. (Sontag et al. 2003; Cengel and Boles 2006) However, studies have shown that only partial evaporation happens in the evaporator. (Wedekind et al. 1978; Solberg et al. 2000) The region is considered to be in non-equilibrium with saturated droplets entrained in the superheated vapor, thus, making the refrigerant quality less than 1. (Wedekind et al. 1978) By the time the fluid reaches the sensor of the expansion valve, when such sensors are used in vapor-compression refrigeration systems, there is not enough time for thorough evaporation of these droplets. (Solberg et al. 2000) There is some measure of void fraction within this region. Previous studies of the vapor volumetric concentration, or void fraction, include Zuber and Staub (1966) and Hancox and Nicoll (1971). Zuber and Staub (1966) presented the solutions to void fraction propagation equations to variations in power, fluid flux, pressure, thermodynamic non equilibrium, vapor and liquid compressibility, and body forces. Hancox and Nicoll (1971) also presented void distribution methods, extending the analysis to include non-valid fully developed void, velocity, and enthalpy flow profiles assumption.

Wedekind and Stoecker (1968) were one of the pioneers to study superheat stability. (Wedekind and Stoecker 1968) His experiment evaluated the location of the last droplet seen in a straight glass tube heat exchanger. The result was that the region's distribution was determined with a stochastic function describing the unpredictable behavior of the region's length. Even after the effective liquid dry-out point, the point where we would consider a quality 1 state, there still exists some fraction of liquid. Later studies observed the same phenomenon, proving Wedekind to be correct with his findings. (Barnhart and Peters 1992) The stochastic nature of the evaporating flow process causes unpredictability in the length of the two-phase region. Even for what is generally considered steady state flow, the length of this region will still fluctuate. Part of this condition happens because of the complicated nature of two-phase flow and the imperfect flow distribution within the evaporator. Figure 1 shows the measured oscillation of the end position of the evaporator region, as measured by Wedekind and Stoecker (1968).

2.1 Two-Phase Flow Nature

The two-phase evaporating flow is composed of a variety of complicated flow patterns, especially if complete evaporation occurs. These flow patterns have a great impact on the evaporating process. The heat transfer and the pressure drop depend of the nature of the flow, resulting in the instability of the superheat degree leaving the evaporator. Figure 2 shows a schematic of a two-phase evaporating flow. The liquid droplet content of the fluid leaving the evaporator influences the level of superheat being measured. However, greater influence occurs when the liquid is present as waves, instead of droplets. (Van der Meer 1987) These waves will have a better contact with the wall of the suction pipe, changing the temperature of the bulb, causing the thermostatic expansion valve (TEV) to oscillate at a much greater rate. This wave flow pattern according to Wallis and Dobson (1973) happens as follows: The liquid and vapor velocities differ from each other in two-phase flow regimes. Vapor travels at a greater velocity than the liquid. At a certain velocity difference, the lower pressure in the center of the tubes due to the higher velocity of the vapor causes ripples to be formed.

The Bernoulli forces from the vapor flow at bigger velocity differences results in the growth of these ripples to waves. In the transversal area where these waves are located, the vapor area section is diminished, which causes the vapor velocity to grow, lowering the pressure and keeping the waves up. A large wave can fill the transversal area section of the tube. This is also called slug flow. These waves are blown forward by the vapor and propelled downwards. Figure 3 illustrates the process of the wave formation. When the waves come in contact with the liquid transition point, it will still have its lower temperature. (Van der Meer 1987) Barnhart and Peters (1995), who conducted a study on entrained liquid carry-over from a serpentine evaporator, also saw a liquid surplus towards the exit of the evaporator resulting in clusters of droplets at irregular intervals. This surplus was transported by slugs, or waves, originating near the inlet of the evaporator in the liquid-rich region. With the liquid's lower temperature, sharp decreases in superheat level were accounted for at these irregular intervals, having a direct effect on the superheated region.

