

MODELING OF THE MINIMIZED TWO-PHASE FLOW FRICTIONAL PRESSURE DROP IN A SMALL TUBE WITH DIFFERENT CORRELATIONS

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Abstract

The major parameters of interest in heat transfer research are the refrigerant charge, pressure drop, and heat transfer capacity. Smaller channels reduce the refrigerant charge with higher heat transfer capability due to the increased in surface area to volume ratio but at the expense of a higher pressure drop. Differences between the predicted and experimental frictional pressure drop of two-phase flow in small tubes have frequently been discussed. Factors that could have contributed to that effect have been attributed to the correlations used to model the flow, some being modified from the originals developed for a macro system. Experimental test-rigs have varied in channel geometry, refrigerant type, and flow conditions. Thousands of data have been collected to find a common point among the differences. This paper reports an investigation of four different two-phase friction factor correlations used in the modeling of the frictional two-phase flow pressure drop of refrigerant R-22. One had been specifically developed for laminar flow in a smooth channel, another was modified from a laminar flow in a smooth pipe to be used for a rough channel, and two correlations are specific for turbulent flow that consider internal pipe surface roughness. Genetic algorithm, an optimization scheme, is used to search for the minimum friction factor and minimum frictional pressure drop under optimized conditions of the mass flux and vapor quality. The results show that a larger pressure drop does come with a smaller channel. A large discrepancy exists between the correlations investigated; between the ones that does not consider surface roughness and that which does, as well as between flow under laminar and turbulent flow conditions.

Keywords: Two-phase flow, friction factor, pressure drop, optimized conditions

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1.0 INTRODUCTION

With the fast development of compact heat exchangers for more effective heat transfer at a lesser refrigerant charge, and a global requirement for new coolants that are more environmentally friendly, exploration of the performance of potential refrigerants has gained much momentum in the last ten years or so. A higher frictional pressure drop is expected from these small channels due to increased frictional forces but related correlations developed to date have discrepancies between the predicted and

experimental pressure drop up to 100% [1,2]. Disagreements could have been attributed to the conditions under which these correlations have been developed for two-phase flows where experimental test-rigs have varied in channel geometry, refrigerant type, and flow conditions. With numerous data and more expected, modified and newer correlations are being analyzed so that the performance of the potential refrigerants may be predicted and heat transfer can be better managed. This study investigates the minimization of the frictional pressure drop under a common platform, optimized conditions,

when different correlations for the friction factor and pressure drop are utilized.

Classical optimization procedure, experimentally or numerically, which entails discrete variations of the variable of interest over a limited range of set parameters involves a large amount of time, effort, and cost. Lately, genetic algorithm (GA), a fast random search mechanism based on the mechanics of natural selection, survival of the fittest, has gained popularity in optimization of processes, components, and systems, most recently in small devices such as the micro-channel heat sink (MCHS) [3-5]. This study reports the outcomes of a single objective optimization using GA to predict the minimized two-phase friction factor and frictional pressure drop of chlorodifluoromethane (R-22) in a small channel using different correlations of the friction factor. Although this refrigerant is being phased out due to its hazardous effects on our environment [6], it is being used here due to the availability of experimental data as well as needed for comparison purposes. Investigation on new potential refrigerants is currently being done experimentally to explore their capabilities but such test-rigs are generally expensive and limited to a range of design and operating conditions [7-10]. This fast GA scheme introduces a new approach in identifying optimized conditions in two-phase flow analysis. To date, the scheme has not been used in the optimization associated with the pressure drop of two-phase flow. This paper reports part of the research completed in utilizing GA for a fast prediction of the hydrodynamic behavior of two-phase flow in small channels. Both laminar and turbulent flows are considered in this study.

2.0 METHODOLOGY

The pressure drop is a very important parameter in designing heat transfer systems because it dictates the circulation rate, and hence the other system parameters in natural circulation systems and the pumping requirement in forced circulation systems due to their direct relationship of pressure drop and pumping power. For two-phase flow in pipes, the co-current flow of liquid and vapor creates design and operational problems due to the formation of different types of flow patterns. Thus, there are complexities associated with the prediction of the pressure drop in two-phase flow.

In two-phase flow, the total pressure drop is contributed by the static pressure drop, the accelerational pressure drop, and the frictional pressure drop,

$$(\Delta P_{2ph})_{total} = (\Delta P_{2ph})_{static} + (\Delta P_{2ph})_{mom} + (\Delta P_{2ph})_{frict} \quad (1)$$

The static pressure drop is due to the difference in density of the fluid at different elevation of the inlet and exit of the pipe. This term is generally negligible for

horizontal pipes. The second term in equation (1) is due to the change in momentum of the flowing fluid whilst the last term is that due to the frictional losses associated with the irreversible energy dispersion caused by fluid-fluid and fluid-wall friction. The contribution from the accelerational pressure drop is insignificant in small tubes compared to the much larger frictional pressure drop associated with the magnified shear stress in smaller channels. Thus, this study is focusing on the third term in equation (1).

