Performance of Natural Refrigerants in Two Phase Flow

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Graphical abstract

Pareto Front
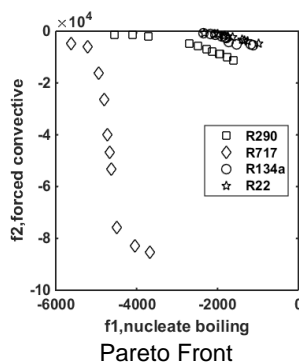
Abstract

The search for alternative environmentally friendly refrigerants have never been so crucial with the increasing demand for effective cooling of increasing miniaturization of our heat exchanging devices in the ever expanding air-conditioning and refrigeration industry. Although propane (R290) and ammonia (R717), natural refrigerants, have been around for decades, their two-phase thermal performance in small channels has yet to be fully investigated. Predictions of the heat transfer using correlations developed based on past experimental data have shown poor agreements, with more correlations being developed to date. This research was done to investigate the optimized conditions for the two-phase boiling heat transfer coefficient of R290 and R717 where the contributions from nucleate boiling and forced convective are represented explicitly. Multi-objective Genetic Algorithm (MOGA) is utilized for the simultaneous maximization of nucleate boiling and forced convective, two conflicting phenomena – the former generally significant in the low vapor quality region while the latter in the high quality region. A superposition correlation is used as it sums up both contributions. Two phased-out refrigerants, R134a and R22 are also being research here for comparison purposes. The range of MOGA design parameters set for mass flux, G, is between 100 - 300 kg/m².s, heat flux q between 5 - 30 kW/m² and vapor quality, x for 0.0009 - 0.9. The optimization is done for 3 mm channel diameter with saturation temperature at 10°C. The optimized results showed a strong contribution of each nucleate boiling and forced convective for R717 with increasing vapor quality, compared to the other three refrigerants. The optimized value of the total heat transfer coefficient for R717 could reach up to 90 kW/m².K and for R290 up to 12 kW/m².K compared to R134a and R22 at 6 kW/m².K and 5 kW/m².K respectively. At lower vapor quality, the nucleate boiling contributes more to the total heat transfer coefficient, and suppressed due to forced convective as the vapor quality reaches middle range. The theoretical results indicate the potential of R717 and R290 as replacement refrigerants for R22 and R134a with further verifications to be done with correlations not using the superposition method.

Keywords: Two-phase flow, natural refrigerant, optimized conditions, nucleate boiling, forced convective

1.0 INTRODUCTION

Research in two phase flow in small channels is entering a new milestone, not only by the application of natural refrigerants in replacement of potentially hazardous conventional refrigerants but also due to the miniaturization of heat exchanging devices with extremely high heat fluxes. Previously, due to concerns over the depletion of the ozone layer, the Montreal Protocol 1987 control the usage of the conventional chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) refrigerants with the phase out plan towards 2010 and 2030 respectively. As an alternative, hydrofluorocarbons (HFCs) which contain no chlorine and bromine replaced their usage. However, HFCs have high Global Warming Potential (GWP), which can reach thousands even though they have zero Ozone Depleting Potential (ODP)[1]. GWP signifies the degree of global warming caused and ODP indicates the severity of ozone depletion capable, by the refrigerants. Thus, natural refrigerants which have zero ODP and low GWP have become potential substitute of choice. Natural refrigerant is a substance which occurred naturally which include hydrocarbons - propane, butane and cyclopentane, CO_2, ammonia, water and air or also known as the 'Gentle Five' [2].

The raising question is how good the performance of these natural refrigerants areas the alternative to conventional refrigerants, particularly in small channels? It is important to accurately predict the heat transfer coefficients as well as the patterns and trends with varies parameters to reduce the cost and avoid grave consequences with under design or over design of heat exchanging devices. Besides, knowledge of the thermal behavior of parameters within control could assist in enhancing the heat transfer capability of the refrigerant used and the devices. Previous studies have been done experimentally to investigate the capability of natural refrigerants in two phase flow small channels[3]–[6]. Each study have used different range of parameters, thus the performance of each refrigerant is achieved under different conditions as can be seen in the work by Pamitran et al. [7]. While experimental studies can provide real-time outcomes, theoretical studies are needed to present to engineers possible highest performance that a system is capable of – weaknesses addressed and improvements can be made.

