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Prediction of the optimized frictional pressure drop in a two-phase flow small-channel with genetic algorithm

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Abstract

Research in energy and material efficiencies has never been more important due to the current global policies towards a sustainable future. Compact heat exchangers involving the complexities of two-phase flows, with their decreasing channel size and low environmentally friendly coolant mass requirement, necessitate intensive investigations into the significant wall friction which must be balanced by the heat transfer capability. This paper reports the initial study into the feasibility of using the fast growing optimization tool of genetic algorithm in predicting the minimized frictional pressure drop across a small channel under optimized vapor quality and mass flow rate. Both the single-objective and double-objective optimizations have been completed. The former involves minimizing the frictional pressure drop and the latter involves minimizing the frictional pressure drop as well as the Martinelli-Lockhart parameter. The single objective optimization and double objective optimization scheme applied show promise with similar trends observed as those that have been previously reported.

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Keywords: Two-phase; Small channel; Genetic algorithm; Pressure drop

1. Introduction

Although considerable amount of research has been completed on the prediction of two-phase flow pattern and heat transfer, the majority of them have been for large tubes. There is still much to be known about two-phase flow in mini-and micro-channels since fluid behavior in small tubes involve more significant tube wall friction and high heat transfer coefficient. Growing demand for smaller heat

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exchangers with increasing heat flux has posed serious challenges to researchers associated with the already unpredictable flow and thermal field of two-phase flows.

There are generally two models that have been used to predict the pressure drop in two-phase flows; the homogeneous model and the separated model. The liquid and vapor phase are assumed to have the same velocity in the simple homogeneous model whilst the two phases are treated as a separate entity in the separated model. Numerous empirical correlations have been developed and their compatibility with experimental data have been analyzed and discussed [1-4]. Discrepancies may be as much as agreements due to the different models, approaches, flow regimes, correlations used as well as new working fluids being introduced in view of the global awareness towards more environmentally friendly coolants [5,6]. This paper reports a preliminary investigation at predicting the frictional pressure drop of propane (C_3H_8) in a small-channel under optimized conditions using genetic algorithm. Propane is a natural refrigerant with zero Global Warming Potential (GWP) and lately has been explored as a potential refrigerant in evaporators and condensers. A statistical approach using genetic algorithm (GA) in predicting the optimized frictional pressure drop has never been attempted probably due to the complexities associated with the flow conditions. In the present study, the properties of propane utilized have been obtained experimentally with single objective and double objectives optimization completed with GA.

2. Mathematical Formulation

The homogenous model is chosen to represent the two-phase flow of propane in the 7.6 mm internal diameter 1.07 mm length tube. The frictional pressure drop is considered to be the most significant factor in the total pressure drop across the mini-channel and its minimization under optimized mass flux and quality (x) is considered in the single objective optimization. The expression for the two-phase frictional pressure drop per unit length is given by [5],

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

where the two-phase friction factor for turbulent flow in a smooth tube is taken to be [7],

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

Equation (2) seems to be most accurate explicit form [5]. The terms G_{tp}, ρ_{tp}, Re, and D each represents the mass flux, density, Reynolds number, and channel diameter respectively. Among the many available correlations for obtaining the density and viscosity of the mixture, that from McAdams et al. [8] is used here,

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

$$\frac{1}{\mu_{tp}} = \frac{x}{\mu_g} + \frac{1-x}{\mu_l} \quad (4)$$

where the subscript l and g refers to the liquid and vapor phase respectively, and x is the vapor quality. In the single objective optimization procedure, equation (1) is the objective, to be minimized subjected to the constraints 200 kg/m^{2}sec < G < 300 kg/m^{2}sec and 0.00001 < x < 0.000346. These limits have been chosen based on the experimental data collected where the propane entering and exiting the 1.07 m small-channel has been determined to be saturated liquid and two-phase respectively (NIST). The properties used are listed in Table 1, obtained at the entrance pressure and temperature to the small-channel, of 604.61 kPa and 9.57°C, respectively.

Table 1. Properties of propane used in the study

Property	Value
Liquid phase density, kg/m^3	515.313
Vapor phase density, kg/m^3	13.621
Liquid phase viscosity, μPa.s	113.84
Vapor phase viscosity, μPa.s	7.7409

Meanwhile, in the double objectives optimization scheme, the second objective to be minimized is the Lockhart-Martinelli parameter,

$$X = \sqrt{\frac{(\Delta P/\Delta L)_l}{(\Delta P/\Delta L)_g}} \tag{5}$$

which simplifies into,

$$X = \left(\frac{f_l}{f_g}\right)^{1/2} \left(\frac{1-x}{x}\right) \left(\frac{\rho_g}{\rho_l}\right)^{1/2} \tag{6}$$

Although equations (5) and (6) are generally applied in the separated model [5], it is still being considered here due to its opposite effect to the minimization of the pressure drop, a necessary condition for the utilization of the two-objective function GA optimization. A quick review of the equations show that as the vapor quality increases along a tube with the increasing frictional pressure drop, this parameter decreases, hence its use here. The optimization scheme in MATLAB toolbox is used to determine the minimized frictional pressure drop of equation (1) in the single objective optimization, and simultaneous minimization of equations (1) and (6) in the double-objective optimization. The same constraints and properties apply with five runs to ensure repeatability and reliability of the outcomes.

