Penerbit Akademia Baru

CFD Letters

Journal homepage: www.akademiabaru.com/cfdl.html
ISSN: 2180-1363

Simulation Analysis of Two-Phase Heat Transfer Characteristics In a Smooth Horizontal Ammonia (R717) Evaporator Tube

Open Access

Pravinth Balthazar[1], Muzathik Abdul Majeed[1,*]

[1] Department of Mechanical Engineering, Faculty of Engineering, South Eastern University of Sri Lanka, Sri Lanka

ARTICLE INFO

Article history:
Received 29 September 2018
Received in revised form 16 December 2018
Accepted 24 December 2018
Available online 28 December 2018

Keywords:
Two-phase, Heat transfer coefficient, Horizontal Evaporator, Pressure drop

ABSTRACT

Ammonia is an important refrigerant in modern refrigeration industry due to zero-ozone depletion potential and zero global warming potential. This paper focused on comparison of horizontal evaporators' two-phase heat transfer coefficient characteristics and pressure drop verses the vapour qualities in a simulated ammonia evaporator refrigeration system in a virtual environment using the experimental results. In this study, two-phase ammonia fluid flow with mass fluxes from 50 to 150 kg/s.m^2, vapour qualities between 0 and 0.6, heat flux 40 kW/m^2 and saturation temperature -20^{o}C were considered. Similarly, two-phase pressure drop correlation also simulated in virtual environment for mass flux 100 kg/s.m^2, heat flux 70 kW/m^2 and vapour qualities in between 0.1 and 1.0. Finally, the simulated results were compared with the experimental values and validated. Results were signified that 100 kg/m^{2}s mass flux showed experimental and simulation deviation 3.52% and 5.5% for pressure drop and two-phase heat transfer coefficient, respectively. Two-phase heat transfer coefficient increased by 75.7% when mass flux is increased from 50kg/m^{2}s to 100kg/ m^{2}s.

1. Introduction

Global warming and ozone depleting are the vital problems faced by the world today. The complaint is these impacts are caused by the refrigerant industry and supermarkets by directly and indirectly. Indirectly contributing by their higher consumption of energy to run the air-conditioning and refrigeration systems and directly contributing by leaking refrigerants to atmosphere. Most of these refrigerants are containing high ozone depleting potential (ODP) and high global warming potential (GWP). New technologies and techniques progressed for more efficient systems and contrastive research interest to replace synthetic refrigerant by natural refrigerant increased, Over the last decade, natural refrigerants such as ammonia (R717) has been studied to replace CFCs, HFCs and HCFCs in heat pump, air-conditioning and refrigeration systems [1-5].

* *Corresponding author.*
E-mail address: muzathik64@yahoo.com (Muzathik Abdul Majeed)

However, using natural refrigerants became increasingly complex and requiring many experiments to find the accurate heat transfer characteristics and flow patterns on these fluids. Combining these details for natural refrigerants with the goal of developing accurate methods for designing energy-efficient systems became very active in this era [6]. This lead to undertake various experiments on two-phase heat transfer coefficients, pressure drops, flow patterns and flow boiling over the last two decades.

Although, there are two-phase heat transfer correlations which have been developed experimentally without including flow pattern information, comparisons clearly shown that generally accuracy has been improved for flow pattern based methods. First, Baker et al. [7] recognized the importance of flow patterns in 1954 and Kattan et al. [8] used it for the establishing heat and mass transfer, pressure drop and void fraction correlations. R134a refrigerant was used by Silva Lima et al. [9] to compare their experimental heat transfer data with several types of correlations (strictly empirical, strictly convective, superposition and flow pattern based). The conclusion showed that their flow pattern based method predicts experimental data most accurately and flow pattern transitions could explain the change in trends in heat transfer data quite well.

However, Thome et al. [6, 10] pointed out that from a predictive standpoint, many features of the existing correlations require refinement to achieve the desired level of accuracy for evaporator design. Using ammonia in such systems require flawless predictive methods for heat transfer characteristics and flow pattern transitions. Therefore, handful reviews has been done on the available experimental work for ammonia [9, 11-12]. Figure 1 shows a horizontal evaporator that absorbs heat into the system. When evaporator absorbing the heat; phase change occur. Phase changes not just occur directly liquid to vapor it is going through different phases while vapor quality increases 0 to 1 from left to right.