A review by Cavallini et al. [8] shows that a most recent study on a natural refrigerant is on CO_2 which is known for having a high heat transfer coefficient. Little study has been done to investigate ammonia (R290) and propane (R717). Although these coolants have been around for decades, their applications in small channels have yet to be fully investigated. It is well known that mini and micro channels provide high heat transfer coefficients accompanied by high frictional losses. This study is hence to predict the optimized performance of natural refrigerants, R290

and R717 in terms of heat transfer coefficient in two phase flow in a small channel. The comparative study is done with R134a and R22, as the phased out conventional refrigerants. The optimization has been completed using multi-objective genetic algorithm (MOGA) which has been proven lately to be capable in the quick and accurate analysis of the optimum performance of heat transfer for single phase flows as well as pressure drop in two-phase flows [9]–[12]. The present research attempts at investigating the utilization of the algorithm on the heat transfer coefficient of two-phase flow of natural refrigerants in a small channel. The outcome would assist designers and engineers in adjusting the controlling parameters to achieve the highest possible thermal performance for the desired high heat flux removal in the complex two-phase flow.

Many correlations have been and are being developed to predict the heat transfer coefficient of two phase flows. There have also been correlations developed for macro channels being utilized in the studies involving small and micro channels. The sole purpose of these correlations is to predict the thermal behavior of refrigerants under different design parameters and flow regimes. However, since these correlations were the results of data obtained under different operating conditions and refrigerants, good agreement between the prediction with these correlations and new experimental data are almost impossible. This research used the correlation that had been developed utilizing the superposition method in predicting the total two phase heat transfer coefficient. This is because the contributions from the two main phenomena in two-phase flow, nucleate boiling and forced convective, can be studied to see how each affect the heat transfer as the vapor quality increases with heating. Nucleate boiling is significant at low quality when bubbles start to form while forced convective is prominent from the medium quality to high quality region.

One of the most cited superposition correlation is by Oh et al. [13]. In superposition method, the total heat transfer coefficient is the sum up between nucleate boiling and forced convective heat transfer given by;

$$h_{tp} = S.h_{nb} + F.h_{lo} \qquad (1)$$

The contribution of nucleate boiling process consists of the Cooper boiling equation [14], h_{nb} and suppression factor, S;

$$h_{nb} = 55P_R^{0.12}(-0.4343ln.P_R)^{-0.55}M^{-0.5}q^{0.67} \qquad (2)$$

$$S = 0.279(\emptyset_l^2)^{-0.029}Bo^{-0.098} \qquad (3)$$

For convective boiling, it consists of a known equation by Dittus-Boelter [15], h_{lo} and forced convective, F given by;

$$h_{lo} = 0.023Re_l^{0.8}Pr_l^{0.4}\frac{k_l}{D_h} \qquad (4)$$

Table 1 Specific properties and properties of refrigerant at T_{sat} = 10°C

Refrigerant	P_{sat} MPa	ρ_l kg/m³	ρ_g kg/m³	μ_l μPa.s	μ_g μPa.s	h_f kJ/kg	h_g kJ/kg	c_p J/g.K	k_l mW/m.K	M kg/kmol	σ mN/m
R290	0.637	514.78	13.77	113.39	7.754	225.49	585.97	2.583	100.95	41.1	8.84
R717	0.615	624.64	4.87	153.03	9.364	389.72	1615.3	4.676	529.12	17.0	29.59
R134a	0.415	1261.0	20.23	234.87	11.099	213.58	404.32	1.370	87.62	102.0	10.14
R22	0.681	1246.7	28.82	193.71	11.798	211.87	408.56	1.199	90.25	865	10.22

$$F = max\left[\left(0.023\left(\emptyset_l^2\right)^{1.1} + 0.76\right), 1\right] \quad (5)$$

where P_R is the reduced pressure, M is the molecular mass, q is the heat flux from the tube wall to fluid, k_l is the thermal conductivity for liquid and D_h is the hydraulic diameter. The Prandtl number, Pr, for liquid is calculated as a function of viscosity, thermal conductivity and specific heat, c_p;

$$Pr = \frac{\mu c_p}{k} \quad (6)$$

Meanwhile, the S factor depends on the effect of heat flux by the Boiling number, Bo;

$$Bo = \frac{q}{G.h_{lg}} \quad (7)$$

where h_{lg} is the latent heat of vaporization. $\emptyset_l^2$ is the two phase friction multiplier calculated by;

$$\emptyset_l^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \quad (8)$$

where the Chisholm parameter, C for turbulent-turbulent, laminar-turbulent, turbulent-laminar, and laminar-laminar liquid vapor conditions are 20, 12, 10 and 5 respectively [16]. For forced convective, it was affected by the Martinelli parameter, X;

$$X = \left(\frac{f_L}{f_g}\right)^{0.5}\left(\frac{\rho_g}{\rho_L}\right)^{0.5}\left(\frac{1-x}{x}\right) \quad (9)$$

