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Entropy Generation Minimization of Two-Phase Flow in a Mini Channel with Genetic Algorithm

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Performance of the two-phase flow in a minichannel had in the past been measured by the pressure drop or/and heat transfer coefficient. The desired low pressure drop across a small channel follows a low heat transfer coefficient. Optimization of the two-phase flow system is generally achieved either experimentally through discrete variations of each of the parameters involved while holding the rest constant, or numerically which is also possible through a parametric study. The objective of this study was to investigate the thermodynamic performance in terms of entropy generation minimization (EGM) of two-phase flow of ammonia, R22, and R134A in a 3-mm minichannel using a random search technique, genetic algorithm. The EGM performance and the optimization approach have never been attempted before. R22 has been identified as a hazardous refrigerant and alternatives are being investigated with performance as good if not better. In this study, under the optimization of the mass flux and vapour quality at the saturation temperature of 10°C, simultaneous minimization of the entropy generation and maximization of the heat transfer coefficient showed that between 250 and 450 kg/m^{2}s, ammonia has a much higher heat transfer coefficient than R22 and R134A, and at a lower quality but with very high entropy generation. Furthermore, ammonia has many sets of optimal solutions, several combinations of entropy generation and heat transfer coefficient under optimized heat flux operation and vapour quality. R22 and R134A have their optimized heat transfer coefficients over a limited range and which occurred beyond the quality of 0.8. The study has shown that ammonia could be the replacement refrigerant to R22 and R134A in terms of heat transfer but at the expense of a higher entropy generation rate.

Keywords: entropy generation minimization, two-phase flow, genetic algorithm

1. Introduction

Since the Montreal Protocol on ozone depleting substances (ODS) was officially introduced in1987, researchers have continuously searched for alternative refrigerants to the current refrigerants that are heavily used in the refrigeration and air-conditioning industry. These substitutes that are more environmentally friendly should first be able to perform as good if not better than those they are replacing, new system aside. R-134a, R507, R-404A, R-407c, and R-410A may be among those refrigerants investigated to replace R-22, the latter commonly used in heat pumps, air-conditioning and refrigeration systems since the 1990s following the phased-out of chlorofluorocarbons (CFCs) in the developed countries [1)].

The main criterion used to identify the potential replacement is generally the compatibility of the "new" coolants in applications; cooling capacity with the pressure drop being also considered since it is related to the power required for operation. Review of the studies completed on alternative refrigerants in small diameter channels within these ten years or so showed that the pressure drop and heat transfer coefficient are the two most frequently used parameters to determine the behaviour of these coolants [2-6)]. Newer correlations based on current experimental data are developed due to the failure of older correlations to map onto the newly collected data. However, the final choice may very well depend on the compressor design and cost, energy efficiency, safety, refrigerant cost and system cost since these new environmentally friendly refrigerants are not "drop-in" refrigerant types – retrofits or totally new systems are necessary.

R134A has been used to replace R22 in some refrigeration applications while ammonia, having been around for decades, is lately being reconsidered by researchers as a potential replacement to R22 [7)]. Ammonia (R-717), carbon dioxide, and the hydrocarbons such as propane (R-290) are natural refrigerants that have recently been investigated as potential refrigerants in any system that may require cooling. Studies completed generally involved experimental set-ups to determine the performance of these potential candidates according to the criteria stated earlier.