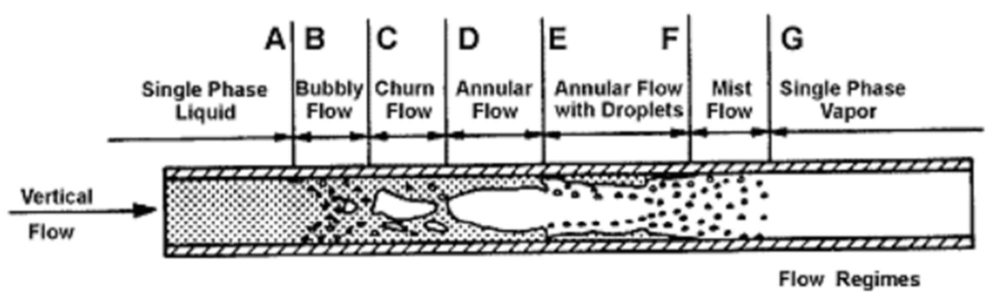

Fig. 1. Two phase flow in horizontal evaporator tube [9]

Finding out the accurate heat transfer correlation is the key. Chen [12] proposed the 1st correlation for evaporation in vertical tubes. This correlation divided into two parts. Nucleate pool boiling (h_{nb}) hinged on Zuber's pool boiling equation [13] and bulk convective equation (h_{bc}) hinged on Boelter's equation [14] defined by Cooper [15]. In 1980 Bennett and Chen [16] modified the equation to analyze boiling near the wall. The bulk convection term (h_{bc}) and two-phase correction factor (S) were modified. The correlation developed by Gungor and Winterton [17] for flow boiling in horizontal tubes. They use Chen correlation to find out this. To find the accuracy of this equation they have done experiment for water and seven other refrigerants and got more than 4300 points. In that experiment ammonia (NH_3) also included. The Eq. 1 to 4 given below were used for simulation in this study because of the compatibility data available, even though few other correlations available for ammonia [18-20].

$$h \quad = Eh_l + Sh_{pool} \tag{1}$$
$$h_{pool} = 55Pr^{0.12}(-log_{10}Pr)^{-0.55}M^{-0.55}q^{0.67} \tag{2}$$
$$E \quad = 1 + 24000Bo^{1.16} + 1.37{X_{tt}}^{-0.86} \tag{3}$$
$$S \quad = \left(1 + 1.15 * 10^{-6}E^2{Re_l}^{1.17}\right)^{-1} \tag{4}$$

The prediction of pressure drop is important as the prediction of two-phase heat transfer coefficients in designing heat transfer equipment. Pressure drop during evaporation can be obtained from the two-phase flow momentum equation given according to Cavallini and homogeneous two-phase pressure drop correlation [4]. The total pressure drop of the system is given below by Eq. 5.

$$\frac{dp}{dz} = \left(\frac{dp}{dz}\right)_f + \left(\frac{dp}{dz}\right)_a + \left(\frac{dp}{dz}\right)_g \tag{5}$$

The pressure gradient consists of frictional, gravitational and acceleration pressure gradients symbolized by subscripts f, g and a respectively. The axial coordinate z is oriented in the flow direction. Pressure gradient for gravitation shown below in Eq. 6 and pressure gradient for acceleration shown in Eq. 7, where $\left(\frac{dp}{dz}\right)$ is the gradient of pressure in the direction of flow.

$$\left(\frac{dp}{dz}\right)_g = g.(\rho_v.\varepsilon - (1-\varepsilon).\rho_l).sin(\phi) \tag{6}$$

$$\left(\frac{dp}{dz}\right)_a = G^2\left\{\frac{x^2}{\rho_v.\varepsilon} + \frac{(1-x^2)}{[\rho_l(1-\varepsilon)]}\right\}.dz \tag{7}$$

Acceleration and gravitational terms can be neglected because it is assumed adiabatic conditions and horizontal flow. Simplified equation shown in Eq. 8. The friction between the liquid and vapor phases and friction between the fluid particles and the tube walls causing frictional pressure drop in two-phase flow.

$$\frac{dp}{dz} = \left(\frac{dp}{dz}\right)_f \tag{8}$$

Martinelli and Nelson [21] introduced two-phase multiplier (Φ) to utilize the two-phase pressure drop correlations. Martinelli and Lockhart [22] associates the two-phase frictional pressure drop in terms of either single-phase vapor or single-phase liquid pressure drop. This is the acceptable most accurate horizontal tube correlation. For this study, vapor only multiplier is defined below in Eq. 9 where the subscript "vo" shows that the flow in the entire pipe is consider as converted into vapor only.

$$\left(\frac{dp}{dz}\right)_f = {\phi^2}_{vo}\left(\frac{dp}{dz}\right)_{vo} \tag{9}$$