The friction factor, f, depends on laminar or turbulent flow condition [7] and is determined using Reynolds number, Re, as follows;

$$Re_g = \frac{xGD}{\mu_g} \quad (10)$$

$$Re_l = \frac{(1-x)GD}{\mu_l} \quad (11)$$

$$f = 16/Re, \text{ if Re} <2300 \quad (12)$$

$$f = 0.079Re^{0.25}, \text{ if Re} > 3000 \quad (13)$$

μ_g and μ_l is the viscosity of vapor and liquid phase respectively.

2.0 METHODOLOGY

Table 1 shows the properties [17] of R290, R717, R134a and R22 at saturation temperature, T_{sat} = 10°C, used in this optimization. The temperature selected is the usual operating temperature and often used by previous researchers mentioned so far. For the maximization of the total two phase heat transfer coefficient, h_{tp}, the objective functions are nucleate boiling effect, $S.h_{nb}$ (Eq. 2 & 3) and forced convective, $F.h_{lo}$ (Eq. 4 & 5). Both equations have a conflicting effect on each other; a high convective factor will eventually decrease the magnitude of the suppression factor. A high degree of suppression of the nucleate boiling phenomena by forced convective represents a transition from slug to annular flow region. The two phase annular flow region has a high heat transfer coefficient before the dry out happens and eventually decreases the heat transfer in a channel [18].

The optimization between the two heat transfer coefficients is done using MOGA which is an evolutionary algorithm. Based on natural biological evolution, MOGA creates new generations of population through selection, crossover and mutation steps to find non-dominated solutions satisfying the optimum performance of the transfer functions [19]. For two conflicting transfer functions as in this present research, the optimized relationship is represented by a Pareto front. The MOGA is invoked in the MATLAB R2014a built in the Optimization Toolbox [20]. Table 2 show the optimization properties used in during the runs.

Table 2 Operators in Optimization Toolbox in MATLAB

Parameter	Value
Solver	Multiobjective genetic algorithm
Population size	30
Selection	Tournament
Mutation	Constraint dependent
Crossover rate	0.6
Stopping criteria	300

There is no clear guidance available to select appropriate GA operators for any particular parameter optimization [21]. Since there have been

no other previous study on optimization of a two-phase flow heat transfer coefficient using GA, several trials had been made to determine a suitable population size, crossover, selection and mutation operators in MOGA.

In studying the heat transfer performance, the design parameters used are mass flux, G, heat flux, q, and vapour quality, x. The constraints are set with the lower and upper bounds as listed in Table 3. These quantities are chosen based on the range of previous experimental work by Oh *et al.* [13].

Table 3 Range of parameter for MOGA

| Parameter	Operating range
G (kg/m². s)	100 - 300
q (kW/m²)	5 - 30
x	0.009 - 0.9
D (mm)	3.0

3.0 RESULTS AND DISCUSSION

Figure 1 shows the Pareto front obtained from the simultaneous optimization of the conflicting functions nucleate boiling and forced convective using MOGA. Each point represents an optimal solution with specific mass flux, heat flux and vapor quality. In Figure 1, the Pareto front for R717 is steeper compared to those of R290, R134a and R22. This would mean that in the low quality region, the contribution from nucleate boiling is very significant compared to the other three refrigerants investigated. In the high quality region, the contribution from forced convective for R717 is very significant.