3. Results and Discussions

Fig 1 shows the outcome of the single objective optimization with GA after five runs. It shows that the homogeneous model which treats propane as a single mixture is expected to have a minimum frictional pressure drop of 0.8743 kPa with the quality of 0.000312 for the test section considered. The optimal flow rate is 200 kg/m^{2}s, which is expected since higher flow rates induces higher pressure drop. The stochastic evolutions have generated the best fitness function, the frictional pressure drop, after matching the constants and constraints imposed before the repeated generations, in this case set at 100 from an initial population of 200.

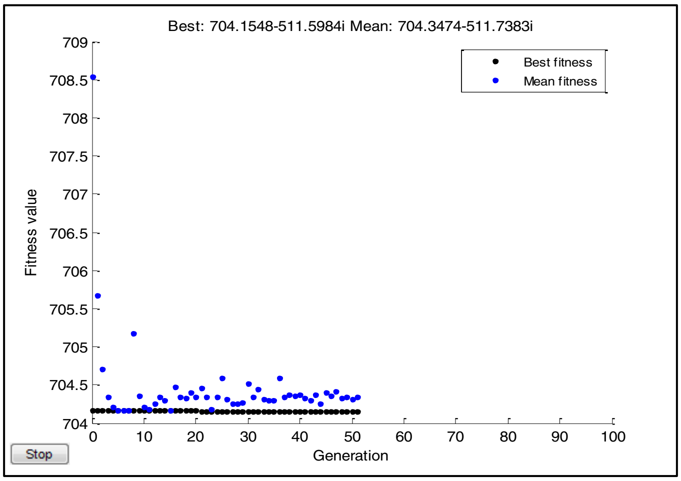

Fig. 1. Best and mean values of the fitness function (frictional pressure drop).

The measured experimental total pressure drop obtained from the test section is 2.2488 kPa with the quality of 0. 000346 calculated at the exit of the tube. Since the static pressure drop is generally negligible for horizontal tubes and the acceleration pressure drop is also insignificant compared to that of the frictional pressure drop, the quantity can be assumed to be representative of the contribution from the frictional losses. Fig 2a shows the Pareto front, the outcome of the double objective optimization with GA, simultaneous minimization of both the frictional pressure drop and the Lockhart-Martinelli (LM) parameter under optimized vapor quality and mass flow rate. The same range for the vapor quality and flow rate is used as in the single objective optimization.

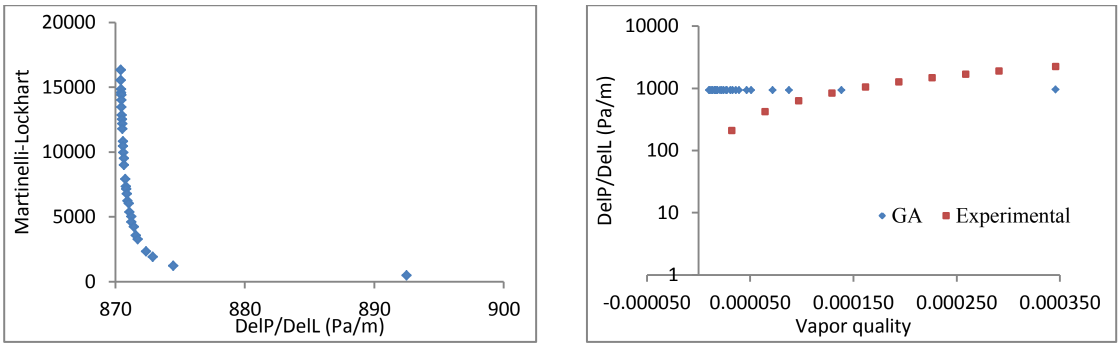

Fig. 2. (a) Optimal frictional pressure drop and LM with GA; (b) Pressure drop comparison

The pressure drop against the vapor quality graph (Figure 2b) shows a similar trend as those of other refrigerants that have been published in Xu et al. [5]. The outcome from GA is lower at the exit quality since smooth tube has been assumed with Fang et al. as well as McAdams frictional pressure drop correlation McAdams [7,8]. There are as many agreements as discrepancies that have been attributed to the different models, approaches, flow regimes, correlations, and new working fluids. Thus, the frictional pressure drop predicted here using GA shows promise – achieving simultaneous minimization of identified objectives subjected to set constraints i.e. design variables.

4. **Conclusion**

A preliminary investigation of the predicted frictional pressure drop minimized under optimal vapor quality and flow rate has been completed with the evolutionary algorithm GA. The stochastic approach produced the minimized frictional pressure drop of 0.8743 kPa with an associated vapor quality of 0.000312, which is achievable at the flow rate of 200 kg/m^{2}sec. The outcome seems promising enough to proceed into investigations with GA on the optimization of the two-phase flow performance in terms of its pressure drop with more parameters involved instead of just two as is done presently. It is believed that further optimization studies could assist in the better understanding and control of heat exchanging devices towards more efficient compact systems.

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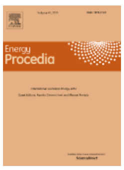

Biography

Normah Mohd-Ghazali graduated with a B.Sc. in Nuclear Engineering from the Univ. of Wisconsin-Madison, USA. Her M.Sc.is from the Univ. of Malaya, Kuala Lumpur, and her Ph.D. from the Univ. of New Hampshire, USA. Currently an Assoc. Prof. in the Fac. of Mech. Engineering at Universiti Teknologi Malaysia, her research interest includes heat sink analysis and thermoacoustics.