Niño (2002) [23] found that "liquid only" based correlations were failing in small channels. Because of Reynolds number is dropping to levels below the laminar-turbulent transition range (Re ~ 2300) so vapor only basis system is chosen to conduct this study. For simulated mass flux ranges, the vapor only parameter keeps the Reynolds number above the transition region, resulting in a more consistent level of reference for the two-phase multiplier. This vapor only basis equation shown in Eq. 10 and mass flux is G, vapor density is ρ_v, hydraulic diameter is D_h and the single-phase friction factor is f_{vo}.

$$\left(\frac{dp}{dz}\right)_{vo} = f_{vo}\left(\frac{G^2}{2\rho_v D_h}\right) \tag{10}$$

Blausius formula and Reynolds number equation used to determine the Turbulent Darcy friction factor shown in the Eq. 11 and 12 respectively and μ_{tp} is the viscosity of the fluid and the viscosity of the fluid is defined in Eq. 13.

$$f_{vo} = \frac{0.316}{Re^{0.25}} \tag{11}$$

$$Re = \frac{GD_h}{\mu_{tp}} \tag{12}$$

$$\mu_{tp} = x\mu_v + (1-x)\mu_l \tag{13}$$

Ammonia is examined in two-phase pressure drop experiments and peak pressure drop is determined to be inversely related to vapor density from two-phase pressure drop experiment by D.C. Adams at el [24]. Two phase fluid flow pressure drop equation for evaporation is given in the Eq. 14.

$$\left(\frac{dp}{dz}\right)_{tp} = {\phi_{vo}}^2\left(f_{vo}\cdot\frac{G^2}{2.D_h.\rho_v}\right) \tag{14}$$

This study focusing on developing a simulation software for designing and modeling refrigeration evaporator system and validating the virtual environment of the software with existing experimental results.

2. Methodology

Heat flux (q), mass flux (m), internal (Di), and external (Do) diameters of tubes, operating temperatures are identified as input experimental conditions that need to be applied for simulation model to create virtual environment for evaporator. The pressure drop occurred in tube was neglected for initial calculations. Then, two phase heat transfer coefficient for ammonia was obtained for given heat flux, mass flux and internal diameter. Two phase heat transfer coefficient varied while changing the vapour quality(x) of the tube. Therefore, two phase heat transfer coefficients calculated by using a computer algorithm while the vapour quality changing 0 to 1.

Total two-phase heat transfer coefficient was obtained by using vapour quality, tube material, internal diameter, outer diameter and temperature difference inside and outside of the tube. The required length calculated by dividing the total length in to 5,10,15,20,25,30,35,40,45,50 equivalent segment at each time. Schematic diagram of the evaporator element by element is shown in Figure 2. Then most suitable number of segment was selected to carry out the research to obtain results.

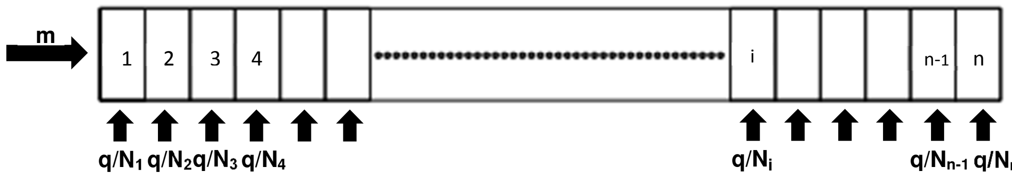

Fig. 2. Schematic diagram of the evaporator element by element

While simulating two-phase flow in evaporator it is very important to obtain required length as a function of vapour quality. Because vapour quality is changing with the length so two-phase heat transfer coefficient is also changing with the length. The total amount of heat absorbed by square meter of the tube is q. Evaporator coil length is assumed as L_{TOTAL} to absorb total amount of thermal energy (N_n.q). Mass flow rate through the tube is m. L_{TOTAL} is calculated as a feedback loop to examine and oversee the experiment length of the evaporator pipe.

Length of evaporator coil for element (*i*) was obtained by Eq. 15 and required total length of evaporator coil is a function of vapor quality (x). Therefore, required total length can be obtained by integrating equation with considering limit of minimum 0 to maximum 1 depending on the selection of segment which was used for analysis. It is shown in Eq. 16.

$$L_i = \left[\frac{1}{\Pi.D_i.h_i} + \frac{ln\left(\frac{D_o}{D_i}\right)}{2\Pi.K}\right].\frac{q}{\Delta T.N_i} \quad (15)$$

$$L_{TOTAL} = \sum_{i=1}^{n}\left(\int_0^1 L_i \, dx\right) \quad (16)$$

These methods were based on an accurate database covering a wide range of experimental conditions to obtain the desired level of accuracy. Especially, flow pattern information included in these databases as the structure of geometrical functions. These functions identified the distribution of the liquid and vapor phases and their influence on the pressure drop and heat transfer. So, the dryness fraction defined in the programming for various type of flow pattern. The flow chart used to simulate the evaporator is shown in Figure 3.