Figure 2 depicts the optimized total two phase heat transfer coefficient towards increasing vapor quality. The heat transfer coefficient is increasing as the vapor quality improved. From the figure, R717 gives a higher heat transfer coefficient compared to the rest of the refrigerants. The increasing value of heat transfer coefficient for R717 is seen clearly at the middle quality with the vapor quality higher than 0.4. R717 gives a higher heat transfer coefficient probably due to an earlier development of annular flow. This is in tandem with Figure 1, the strong relationship between nucleate boiling and forced convection for R717.
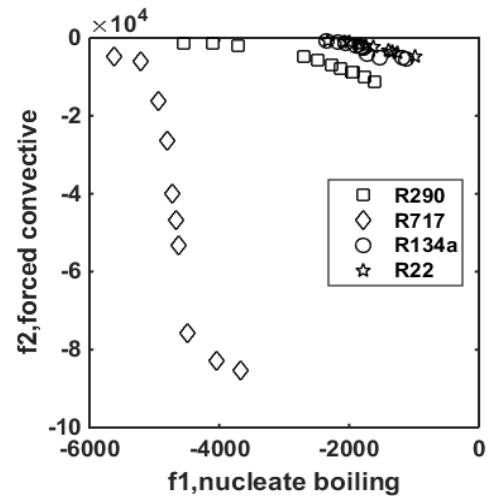
Figure 1 Pareto Front
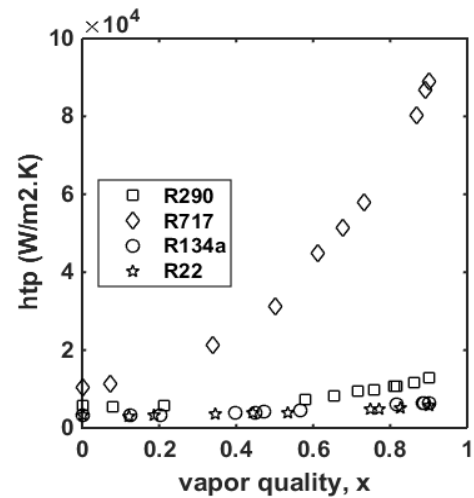
Figure 2 Total two phase heat transfer coefficient

Further, Figure 3 shows the contribution from nucleate boiling and forced convective mechanism towards the magnitude of total heat transfer coefficient for each refrigerant. R290 has shown the same trend as R134a and R22, a dominant nucleate boiling at the early stage of boiling. A high heat transfer coefficient for R717 is achieved due to the effect of forced convective as the vapor quality increases. For a refrigerant with properties in high heat of vaporization, a high heat transfer can be achieved at high mass flux. A high heat of vaporization of R717 indicates low Boiling number thus, represents a high suppression of boiling [22] which leads to a high heat transfer coefficient by forced convection.
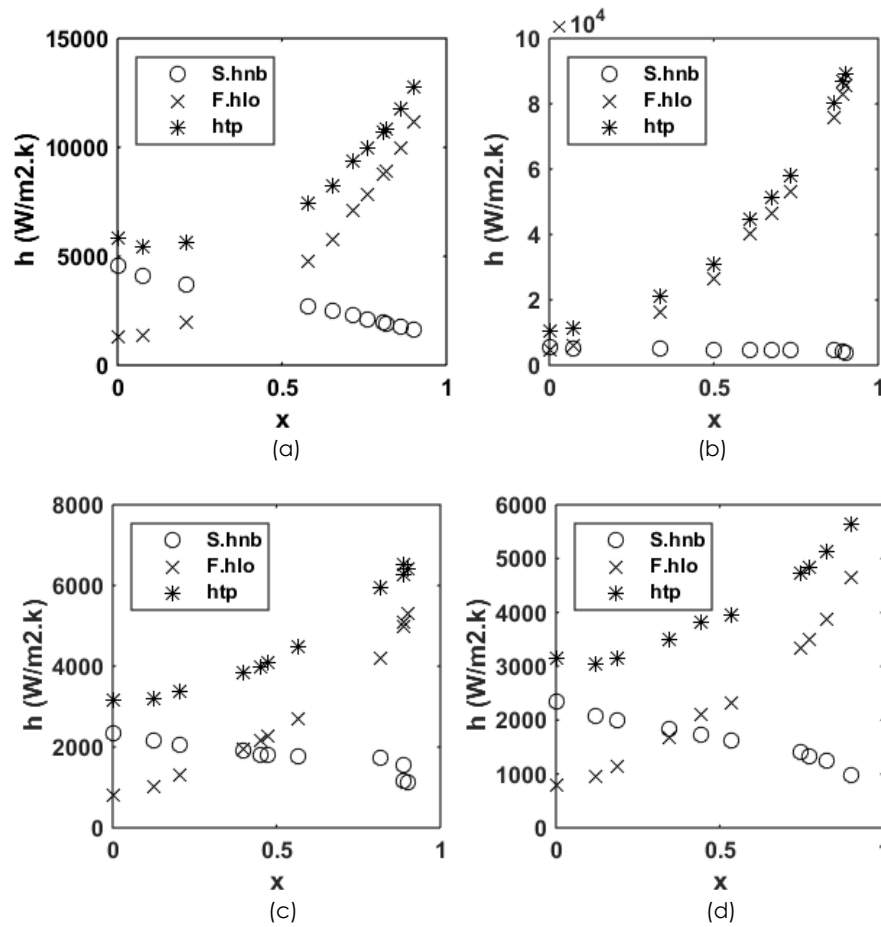
Figure 3 Nucleate boiling and forced convective for (a) R290, (b) R717, (c) R134a and (d) R22