New refrigerants are commonly first investigated by researchers in terms of their heat transfer capacity i.e. the heat transfer coefficient, since this is the main function of the coolants. Evaluations of heat transfer systems based on entropy generation was probably first promoted by Bejan in the early 1980s [8)]. In 2001, Bejan.[8)] completed a review on entropy generation minimization (EGM) of flow geometry in engineering flow systems where irreversibilities that minimize the system performance are contributed by the heat transfer and pressure drop [8)]. Although EGM has been numerously applied in the analysis of single-phase systems, hardly any study on the two-phase flow had utilized the EGM approach. The single analysis of two-phase flow using EGM has been reported by Revellin et al. [9)]. Their published paper discussed the contributions of heat transfer and pressure drop to the entropy generation. It is reported that the entropy generation rate is increased with the increasing of the pressure drop [10)] and the increasing of the channel diameter [11)]. However, no report on the utilization of the EGM approach on two-phase flow has been found for comparison between the selected refrigerants of ammonia, R22 and R134A. Nor any that reported on the simultaneous minimization of the entropy generation and the heat transfer contribution such as in the current study.

Optimization work has been reported in previous literature in reducing the cost where the focus was mostly in getting the optimal design of the system [12,13)]. Several works successfully gained the optimal design of a heat exchanger using the geometrical properties as the optimized parameters to minimize the entropy generation rate [14-16)].

This study looks at the potential of an evolutionary algorithm approach as a tool in simultaneously minimizing the entropy generation and maximizing the heat transfer coefficient. Smaller channels with a large surface to volume ratio are known to have excellent heat transfer capacity but a high entropy generation follows a high heat transfer. The desired increase in the heat transfer coefficient is at the expense of a large entropy generation rate whilst a low entropy generation is associated with a low heat transfer. Genetic algorithm has recently found its application in the optimization of single phase flows in micro-channels [17-19)]. The current study is part of a research effort to look at the controlling parameters in a complex two-phase evaporating flow in small channels under optimized conditions.

2. Methodology

Two conventional models may be found in the literature used in modelling two-phase flow; the simpler homogenous or mixture model and the detailed separated model. In the former, the two-phase fluid is assumed to travel at the same velocity with a zero slip between the liquid and vapour phase. In the latter, each liquid and vapour phase is assumed to have its own velocity with a non-zero slip ratio. For the homogenous model taken in this analysis, the entropy generation per unit length of a 3-mm diameter small channel, dS given by Revellin et al. [9)] is,

$$dS_{gen} = \frac{q^2 P}{h T_{sat}^2} + \frac{m_t v_m}{T_{sat}}\left(-\frac{dP}{dz}\right) \tag{1}$$

where the first term is the contribution from heat transfer with q being the heat flux taken to be 10 kW/m^2, P the perimeter of the channel, h the heat transfer coefficient, and T_{sat} the saturation temperature of the refrigerant (where all properties are evaluated at). The contribution to the entropy generation from the pressure drop, is in the second term, where m_t is the mass flow rate and v_m the two-phase specific volume. The pressure drop in the mixture model is a function of the mass flux, G, channel diameter, D,

Table 1: Refrigerant thermal properties at 10˚C

Refrigerant	P_{sat} (kPa)	ρ(kg/m³)		μ (kg/m.s)		k (W/m.K)	v (m³/kg)
		ρ_l	ρ_g	μ_l	μ_g		
R134A	414.9	1261	20.22	2.43×10^{-4}	9.081×10^{-6}	0.0903	0.04864895
R22	680	1246.7	28.82	1.9371×10^{-4}	11.798×10^{-6}	0.090247	0.033897
Ammonia	615.3	624.6	4.87	1.697×10^{-4}	9.784×10^{-6}	0.5158	0.04864895

refrigerant density, ρ, and the friction factor, f, given by [6],

$$\left(\frac{dP}{dz}\right)_{tp} = \frac{G_{tp}^2}{2D\rho_{tp}} f_{tp} \tag{2}$$