Engineering Equation Solver (EES) Academic Version is used as a platform to analyze and simulate the results. Which is a combined with NIST - REFPROP and FORTRAN software. After that, experimental conditions were applied for simulation. Then, two-phase heat transfer coefficient was obtained from simulation for changing vapor qualities. Finally, simulated evaporator model results and experimental results were compared.

3. Results

3.1 Characteristics of Two-phase Heat Transfer Coefficient

Total length of evaporator and calculation time is observed for different number of segments, mass flow rate, cooling capacity, operating temperature and tube diameters. Maximum length of evaporator obtained at when selecting twenty (20) numbers of elements in the programme. Calculation time also increased while increasing the number of elements.

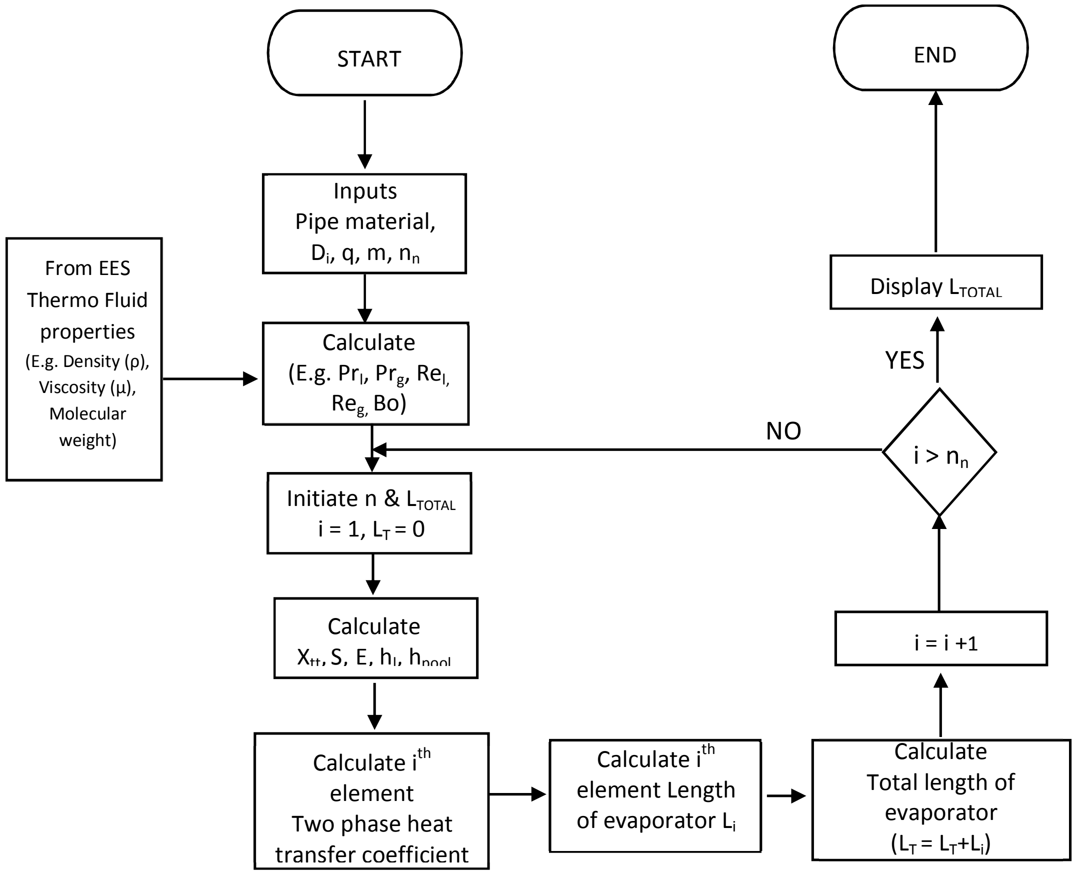

Fig. 3. Flow chart for model an evaporator length