As the mass flux increases, the annular flow becomes dominant [23] as shown in Figure 4. The value of mass flux and heat flux for R717 is optimized at the higher range. As it has a high liquid and vapor conductivities, heat is transferred easily [1] at high mass flow and heat energy compared to others which contributed to a high heat transfer coefficient from forced convective mechanism. For R290, R134a and R22, a high heat flux is required for a high nucleate boiling at the lower vapor quality. One advantage of R290 is the optimized values of heat transfer coefficient being spread out over the heat flux which indicates flexibility of its properties.

The heat transfer behavior exhibited here, obtained under optimized conditions showed the expected trend in agreement with the physics of two-phase boiling heat transfer. The novelty is the optimized outcomes achieved with the simultaneous maximization of the conflicting heat transfer coefficients due to nucleate boiling and forced convective, which could not have been obtained experimentally or with a theoretical parametric study. In addition, the design variables of mass flux, heat flux and vapor quality showed what the conditions are to achieve the simultaneous maximization of the two objectives. The outcomes presented here indicate the potential of using MOGA in predicting the optimized conditions of heat transfer coefficient based on correlations that have been developed, in particular the investigation of new potential refrigerants. Patterns and trends can be studied with the outcomes achieved fast for future guide towards selecting a particular refrigerant based on its thermal performance. With more correlations being modified and developed to address the requirement for a general correlation across refrigerants, tube diameters, and flow regimes, this study has shown that optimized conditions provide a common platform by which to compare the performance, patterns and trends.

(a)

(b)
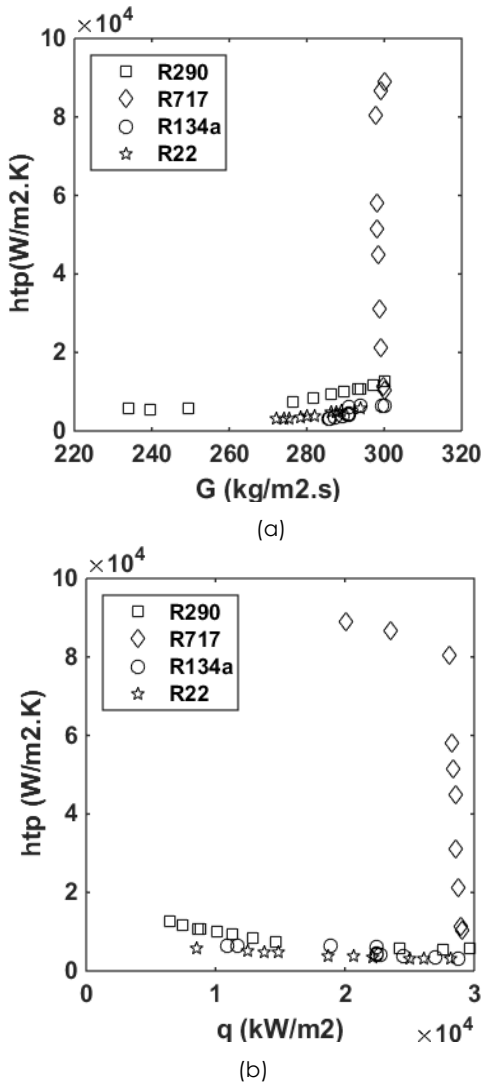
Figure 4 Effect of (a) mass flux and (b) heat flux towards the total value of heat transfer coefficient

4.0 CONCLUSION

The two phase heat transfer performance for natural refrigerants in a horizontal small channel has been predicted by using MOGA. By applying a superposition heat transfer coefficient correlation by Oh *et al*. [13], the contributions from nucleate boiling and forced convective as the vapor quality increases with heating can be studied. All refrigerants investigated showed similar trends and patterns with the increasing mass flux and vapor quality. From the simultaneous maximization of nucleate boiling and forced convective heat transfer coefficient, these two phenomena contribute strongly to the increasing total heat transfer with increasing vapor quality for R717. A high prediction of heat transfer coefficient for R717 achieved 90 kW/m^2.K. Both the natural refrigerants, R717 and R290, investigated shows potential with a good predicted heat transfer performance. Future research will look at the same

refrigerants studied here using other correlations that have not have used the superposition method, to investigate their thermal performance patterns and trends.

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