2.2 Refrigerant Maldistribution

The majority of commercially available evaporators today use a parallel channel configuration in order to increase its capacity in a limited amount of space. Inlet headers are used to assure flow distribution. The efficiency of these evaporators rely on the even distribution of fluid in the parallel channels. However, non-uniform distribution generally occurs, decreasing the effectiveness of the heat exchanger. This is especially true for evaporators since the supplied refrigerant is usually in a two-phase state. Mueller (1987) evaluated the thermal performance loss of the evaporator of most usual applications in 5-10%. Fluid maldistribution also results in a lowered coefficient of performance (COP) of the system. Groll et al. (2011) measured on a combination of experiments and simulations the maldistribution in test circuits. It was found that specific circuits had 61% less flow than the average while others had 45% more than the average. The maldistribution of refrigerant can happen in both single and two phase flow. However, due to the different properties of vapor and liquid, two phase flows are notably unfavorable since there is phase separation in the header. (Zou and Hrnjak 2014a) This uneven distribution creates unwanted superheated regions with lower heat transfer coefficients and high temperatures in the evaporator. Considering that some tubes reach a superheated state, other parallel tubes deliver refrigerant in a two-phase state to the outlet header of the evaporator, which can cause excess liquid to spill from the evaporator. (Shannon et al. 2001) This superheated vapor has to compensate for the two-phase refrigerant. However, overly superheated tubes can be very detrimental to evaporator performance. (Tuo and Hrnjak 2013)

Overall, the causes of evaporator maldistribution can be classified into two types: geometric factors and operational factors. Geometrical factors can encompass differences in diameter and length of parallel paths, pressure drop in headers due to its geometry, the coupling arrangement between the channels and the header, and the orientation and position with respect to gravity. Operational factors include quality induced maldistribution, flow patterns, mass flow rates, and changes in lubricating oil distribution. (Mader et al. 2015; Mueller 1987; Mueller and Chiou 1988; Shannon et al. 2001; Tuo and Hrnjak 2013)

3. Effect of the Lubricant Oil Mixture in the Superheated Region

The primary role of the lubricant oil in the vapor compression refrigeration system is to ensure the efficacy and normal operation of the compressor by lubricating its moving parts. The lubricant oil also serves as a noise limiter, a tightness element, and in some situations, it is used for compressor cooling, working as a heat transfer medium. (Youbi-Idrissi and Bonjour 2008) Even though its role is only related to the compressor, inevitably, some amount of oil will flow with the refrigerant throughout the system. It flows through the entire refrigeration system along with the refrigerant as droplets. (Wujek 2011). The presence of oil in the system causes changes in the pressure drop and heat transfer along system components, and alters the thermodynamic equilibrium and transport properties of the refrigerant (such as density, saturated temperature, thermal conductivity, viscosity, etc.). (Li and Hrnjak 2015) These changes will have an impact on the superheat of the system. The three important effects on the superheated region caused by the lubricant oil are the changes in heat transfer properties, changes in the flow patterns, and increases in the refrigerant-side pressure drop.

No consensus has been reached by the scientific community on the effect of oil addition on the heat transfer properties. However, experimental evidence can be found of its effect on flow patterns and pressure drop.

Various studies have been conducted on two-phased flow patterns of refrigerants. (Haverkamp et al. 2006; Chinnov and Kabov 2006; Saisorn and Wongwises 2008; Shao et al. 2009; Rebrov 2010; Awad and Muzychka 2014) However, this is not true regarding refrigerant-oil mixtures due to the difficulties found in its evaluation and experimentation. Nonetheless, the changes in flow pattern by the addition of oil can be explained through foaming. (Li and Hrnjak 2015) Lubricant oil foaming can also affect the heat transfer in the evaporator. (Youbi-Idrissi and Bonjour 2008) Worsøe-Schmidt (1960) observed that when oil was added to the refrigerant, increased stratified-wavy flow was detected in the wetted perimeter of the wall, which can be explained by the increased surface tension of the refrigerant-oil mixture. Figure 4 shows the evolution of the flow pattern of an R-12/oil mixture at the inlet (a), middle (b) and outlet (c) of his evaporator. Studies have shown that the surface tension can be increased by as much as 18% (Bandarra Filho et al. 2008). This effect on surface tension can also explain the pressure drop increase in system components and lines. Wei et al. (2007) studied the influences of oil on refrigerant flow boiling inside horizontal smooth tubes with inside diameters of 6.34 mm and 2.50 mm and found alterations in the flow regime of the refrigerant-oil mixture in the different diameter tubes. They found wavy, wavy-annular, annular and mist-annular flow pattern in the 6.34 mm inside diameter tube and slug-annular and annular flow pattern in the 2.50 mm inside diameter tube.