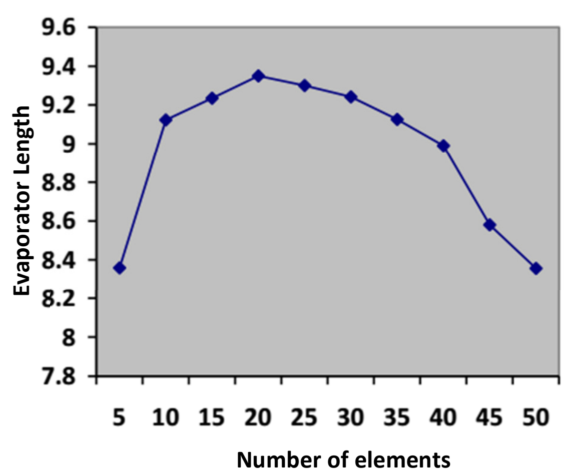

Fig. 4. Evaporator length varies with number of elements

Therefore, twenty elements were selected to simulate the programming because of simulation time is moderate and evaporator length is highest and this is a worst-case scenario. Figure 4 shows the variation of length while increasing number of elements.

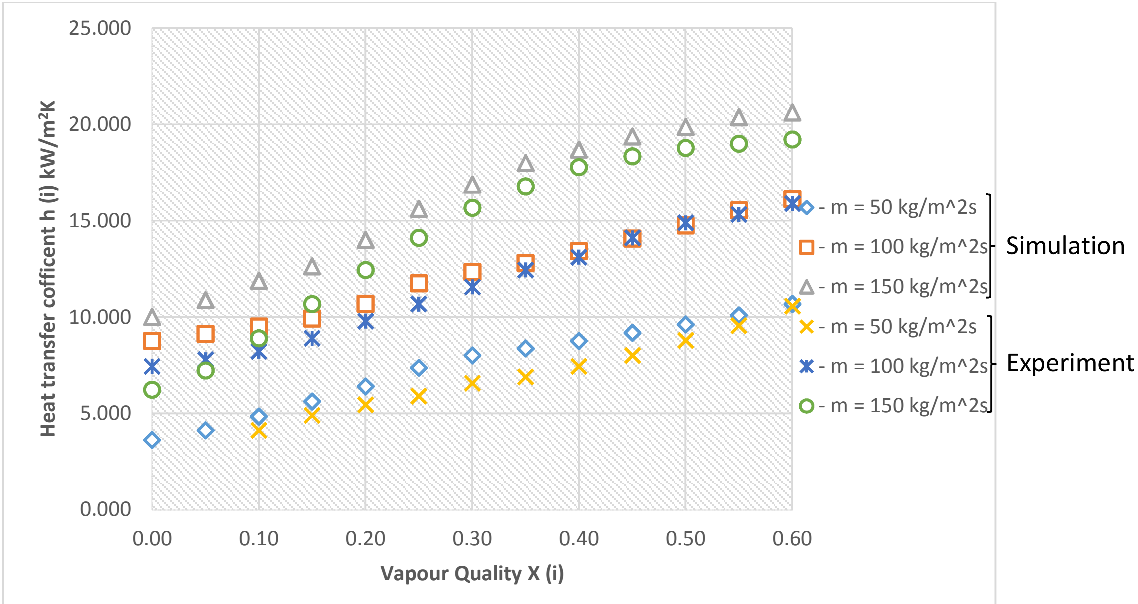

Fig. 5. Comparison of two phase heat transfer coefficients simulated and experimental results

Ammonia evaporator model is validated by using flow boiling of ammonia in a plain horizontal tube results extracted from Kabelac et al [25]. Virtual environmental conditions were set as heat flux is 40 kW/m^2, operating temperature -20^{o}C and geometrical parameters as internal diameter of 10 mm, length of 450mm. Mass flux is varied as 50, 100, 150 kg/ m^{2}s and two-phase heat transfer coefficient results were obtained.

