Optimal Frictional Pressure drop and vapor quality relationship of ammonia and R22 in two-phase flow

NormahMohd-Ghazali[1, a *],OhJong-Taek[2,b], Robiah Ahmad[3,c],and Nor AtikahZolpakar[1,d]

[1]Faculty of Mechanical Engineering, UniversitiTeknologi Malaysia, 81310 Skudai, Johor Bahru, Malaysia

[2]Dept. Refrigeration & Air-Conditioning Engineering, Chonnam National Univ., San 96-1, Dunduk-Dong, Yeosu, Chonnam 550-749, Republic of Korea.

[3]UTM Razak School of Engineering & Adv. Tech., UniversitiTeknologi Malaysia, 54100 JalanSemarak, Kuala Lumpur, Malaysia

[a*]normah@fkm.utm.my, [b]ohjt@chonnam.ac.kr, [c]robiah@ic.utm.my, [d]callister89@yahoo.com

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Abstract. Research in two-phase flow in heat exchanging devices plays an important part in today's applications in miniaturization of engineering systems. The phase change process factors in the flow conditions and heat transfer in evaporators and condensers. Numerous studies in the past have looked at the predicted and measured frictional pressure drop of coolants as the vapor quality increases. This paper reports a preliminary attempt at modeling of the relationship between the frictional pressure drop and vapor quality in an ammonia-cooled and R22-cooled mini-channel of 1.5 mm diameter under optimized conditions using multi-objective genetic algorithm. R22 is a being phased-out due to its ozone-depleting characteristic and ammonia is being considered as its potential replacement. The properties of ammonia and R22 used have been obtained experimentally at the saturation temperature of 5°C and 10°C respectively. Modeling of the minimized pressure drop per unit tube length together with the Lockhart-Martinelli parameter was completed under optimized flow rate and vapor quality.The outcomes obtained are similar to those that have been reported experimentally with other coolants, increasing pressure drop with increasing vapor quality.

Introduction

Two-phase flows in mini- and micro-channels have become an integral part of compact heat exchangers where low coolant inventory with high heat transfer coefficients have become the general expectation. With demand for more environmentally friendly refrigerants which are able to perform as good if not better than the ones to be replaced, designers and engineers have to come up with design requirements for optimized performance in exploratory studies of new coolant candidates. Many experimental studies have been reported on the compatibility of collected data and the correlations developed for the flow and thermal conditions of coolants [1-6]. In particular, the calculations of the pressure drop for two-phase flow in mini-channels for new coolants have been lately, intensively studied and discussed [7-8]. Some correlations seemed to be agreeable under certain conditions whilst others may differ significantly, mainly due to the lack of data for mini- and micro-channels – past correlations developed to predict the pressure drop and heat transfer have been based on macro-channels with conventional coolants. Awareness towards environmental protection against ozone-depleting Chlorofluorocarbons (CFCs) refrigerants have led researchers to investigate alternatives to R22 refrigerant which is still widely used in the refrigeration and air-conditioning industry particularly in the developing and under-developed countries. Natural refrigerant Ammonia could be an alternative coolant due to its zero ozone-depleting potential (ODP) as well as no direct greenhouse effect [9].

Theoretical optimization of two-phase flow in a mini-channel has not been investigated before probably due to the complexity of the behavior of the flow itself. Furthermore, the number of correlations developed over many decades meant for specific tubes, the various coolants being introduced, and the models representing the two-phase flow itself have posed a serious challenge towards a general optimization scheme of the system. This study was undertaken to look at the possible relationship between the pressure drop and vapor quality of two coolants under optimized flow rate and quality. The coolants investigated are R22, which is currently being periodically replaced, and ammonia, a coolant being considered to replace the former.Optimization is completed using genetic algorithm towards minimization of the pressure drop and Lockhart-Martinelli parameter under optimized flow rate and vapor quality.

Mathematical Formulation

The two conventional models typically used to predict the pressure drop in two-phase flows are based on the separated flow model and the mixture model. In the former, each phase is assumed to travel at different velocity while in the latter both phases have the same velocity. In this preliminary study, the mixture model is assumed since it has been reported to be able to predict over a wide range of applications [7]. The total two-phase pressure drop is contributed by the friction, acceleration, and static components but for evaporation/boiling in small horizontal tubes the contribution from the gravitational effects is negligible [8]. The acceleration pressure drop could be obtained from the Martinelli-Nelson [10] and the frictional pressure drop which is being considered here is based on the homogeneous model [7],

$$\left(\frac{\Delta P}{\Delta L}\right)_{tp} = \frac{G_{tp}^2}{2\rho_{tp} D} f_{tp} \, , \qquad (1)$$

where the two-phase friction factor, f_{tp}, is given by [11],

$$f_{tp} = 0.25 \left[log \left(\frac{150.39}{Re^{0.98865}} - \frac{152.06}{Re} \right) \right]^{-2} . \qquad (2)$$