These two-phase flow pattern alterations are very important in the evaporator. The altered flow regime can cause maldistribution in the parallel tubes, which in turn, causes unwanted superheated regions with lower heat transfer coefficients (Zou and Hrnjak 2014b). Burr et al. (2005) visualized flow regime of R134a and polyolester oil mixture. It was observed that maldistribution was exacerbated by the oil addition and the void fraction was depressed by the presence of lubricant. The other impact of the lubricant oil addition is on the pressure drop in the liquid phase of high quality regions in the evaporator. Since the oil is nearly non-volatile, it remains in the liquid phase. As the liquid refrigerant vaporizes, the oil remains in the liquid form, causing a high concentration of oil in the liquid phase near the end of the evaporation process (Bandarra Filho et al. 2008). Thome (1995) observed in many experiments that the effect of oil concentrations only became important in vapor qualities above 85%. Since oil has a higher viscosity than refrigerants, accumulation of oil tends to occur at the end of evaporators, causing increased pressure drops and decreased heat transfer. (Bandarra Filho et al. 2008) This in turn can cause an increase in the liquid carry-over length in the suction pipe.

4. Impact on Components:

4.1 Expansion Device

Expansion devices are important components of the vapor compression refrigeration systems. The most commonly used devices are the capillary tube and the TEV, or the electronic expansion valve (EEV), which functions with the same principal as the TEV. Their primary functions are to decrease the pressure at the entrance of the evaporator and to regulate the mass flow of refrigerant. The TEV uses superheat as its control signal in order to adjust the valve opening and closing. The remote thermal bulb attached to the suction line wall near the evaporator exit is used to receive this signal. Since liquid carry-over has to be avoided in order to maintain safe operation of the compressor, a finite level of superheat is desired. This finite desirable superheat is called the static superheat setting (SSS) (Mithraratne and Wijesundera 2003) and can be adjusted by changing the tension of the spring in the TEV. When the superheat level is above or below the set point, the intervention of the TEV has to bring the superheat to the desirable level. The minimum amount of superheat level acceptable by the system is directly related to the means by which the superheat is measured. (Solberg et al. 2000) If the SSS is too high, loss of efficiency can occur, and if too low, the safe operation of the compressor can be compromised along with the stability of the system. Thus, it is of the uttermost importance that the TEV remote thermal bulb measures a reliable representation of the level of superheat in the system. This will ensure the effective and efficient use of the TEV.

As explained in the previous section, the fluid leaving the evaporator is in a non-equilibrium state. The liquid entrained in the superheat region by means of liquid droplets or waves has both lower temperatures and higher heat transfer coefficients. When in contact with the wall section where the thermal bulb is located, it will render a false representation of the superheat level. In the case of liquid droplets, there needs to be a relatively even distribution throughout the cross sectional area where the bulb is located in order to minimize its effect of the measurement. The slugs that originate in the liquid-rich region of the evaporator, on the other hand, have a greater impact on the measurement of superheat, therefore, complicating the use of exit superheat reading in control strategies. (Barnhart and Peters 1995). The result of these phenomena is that the signal from the thermal bulb will exhibit large variances. The bulb can be measuring temperatures anywhere from the saturation temperature of the liquid droplets or slugs to the temperature of the superheated vapor. When a large variance in the signal occurs, it may cause the controller to hunt. When hunting takes place, the valve will fluctuate from open to close in a sustained manner, changing the refrigerant flow rate continuously, resulting in the change of evaporator pressure and superheat level. (Mithraratne and Wijesundera 2003) Figure 5 shows the variation of superheat temperature under hunting conditions for different static superheat settings (SSS). The two main factors that contribute to the hunting behavior of the TEV are (i) the unpredictable oscillation of the transition point between the two-phase region and the superheated vapor region inside the evaporator along its internal channels (Wedekind 1971), and (ii) the system's response to fluctuations in the cooling load. (Mithraratne and Wijesundera 2003)

4.2 Evaporator Instability

The operating stability in a vapor compression refrigeration system strongly depends on the degree of superheat. It is understood that having low superheat levels results in the efficient use of energy of the system. However, when running at low superheats, unstable behavior of the system may occur.