The subscript tp denotes two-phase. Minimization of the entropy generation is the first desired objective to be achieved. Many correlations are available for the two-phase friction factor as seen from the reviews [6,20]. In this study, the friction factor from Fang et al. [21] is utilized,

$$f = 0.25\left[\log\frac{150.39}{\mathrm{Re}^{0.98865}} - \frac{152.66}{\mathrm{Re}}\right]^{-2} \tag{3}$$

for turbulent flow in a smooth channel where Re is the Reynolds number. Although there are several representations of the fluid properties available, the mixture viscosity, μ, and density used in this study are obtained from the generally used equation of McAdams [22],

$$\rho_{tp} = \left[\frac{x}{\rho_g} + \frac{1-x}{\rho_f}\right]^{-1} \tag{4}$$

$$\mu_{tp} = \left[\frac{x}{\mu_g} + \frac{1-x}{\mu_f}\right]^{-1} \tag{5}$$

Subscript g and f each represents the vapour and liquid phase respectively and x is the vapour quality. The heat transfer coefficient to be maximized, the second objective, is determined from the Nusselt number,

$$h = \frac{Nuk}{D} \tag{6}$$

where k is the thermal conductivity of the two-phase mixture and Nu is from the often used Dittus-Boelter correlation,

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \tag{7}$$

The fluid thermal properties of the refrigerants are taken from a thermodynamics text book [18] and NIST Webbook [24]. Table 1 lists the properties used in this study, obtained at 10°C saturation temperature; R134A, R22, and ammonia.

The search algorithm for the simultaneous minimization of the entropy generation and maximization of the heat transfer coefficient used is available in MATLAB toolbox [25] for multi-objective optimization. The mass flux and vapour quality are the two parameters to be optimized to achieve the two conflicting objective functions. They are set to be 150 ≤ G ≤ 450 kg/m²s and 0.1 ≤ x ≤ 0.9 based on the literature review.

3. Result and Discussion

Fig.1 shows the outcomes of the simultaneous minimization of the entropy generation, S_{gen}, and heat transfer coefficient, h, of ammonia, R22, and R134A using GA.

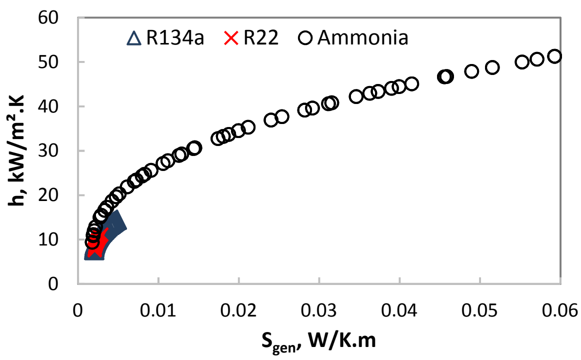

Fig.1: Optimized heat transfer coefficient and entropy generation

It seems that optimized h for ammonia covers a large range compared to that of R22 and R134A, increasing h is possible but with the increase in the entropy generation as well. Unlike the deterministic optimization procedure that generally looks for a single minimum/maximum in the locality of the search region, GA searched for a set of optimal solutions in the solution space that could satisfy both conflicting objectives simultaneously. Thus, depending on the desired particular value of high heat transfer coefficient or low entropy generation rate, the choice is presented in the form of the set of optimal solutions in Fig.1. However, the outcome of the optimization has shown that R22 has a limited number of optimal solutions compared to that for R134A while ammonia has a wide range of optimal solutions. The graph is better explained with Fig.2 and Fig.3.

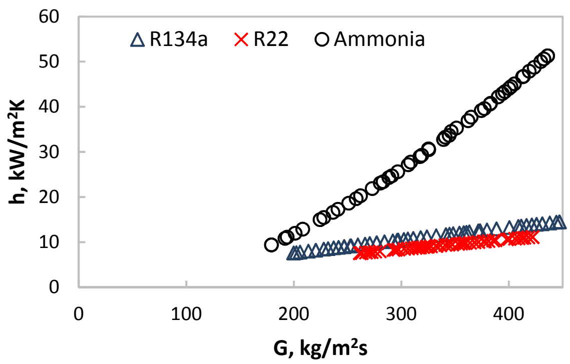

Fig. 2: Optimized heat transfer coefficient at various refrigerant mass flux.