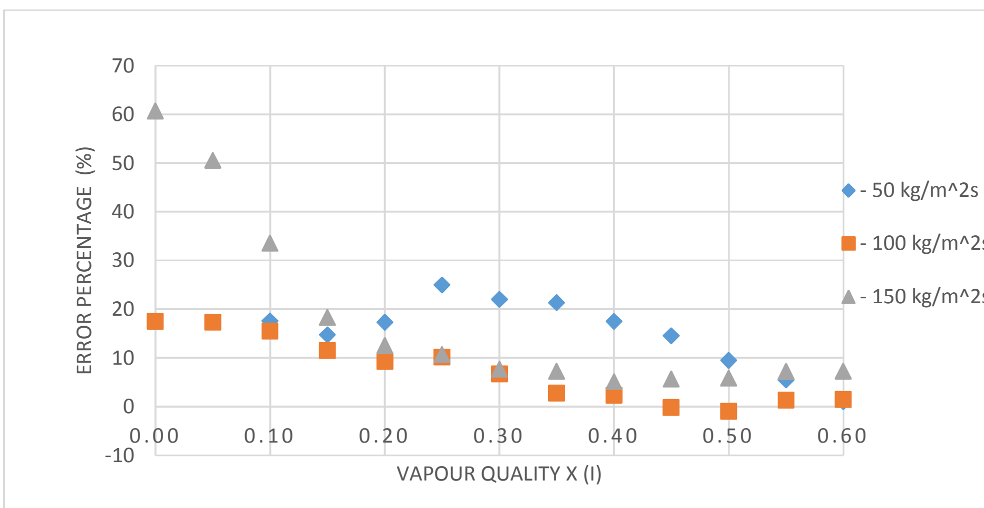

Fig. 6. Comparison for error percentage of simulated and experimental results

Figure 5 showing the comparison of two-phase heat transfer coefficient between experimental and simulation results. All the experimental and simulation graph are looking almost identical in their pattern respective to their mass flow rate. However, 150 kg/m^{2}s mass flow rates' heat transfer coefficient values showed significant deviation between 0 to 0.15 vapor qualities. Similar pattern was spotted 50 kg/m^{2}s and 100kg/m^{2}s mass flow rates, but the deviations are smaller compare to 150 kg/m^{2}s mass flow rates.

Error percentage and vapor quality variation were plotted using standard average deviation equation for simulated and experimental two-phase heat transfer coefficient for 50, 100, 150 kg/ m^2s mass fluxes. The results are illustrated in Figure 6 concluding the factor is that virtual environmental simulation values and experimental result values are deviating in between 0 to 0.15. This is because of bubbly flow is not accurately model up-to-date and there is no accurate heat transfer correlation to model or simulate that region. Average error deviation for 50, 100, 150 kg/ m^2s mass fluxes are respectively 15.1%, 5.5% and 11%.

3.2 Characteristics of Two-phase Pressure drop

Pressure drop of Ammonia evaporator model is validated by using an experimental investigation of pressure drop which done by Balthazar P. et al [26-27]. When heat flux is 70 kW/ m^2, internal diameter of 8.1mm, external diameter of 9.5mm, -20^o C operating temperature and when mass flux 100 kg/ m^2s pressure drop result obtained. Differentiations of experimental and simulated pressure drop results are shown in Figure 7. Simulation shows that two-phase pressure drop increased with vapour quality and peaked around 0.8 dropped significantly drops after 0.9. Although simulation results are showing smooth transition curve compared to experimental graph, there are significant spike increase in pressure drop 0.45 – 0.55 and 0.78 - 0.89 vapor quality range in experimental graph. This is may be because of less accurate experimental results or flow pattern change from stratified wavy flow collision with walls around 0.5 vapour quality and annular flow droplet/ mist collision with walls and themselves around 0.8 caused an additional turbulence within the pipe. However, trend line for experimental and simulation graph showing similar pattern between 0.4 – 0.95 vapor quality.

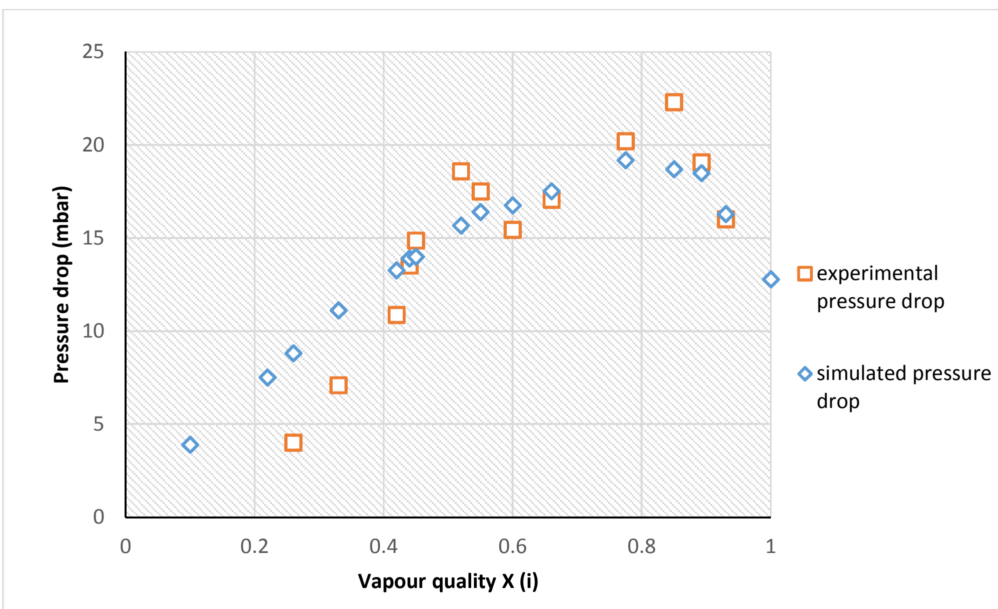

Fig. 7. Experimental and simulated pressure drop results for mass flux 100 kg/m^2s