(Shang et al. 2015) The concept of the minimum stable superheat (MSS) line was created by Huelle (1967; 1972) in light of the unstable behavior observed at low superheat levels. Huelle found that there has to be a minimum degree of superheat in the system for a constant cooling capacity in order to achieve stable running conditions of the evaporator in systems with TEV. He observed that the hunting behavior occurred often when running at low superheat levels. Figure 6 below shows the MSS line and its relationship to stable and unstable conditions developed later by Huelle (1972). The MSS line was confirmed experimentally by Chen et al. (2002), proposing that the variation of flow type and heat transfer coefficient are also reasons for the existence of the MSS line. When operating conditions are at the right of the MSS line, as seen in Fig. 6, the evaporator will work at stable conditions; when the system is running to the left of the MSS line, the evaporator will work at unstable conditions; and when running on the MSS line, the evaporation is at the critical point between unstable and stable conditions. Huelle believed that the line is influenced by the characteristics of the system. Thus, extrapolating a MSS line from one system to another can result in lack of precision. (Chen et al. 2008)

At the time, the MSS theory was developed for single speed compressors. Varying compressor speed is known to reduce energy consumption in refrigeration systems and it is becoming widely used today. The problem with the MSS line for variable speed compressor is that while the speed of the compressor varies, and the cooling capacity changes in result, the SSS will normally remain the same. Chen (2008) proposed a modified MSS line having a maximum and minimal MSS value for systems with variable speed compressors (VSC) and EEV. The modified MSS line is shown in Fig.7. The suggested modified line is a piecewise curve with a minimum MSS amount, θ_{min} , and a maximum MSS amount, θ_{max} . For stable operations, the superheat level should always be set in between the maximum and minimum values regardless of cooling loads, as running above the maximum value result in low efficiency and when running below the minimum value result in unstable operating conditions. It was also observed that decreasing compressor speeds may cause the hunting phenomenon during the change in the system. Thus, Chen stated to be beneficial to have smaller magnitude speed reductions. (Chen et al. 2008)

5. Conclusion

In this brief review study, the impact of changes in the void fraction of the superheated region on the TEV operation and evaporator stability is analyzed. Explanation is given to the concept of void fraction and the length of the liquid dry-out point and its unpredictability. The complicated nature of two-phase flow and the imperfect flow distribution are discussed in relation to the void fraction. A review of the effects of the oil-refrigerant mixture in the superheated region is presented. Eventhough there is no agreement in regards to the heat transfer effect of the addition of lubricant oil, the effect on flow patterns and pressure drop was considered. The final and main section presents the impacts of liquid carry-over and degree of superheat, with their causes explained in the previous section, on the TEV and evaporator stability.