The terms G_{tp}, ρ_{tp}, Re, and D stand for the two-phase flow rate, density and Reynold number, and channel diameter respectively. The two-phase density is determined from McAdams et al. [12],

$$\frac{1}{\rho_{tp}} = \frac{x}{\rho_g} + \frac{1-x}{\rho_l} . \qquad (3)$$

Meanwhile, the Martinelli parameter is defined by,

$$X = \sqrt{\frac{(\Delta p/\Delta L)_l}{(\Delta p/\Delta L)_g}} , \qquad (5)$$

where when simplified becomes,

$$X = \left(\frac{f_f}{f_g}\right)^{1/2} \left(\frac{1-x}{x}\right) \left(\frac{\rho_f}{\rho_g}\right)^{1/2} . \qquad (6)$$

The properties appearing in the equations above have been obtained from Oh [13] where extensive experiments on two-phase flow of R22 and ammonia in minichannels have been completed. The data used in the current optimization scheme is presented in Table 1.

It has been noted that the frictional pressure drop and the vapor quality has a direct relationship; though it is undesirable, the former increases when the latter increases as two-phase flow progresses along a minichannel. The current study attempts at investigating if the relationship between the two variables can be predicted using multi-objective genetic algorithm (GA), which is well-known for its stochastic ability to seek for optimal solutions. Since multi-objective GA is suitable for a search of objective functions that are contradictory to each other, Eq. 1 and Eq. 6 have been selected to be minimized due to an initial analysis of their opposite effects. Solutions for optimized flow rate and vapor quality are searched for. MOGA optimization scheme in MATLAB toolbox is used subjected to 300 kg/m^{2}sec <G< 600 kg/m^{2}sec for R22, 100 kg/m^{2}sec <G< 500 kg/m^{2}sec for NH_3, and 0 < x< 0.8, the upper limit for the quality being chosen based on experimental experience [13].

Table 1: Data used in this study [13].

	Parameter	R22	NH_3
D	diameter of tube [mm]	1.5	1.5
G	flow rate[kg/m^{2}sec]	300-600	100-500
ρ_f	liquid phase density[kg/m^3]	1246	631.7
ρ_g	vapor phase density[kg/m^3]	28.82	4.1
μ_f	liquid phase viscosity [µPa.sec]	193.71	161
μ_g	vapor phase viscosity [µPa.sec]	11.78	9.2

The data in Table 1 was obtained with a mass flow rate of 22-53 g/min, at a working pressure of 0.515 MPa and 0.68 MPa for ammonia and R22 respectively. The saturation temperature for R22 was measured at 10°C whilst that for ammonia was at 5°C with the Reynolds number calculated to be in the turbulent region.

Results and Discussions

Since GA is a stochastic approach, where most probable solutions to achieve the desired objectives (minimization) for optimized vapor quality and flow rate under constraints that have been set, five optimization processes were completed for each coolant, the average being utilized to be presented here. Fig. 1 shows the Pareto front that was obtained using GA, simultaneous minimization of objective 1 and objective 2, the frictional pressure drop and Lockhart-Martinelli parameter respectively, for optimization of the vapor quality and flow rate.

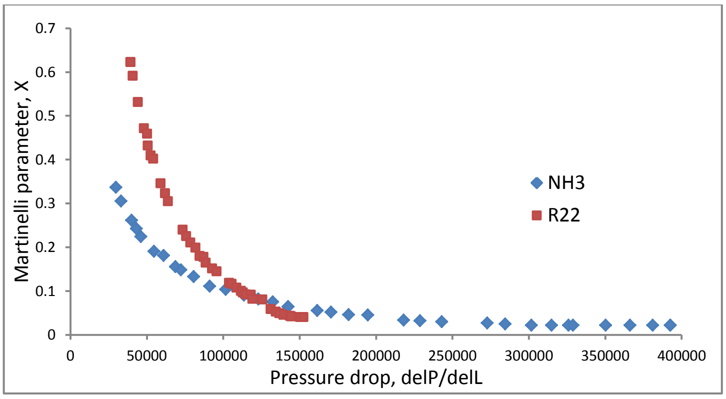

Figure 1: Pareto optimal solution for frictional pressure drop and Lockhart-Martinelli parameter

There are 35 optimal solutions for ammonia compared to 39 of R22. Although it is expected that the pressure drop for ammonia is higher due to the higher ratio of $\frac{\rho_f}{\rho_g}$, ammonia seems to have a lower pressure drop until X reaches 0.11 when it starts to follow the expected trend [7]. A higher $\frac{\rho_f}{\rho_g}$ means a higher vapor velocity for the coolant. The GA scheme, however, only searched for the most probable solution to achieve optimized vapor quality and flow rate when Eq. 1 and Eq. 6 are simultaneously minimized, no consideration of the thermophysical behavior were taken into account. The values are treated as numbers in this stochastic approach.

Fig. 2 and Fig. 3 show the optimized flow rate against minimized frictional pressure drop, and pressure drop against optimized vapor quality, for R22 and ammonia.