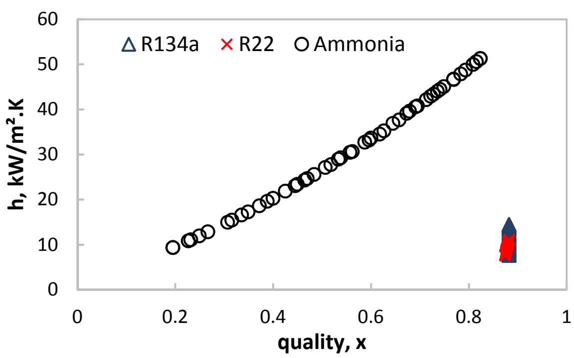

Fig.3: Optimized heat transfer coefficient at various refrigerant mass flux.

Fig.2 indicates that as the refrigerant mass flux increases, the heat transfer coefficient also increases; expected since there can be a larger amount of heat removed. However, this optimized outcome has shown that for a mass flow between 250 and 450 kg/m^{2}s, the heat transfer coefficient for ammonia increases sharply, possibly double the increase of that with the mass flux increase. This of course is at the expense of a high entropy generation, as shown in Fig.1. At any mass flux operation for the same channel diameter and length, a higher heat transfer is obtainable for ammonia, almost thrice that of R22, and twice that of R134A. Meanwhile, the heat transfer coefficient of R22 and R134A increases at the same rate as that of the mass flux, their vapour and liquid density being close to each other as seen in Table 1. Fig.3 shows that optimized heat transfer coefficient for R22 and R134A is possible at a high vapour quality, over a very tight range, between 0.85 and 0.9. Ammonia has its optimized heat transfer coefficient over the lower quality range, over a larger range of vapour quality, between 0.2 and 0.8. This indicates the increasing heat transfer capacity of ammonia in two-phase flow, increasing quickly with evaporation of the liquid phase. In particular, heat transfer coefficient i.e. 9000 W/m^{2}K, is achievable at the low vapour quality for ammonia but at the high end of the quality for R22 and R134A. Based on the heat transfer coefficient alone, ammonia seems highly capable of removing heat compared to R22 and R134A. Fig.1 and Eq. (1) show us how much we have to pay as higher heat transfer capacity is desired, the high entropy generation contributed by the large pressure drop associated with decreasing channel size.

This study has been completed on a smooth channel assuming that both the liquid and vapour phase act as a mixture. Investigation of the performance of the potential candidate for replacement refrigerant of ammonia has shown the expected patterns with this new approach at analyzing the performance of two-phase flow in a small channel with entropy generation minimization and heat transfer coefficient. Ammonia showed promise despite being around for decades being applied in macro systems. GA has also shown its capability as a new tool in searching for the optimal solution to achieve double objectives simultaneously with many varied parameters, in this case the mass flux and vapour quality. However, the performance is only in terms of the heat transfer coefficient capacity as is usual with the exploration of potential replacement refrigerants. Despite this fact, global concerns over hazardous effects posed by non-environmentally refrigerants should encourage further research into prospective candidates of natural refrigerants in our efforts to move towards a sustainable future.

4. Conclusion

Simultaneous minimization of the entropy generation, S_{gen}, and maximization of the heat transfer coefficient, h, has been completed with genetic algorithm (GA). Performance of the refrigerants ammonia, R22 and R134A has been obtained in terms of these two objective functions, S_{gen} and h, where under optimized conditions;

- Ammonia showed a fast increase in h at a lower vapour quality but over a wider range, between 0.2 and 0.8. This is at the expense of high entropy generation.

- R22 and R134A showed a limited high *h* which is only attainable at very high vapour quality over a tight range, between 0.8 and 0.9.
- At any mass flux operation, for the same channel diameter and length, ammonia has thrice the heat transfer coefficient of R22 and twice that of R134A.

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