6. References

- Awad, M.M., & Muzychka, Y.S., (2014). Review and Modeling of Two-Phase Frictional Pressure Gradient at Microgravity Conditions. *Interfac. Phenomena Heat Transfer*, 2 (1), 15–40.
- Bandarra Filho, E.P., Cheng, L., & Thome, J.R., (2008). Flow Boiling Characteristics and Flow Pattern Visualization of Refrigerant/Lubricant Oil Mixtures. *Int. J. Refrigeration*, 32, 185-202.
- Barnhart, J.S., & Peters, J.E., (1992). An Experimental Investigation of Flow Patterns and Liquid Entrainment in a Horizontal -Tube Evaporator. ACRC TR 28, College of Engineering, University of Illinois at Urbana-Champaign.
- Barnhart, J.S., & Peters, J.E., (1995). An experimental investigation of entrained liquid carry-over from a serpentine evaporator. *Int. J. Refrigeration*. 18, 343-354.
- Burr, J.D., Newell, T.A., & Hrnjak, P.S., (2005). Experimental Investigation of Viscous Two-Phase Flow in Microchannels. ACRC, TR-252, College of Engineering, University of Illinois at Urbana-Champaign.
- Cengel, Y.A., & Boles, M.A., (2006). *Refrigeration Cycles*, in: McGraw-Hill Inc., *Thermodynamics: An Engineering Approach*, 5th Edition, New York, pp. 607-649.
- Chen, W., Chen, Z., Zhu, R.Q., & Wu, Y.Z., (2002). Experimental investigation of a minimum stable superheat control system of an evaporator. *Int. J. Refrigeration*. 25(8), 1137–1142.
- Chen, Y., Deng, S., Xu, X., & Chan, M., (2008). A study on the operational stability of a refrigeration system having a variable speed compressor. *Int. J. Refrigeration*. 31(8), 1368-1374.

- Chinnov, E.A., & Kabov, O.A., (2006). Two phase flow in pipes and capillary channels. *High Temperatures* 44 (5), 773–791.
- Chinnov, E.A., & Kabov, O.A., (2006). Two phase flow in pipes and capillary channels. *High Temperatures* 44 (5), 773–791.
- Groll, E.A., Braun, J.E., & Bach, C.K., (2011). Optimizing Refrigerant Distribution in Evaporators - Final Report. California Energy Commission, Publication number: CEC-500-2013-089.
- Hancox, W.T., & Nicoll, W. B., (1971). A General Technique for the prediction of void distributions in non-steady two phase forced convection. *Int. Heat Mass Tran.* 14(9), 1377-1394.
- Haverkamp, V., Hessel, V., Löwe, H., et al., (2006). Hydrodynamics and mixer-induced bubble formation in micro bubble columns with single and multiple channels. *Chem. Eng. Technol.* 29 (9), 1015–1026
- Huelle, Z.R., (1967). Heat load influences upon evaporator parameters. *International Refrigeration and Air Conditioning Conference*, 3(32).
- Huelle, Z.R., October (1972). The MSS line – a new approach to the hunting problem. *ASHRAE Journal*, 43-46.
- Li, H. & Hrnjak, P., (2015). An experimentally validated model for microchannel heat exchanger incorporating lubricant effect. *Int. J. Refrigeration.* 59, 259-268.
- Mader, G., Palm, B., & Elmegaard, B., (2015). Maldistribution in air-water heat pump evaporators. Part 1: Effects on evaporator, heat pump and system level. *Int. J. Refrigeration.* 50, 207–216.
- Mithraratne, P. & Wijesundera, N.E., (2003). An experimental and numerical study of hunting in thermostatic-expansion-valve controlled evaporator. *Int. J. Refrigeration.* 25: 992-8.
- Mueller, A.C., (1987). Effects of some types of maldistribution on the performance of heat exchanger. *Heat Transfer Eng.* 8(2), 75-86.
- Mueller, A. C., & Chiou, J. P., (1988). Review of various types of flow maldistribution in heat exchangers. *Heat Transfer Eng.* 9(2), 36-50.
- Rebrov, E.V., (2010). Two-phase flow regimes in micro channels. *Theor. Found. Chem. Eng.* 44 (4), 355–367.
- Saisorn, S., & Wongwises, S., (2008). A review of two-phase gas–liquid adiabatic flow characteristics in micro-channels. *Renewable Sustain. Energy Rev.* 12, 824–838
- Shang, Y., Wu, A., & Fang, X., (2015). A study on the modeling of the minimal stable superheat for a variable speed refrigeration system. *Int. J. Refrigeration.* 59, 182-189.
- Shannon, M. A., Leicht, T., M., Hrnjak, P. S., Miller, N.R., & Khan, F. A., (2001). Thin-film resistance sensor for measuring liquid mass fraction in super-heated refrigerant. *Sensor Actuat A-Phys.* 88(2), 164–177.
- Shao, N., Gavriilidis, A., & Angeli, P., (2009). Flow regimes for adiabatic gas–liquid flow in microchannels. *Chem. Eng. Sci.* 64, 2749–2761.
- Solberg, J., Miller, N., & Hrnjak, P., (2000). A Sensor for Estimating the Liquid Mass Fraction of the Refrigerant Exiting an Evaporator. SAE. Paper 2000-01-0976.
- Sontag, R.E., Borgnakke, C., & Van Wylen, G.J., (2003). *Power and Refrigeration Systems*, in: John Wiley & Sons, Inc., *Fundamentals of Thermodynamics*, Sixth Edition, United States of America, pp. 434-450.
- Thome, J.R., (1995). Comprehensive Thermodynamic approach to modeling refrigerant–lubricating oil mixtures. *HVAC&R Research.* 1(2), 110–126.
- Tuo, H., & Hrnjak, P., (2013). Effect of the header pressure drop induced flow maldistribution on the microchannel evaporator performance. *Int. J. Refrigeration.* 36(8), 2176–2186.
- Van der Meer, J.S., (1987). Simulation of a refrigerant evaporator. Ph.D, Thesis, University of Technology, Delft, The Netherlands.
- Wallis, G.B., & Dobson, J.E., (1973). The onset of slugging in horizontal stratified air-water flow. *Int. J. Multiph. Flow.* 1(1), 173-193.
- Wedekind, G.L., & Stöcker, W.F., (1968). Theoretical model for predicting the transient response of the mixture-vapor transition point in horizontal evaporating flow. *J. Heat transfer.* 90(1), 165-174.
- Wedekind, G.L., (1971). An experimental investigation into the oscillatory motion of the mixture-vapor transition point in horizontal evaporating flow. *J. Heat Transfer.* 93(1), 47–54.
- Wedekind, G.L., Bhatt B.L. & Beck B.T., (1978). A System Mean Void Fraction Model for Predicting Various Transient Phenomena Associated with Two-Phase Evaporating and Condensing Flows. *Int. J. Multiph. Flow.* 4(1) 97–114.