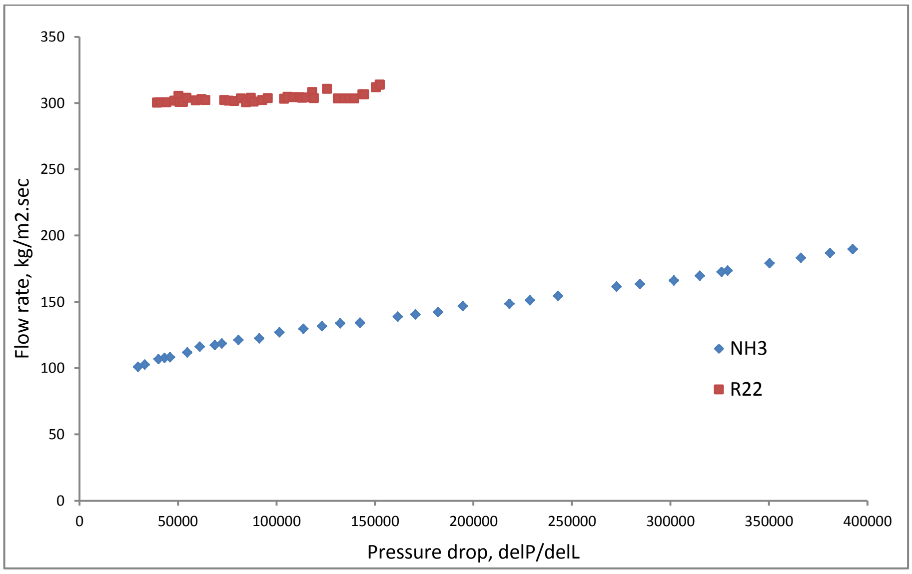

Figure 2: Optimized flow rate against frictional pressure drop.

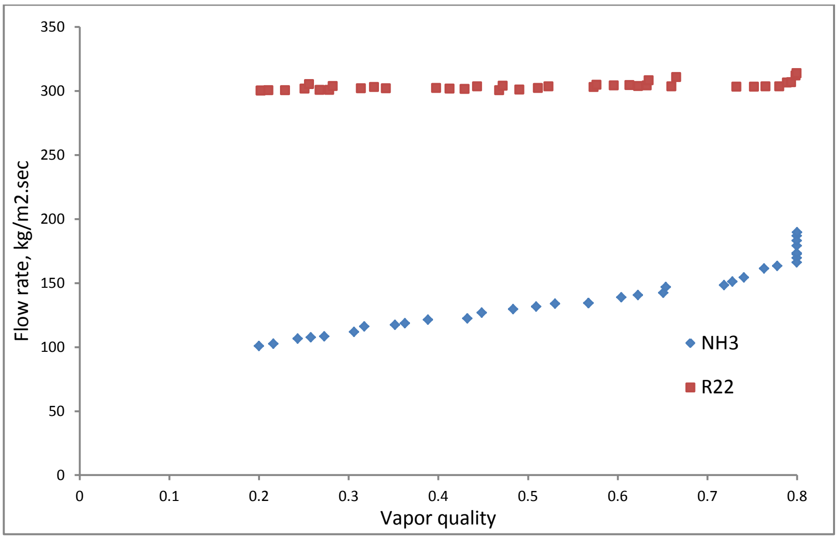

Figure 3: Optimized flow rate against optimized vapor quality.

Under optimized conditions and based on the constraints set (from experiments), the outcome shows a much higher flow rate is expected from R22, almost three times larger to achieve the same pressure drop as ammonia.This would mean that a higher flow rate for R22 results in the same pressure drop as ammonia. Further conclusion could be made if the heat transfer property can be determined to show the capability of each coolant under these conditions. A low flow rate operation is desirable for low frictional pressure drop for both coolants. A higher flow rate is needed for R22 to achieve the same optimized vapor quality as ammonia. Fig. 4 shows the expected trend as those found experimentally, the increase of the frictional pressure drop as vapor quality increases, ammonia the higher pressure drop due to the high $\frac{\rho_f}{\rho_g}$.

The outcome of the optimization completed in this preliminary study using GA on two-phase flow of R22 and ammonia shows some promise with the homogeneous model used. The algorithm takes a short time to accomplish and though cannot be used independently in the study of complex two-phase flow behavior; it could assist researchers in their exploration of new coolants towards sustainable refrigeration and air-conditioning industry. Together with the limited experimental and theoretical exercise, they could prove to be a powerful tool in today's fast and effective research environment. Further study will be done to look at the separated model which includes more coolant properties in the analysis.

Conclusion

The outcome of a preliminary study of using multi-objective algorithm (MOGA) on the simultaneous minimization of the frictional pressure drop and Lockhart-Martinelli parameter for optimized vapor quality and flow rate has been completed. The Pareto optimal solution shows a slight difference from the expected until halfway through the optimization scheme. The frictional pressure drop for ammonia is higher than R22 because of the higher vapor velocity. The results show promise for the MOGA to be utilized for further investigation of the flow pattern to identify if it can predict the pressure drop and subsequently help researchers determine optimized parameters for better control of the complex two-phase flow in minichannels of compact heat exchangers.

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