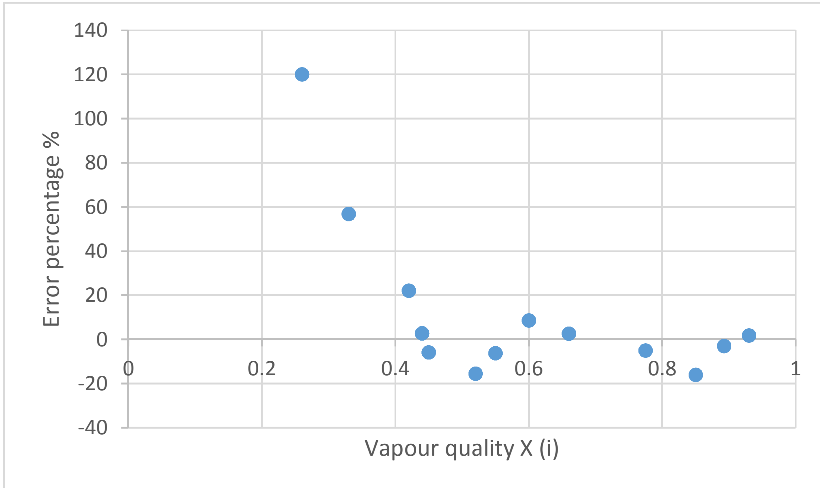

Fig. 8. Error percentage of the experimental and simulated pressure drop result for 100 kg/m^{2}s mass flux

Figure 8 concluding the factor is that, although, virtual environmental simulation values and experimental result values were deviating a lot between 0 to 0.4 vapor quality; it also showing that less than ± 20% error in experimental and simulation data between 0.4 to 0.95. Average deviation and absolute average deviation error is 3.52% and 12.2% respectively. At lower vapor quality, pressure drop predictions were not so good, probably due to partial suppression of nucleation and bubbly flow not modeled accurately yet. However, overall it predicts the data very well more than 0.4 vapor quality.

4. Conclusions

Ammonia is an important natural refrigerant and it has excellent thermo physical properties. Evaporation process can be studied by using two phase boiling. Two phase heat transfer boiling not only depends on mass flux and heat flux, internal diameter, type of material and fluid it's also depend on types of flow pattern. When the mass flux is increased 50kg/m^{2}s to 100kg/ m^{2}s and 100kg/ m^{2}s to 150 kg/m^{2}s two-phase heat transfer coefficient also respectively increased by 75.7% and 26.8% with vapor quality. This developed simulation tool can be used in designing length of the evaporator accurately for mass fluxes 50 kg/m^{2}s to 100 kg/m^{2}s and vapor qualities 0.15 to 0.60 for 150 kg/m^{2}s. Comparison between simulation and experiment data concluded that vapor quality in between 0.4 to 0.95 validated with 3.52% average deviation for pressure drop and 5.5% for two phase heat transfer coefficient for 100 kg/m^{2}s mass flux and suggested that developed software can be used in designing process of horizontal evaporator for refrigeration system with further study on hiccupped vapor quality region.

References

[1] Granryd, Eric. "Hydrocarbons as refrigerants—an overview." *International journal of refrigeration* 24, no. 1 (2001): 15-24.
[2] Lorentzen, Gustav. "Revival of carbon dioxide as a refrigerant." *International journal of refrigeration* 17, no. 5 (1994): 292-301.
[3] Lorentzen, G. "Ammonia: an excellent alternative." International journal of refrigeration 11, no. 4 (1988): 248-252.
[4] Cavallini, Alberto. "Working fluids for mechanical refrigeration—Invited paper presented at the 19th International Congress of Refrigeration, The Hague, August 1995." *International Journal of Refrigeration* 19, no. 8 (1996): 485-496.

[5] Sarbu, Ioan. "A review on substitution strategy of non-ecological refrigerants from vapour compression-based refrigeration, air-conditioning and heat pump systems." *International Journal of Refrigeration* 46 (2014): 123-141.

[6] Thome, John R. "Boiling of new refrigerants: a state-of-the-art review." International Journal of Refrigeration 19, no. 7 (1996): 435-457.

[7] Baker, Ovid. "Design of pipelines for the simultaneous flow of oil and gas." In Fall Meeting of the Petroleum Branch of AIME. Society of Petroleum Engineers, 1953.