Wei, W., Ding, G., Hu, H., & Wang, K.,(2007). Influence of lubricant oil on heat transfer performance of refrigerant flow boiling inside small diameter tubes, Part 1: Experimental study. *ExpTherm Fluid Sci.* 32(1), 67–76.

Worsøe-Schmidt, P., (1960). Some characteristics of flow pattern and heat transfer of Freon-12 evaporating in horizontal tubes.*Int. J. Refrigeration.* 40, 40–44.

Wujek, S., (2011). Mist to Annular Flow Development Quantified by Novel Video Analysis Methods. Dissertation, Ph.D., University of Illinois at Urbana-Champaign, Urbana, USA.

Youbi-Idrissi, M., & Bonjour, J., (2008). The effect of oil in refrigeration: Current research issues and critical review of thermodynamic aspects. *Int. J. Refrigeration.* 31(2), 165-179.

Zou, Y. & Hrnjak, P.S., (2014a). Effects of Fluid Properties on Two-Phase Flow and Refrigerant Distribution in the Vertical Header of a Reversible Microchannel Heat Exchanger—Comparing R245fa, R134a, R410A, and R32.*Appl. Therm. Eng.* 70(1), 966-976.

Zou, Y., & Hrnjak, P.S., (2014b). Effect of oil on R134a distribution in the micro channel heat exchanger with vertical header.*Int. J. Refrigeration.* 40, 201-210.

Zuber, N., & Staub, F. W., (1966). The propagation and the wave form of the vapour volumetric concentration in boiling, forced convection system under oscillatory conditions. *Int. Heat Mass Tran.* 9(9), 871-895.

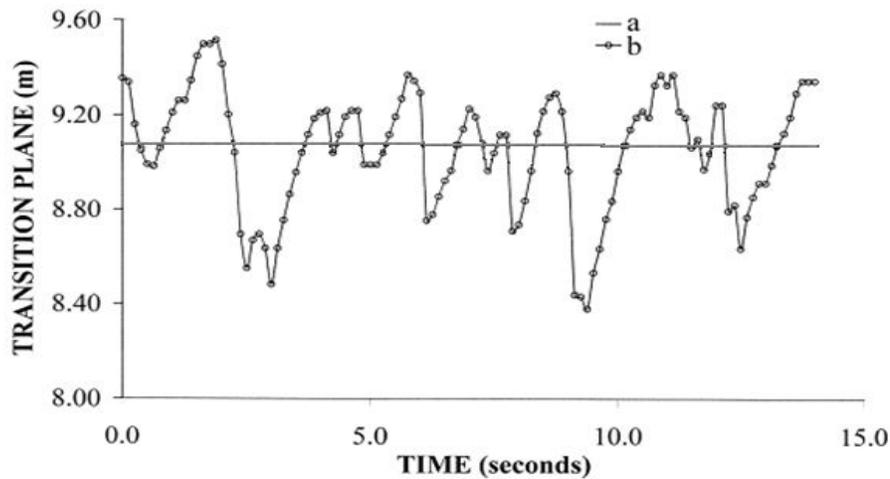


Figure 1: Measured oscillations at the end position of the evaporator region with (a) being the mean position of transition point and (b) the actual motion as measured experimentally. (Wedekind and Stoecker 1968)

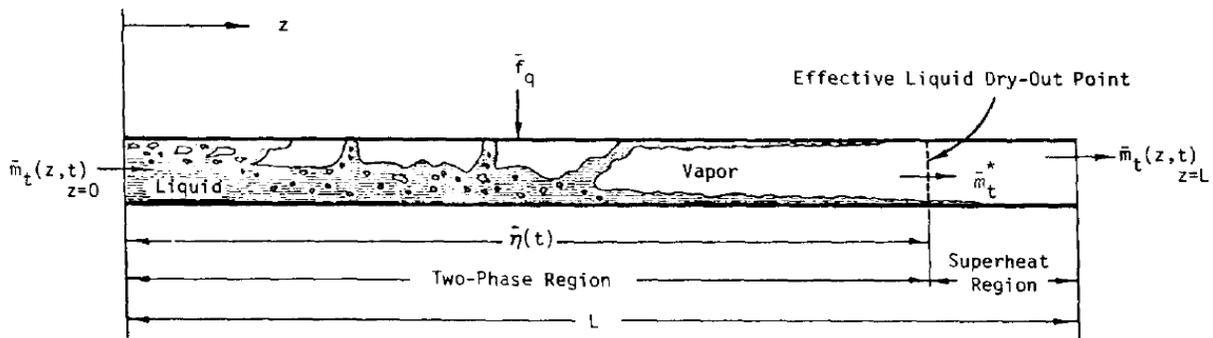


Figure 2: Schematic of a two-phase evaporating flow (Wedekind et al. 1978)

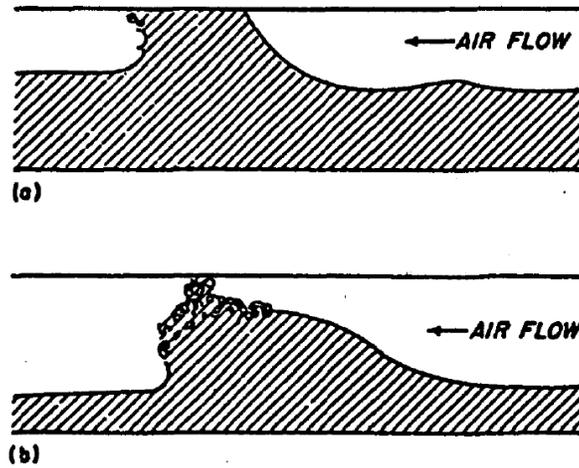


Figure 3: Wave flow formation (Wallis and Dobson 1973)