[8] Kattan, Nakhlé, John R. Thome, and D. Favrat. "Flow boiling in horizontal tubes: part 3—development of a new heat transfer model based on flow pattern." Journal of Heat Transfer 120, no. 1 (1998): 156-165.

[9] da Silva Lima, Ricardo J., Jesús Moreno Quibén, and John R. Thome. "Flow boiling in horizontal smooth tubes: New heat transfer results for R-134a at three saturation temperatures." Applied Thermal Engineering 29, no. 7 (2009): 1289-1298.

[10] Thome, John R. "On recent advances in modeling of two-phase flow and heat transfer." Heat Transfer Engineering 24, no. 6 (2003): 46-59.

[11] Park, C. Y., and P. S. Hrnjak. "Pure NH3 and CO2 heat transfer and pressure drop in horizontal smooth tubes for NH3 two-stage and NH3/CO2 cascade refrigeration systems: a review." International Journal of Air-Conditioning and Refrigeration 18, no. 02 (2010): 85-100.

[12] Chen, John C. "Correlation for boiling heat transfer to saturated fluids in convective flow." Industrial & engineering chemistry process design and development 5, no. 3 (1966): 322-329.

[13] Forster, H. K., and Novak Zuber. "Dynamics of vapor bubbles and boiling heat transfer." AIChE Journal 1, no. 4 (1955): 531-535.

[14] Dittus, F. W., and L. M. K. Boelter. "University of California publications on engineering." University of California publications in Engineering 2 (1930): 371.

[15] Cooper, M. G. "Heat flow rates in saturated nucleate pool boiling-a wide-ranging examination using reduced properties." In Advances in heat transfer, vol. 16, pp. 157-239. Elsevier, 1984.

[16] Bennett, Douglas L., and John C. Chen. "Forced convective boiling in vertical tubes for saturated pure components and binary mixtures." AIChE Journal 26, no. 3 (1980): 454-461.

[17] Gungor, Kernal Ersin, and R. H. S. Winterton. "A general correlation for flow boiling in tubes and annuli." International Journal of Heat and Mass Transfer 29, no. 3 (1986): 351-358.

[18] Zurcher, O., J. R. Thome, and D. Favrat. "Evaporation of ammonia in a smooth horizontal tube: heat transfer measurements and predictions." Journal of Heat Transfer 121, no. 1 (1999): 89-101.

[19] Zürcher, Olivier, D. Favrat, and J. R. Thome. "Evaporation of refrigerants in a horizontal tube: an improved flow pattern dependent heat transfer model compared to ammonia data." International journal of heat and mass transfer 45, no. 2 (2002): 303-317.

[20] Pamitran, A. S., Kwang-Il Choi, and Jong-Taek Oh. "Evaporation heat transfer coefficient in single circular small tubes for flow natural refrigerants of C3H8, NH3, and CO2." International Journal of Multiphase Flow 37, no. 7 (2011): 794-801.

[21] MARTINELLI, RC T. "Prediction of pressure drop during forced-circulation boiling of water." Trans. of the ASME 70 (1948): 695-702.

[22] Lockhart, R. W., and R. C. Martinelli. "Proposed correlation of data for isothermal two-phase, two-component flow in pipes." Chem. Eng. Prog 45, no. 1 (1949): 39-48.

[23] Nino, Victor German, P. S. Hrnjak, and T. A. Newell. Characterization of two-phase flow in microchannels. Air Conditioning and Refrigeration Center. College of Engineering. University of Illinois at Urbana-Champaign., 2002.

[24] Adams, David C., P. S. Hrnjak, and T. A. Newell. Pressure drop and void fraction in microchannels using carbon dioxide, ammonia, and R245fa as refrigerants. Air Conditioning and Refrigeration Center. College of Engineering. University of Illinois at Urbana-Champaign., 2003.

[25] Kabelac, S., and H-J. De Buhr. "Flow boiling of ammonia in a plain and a low finned horizontal tube." International journal of refrigeration 24, no. 1 (2001): 41-50.

[26] Balthazar, P., D. L. A. Mihindukulasooriya, P. Sukirtha, and A. M. Muzathik. "Two phase pressure drop characteristics in a horizontal smooth pipe refrigeration ammonia (R717) system." (2016).

[27] Balthazar, P., D. L. A. Mihindukulasooriya, P. Sukirtha, and Rajapaksha L, ''Modeling and analysis vapour compression refrigeration system using natural refrigerants –The case of Carbon dioxide and Ammonia'', Group project thesis, Bachelor of Engineering Honors. Faculty of Engineering. University of Peradeniya. (2013).