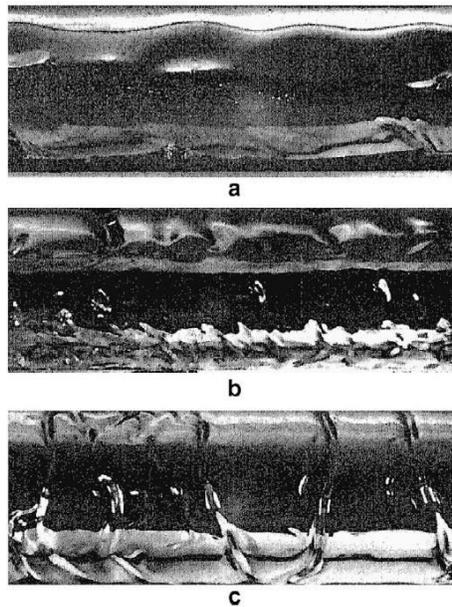


Figure 4: Visualization of the evolution of the flow pattern of R-12/oil mixture at the inlet (a), middle (b), and outlet (c). (Worsoe-Schmidt 1960)

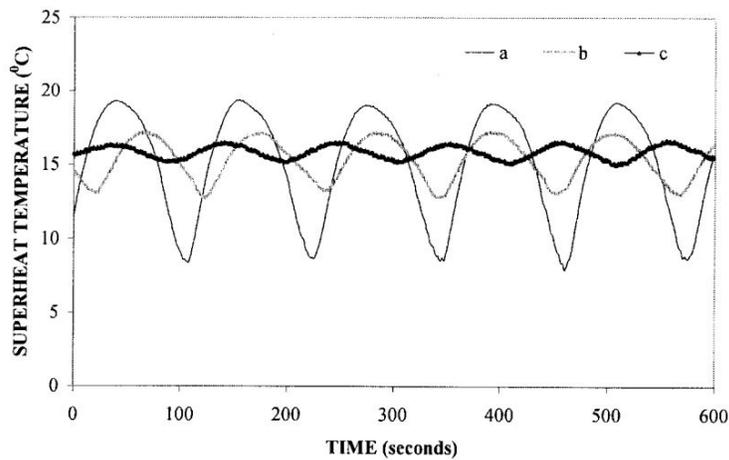


Figure 5: Variation of superheat temperature under hunting conditions. (a) SSS1, (b) SSS2, (c) SSS3 under condition: $SSS1 < SSS2 < SSS3$. (Mithraratne and Wijeyesundera 2003)

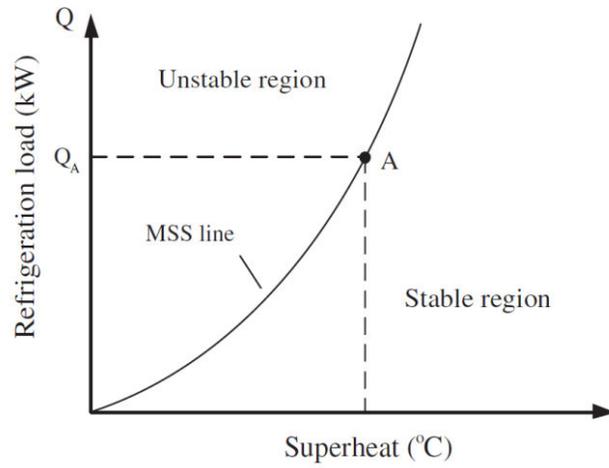


Figure 6: MSS line proposed by Huelle (1972)

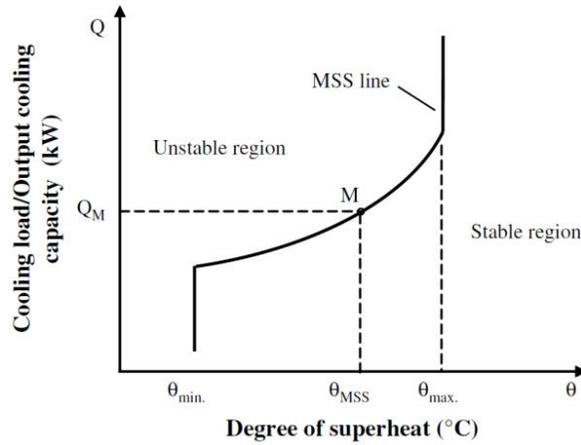


Figure 7: The modified MSS line proposed by Chen et al. (2008)