There are generally two models representing the two-phase flow pressure drop; the homogenous model and the separated model [2]. The homogeneous equilibrium model assumes that the liquid and vapor phase have the same velocity while in the separated model the liquid and vapor phase behaves as a separate entity. The first model, also called the no-slip model, is used here and only the frictional pressure drop is considered because in small channels, this factor is of main consequence. The frictional pressure drop $(\Delta P)_{fric}$ for a steady flow in a channel with a constant cross-section is given by the Darcy-Weisbach equation. It is described as a function of the friction factor, f_{2ph} , tube length, L , tube diameter, D , mass flux G_{2ph} , and density, ρ_{2ph} .

$$(\Delta P)_{fric} = f_{2ph} \cdot \frac{L}{D} \cdot \frac{G_{2ph}^2}{2\rho_{2ph}} \quad (2)$$

where the Darcy friction factor, f_{2ph} , for laminar flow ($Re < 2300$) in a smooth channel is inversely proportional to the two-phase Reynolds number, Re_{2ph} . It is determined from the Hagen-Poiseuille, Poiseuille law or Poiseuille equation [11, 12],

$$f_{2ph} = \frac{64}{Re_{2ph}} \quad (3)$$

Reynolds number is a function of the channel diameter, mass flux and two-phase viscosity, defined by,

$$Re = \frac{G_{2ph}D}{\mu_{2ph}} \quad (4)$$

For a turbulent flow, $Re > 4000$, many correlations are available. In the present study, the Haaland [13], Swamee-Jain [14], Serghides [15] and Blasius [16] friction factor correlations are chosen. The first three correlations are among many, based on numerical solutions to the implicit Colebrook friction factor for rough channels [17, 18],

$$\frac{1}{\sqrt{f_D}} = -2 \log_{10} \left(\frac{\varepsilon/D_h}{3.7} + \frac{2.51}{Re\sqrt{f_D}} \right) \quad (5)$$

Meanwhile, the Blasius equation is a modified version, originated from the friction factor for smooth pipes, often used for its simplicity. The Haaland, Swamee-

Jain, Serghides, and Blasius equations are, respectively,

$$f_D = \left[-1.8 \log_{10} \left\{ \left(\frac{\varepsilon/D_h}{3.7} \right)^{1.11} + \frac{6.9}{Re} \right\} \right]^{-2} \quad (6)$$

$$f_D = 0.25 \left[\log_{10} \left(\frac{\varepsilon/D_h}{3.7} + \frac{5.74}{Re^{0.9}} \right) \right]^{-2} \quad (7)$$

$$f_D = \left(A - \frac{(B-A)^2}{C-2B+A} \right)^{-2} \quad (8)$$

$$f_D = \frac{0.3164}{Re^{0.25}} \quad (9)$$

where the A, B, and C are function of the surface roughness, ε , D and Re,

$$A = -2 \log_{10} \left(\frac{\varepsilon/D_h}{3.7} + \frac{12}{Re} \right) \quad (10)$$

$$B = -2 \log_{10} \left(\frac{\varepsilon/D_h}{3.7} + \frac{2.51A}{Re} \right) \quad (11)$$

$$C = -2 \log_{10} \left(\frac{\varepsilon/D_h}{3.7} + \frac{2.51B}{Re} \right) \quad (12)$$

They have been chosen because they were among the first few explicit forms of the Colebrook equation. For the homogeneous model, many correlations representing the refrigerant properties exist [2]. In the present study, the Mc Adams [19] equation is used, where,

$$\rho_{2ph} = \left(\frac{x}{\rho_g} + \frac{1-x}{\rho_l} \right)^{-1} \quad (13)$$

$$\mu_{2ph} = \left(\frac{x}{\mu_g} + \frac{1-x}{\mu_l} \right)^{-1} \quad (14)$$

The parameters used in equations (2) through (14) are listed in Table 1 for the operating pressure of 0.7 MPa. These values are experimental values obtained from two-phase flow tests conducted in a 7.6 mm diameter stainless steel tube of 1.07 meter heated electrically at 12923.71 W/m [20]. Minimization of the single objective function is completed with MATLAB toolbox [21] where in the first part, equations (2) and (4) through (7) representing the friction factor, each are considered individually. Then, minimization of the frictional pressure drop (1) is completed with the minimized friction factor from equations (2) and (4) through (7). The roughness value is taken as 0.03, associated with stainless steel pipe materials. Discrepancies that have been reported between the predicted and experimental pressure drop could reach as high as 100% [2], probably due to the different models assumed and test-rigs used. Thus, this study attempts at analyzing the models representing the Darcy friction factor appearing in the pressure drop, under a common platform i.e. optimized conditions.

Table 1 The parameters and physical properties of the refrigerant R-22

Parameter	Value
Mass flux, G	50-350 kg/m ² s
Vapor quality	0 – 1
Gas-phase density, ρ_g	28.84326657 kg/m ³
Liquid-phase density, ρ_l	1246.59834 kg/m ³
Gas-phase viscosity, μ_g	11.79927077 μ Pa.s
Liquid-phase viscosity, μ_l	193.6475014 μ Pa.s

The structure of the GA solution approach is shown in Figure 1. Based on the concept of survival of the fittest, the evolution of a “strong solution” set begins with a random initial population of solution, in this case 100. The average fitness function, the objective function, is determined through the selection, crossover, and mutation operators. Iterations continue until a specified convergence is reached.

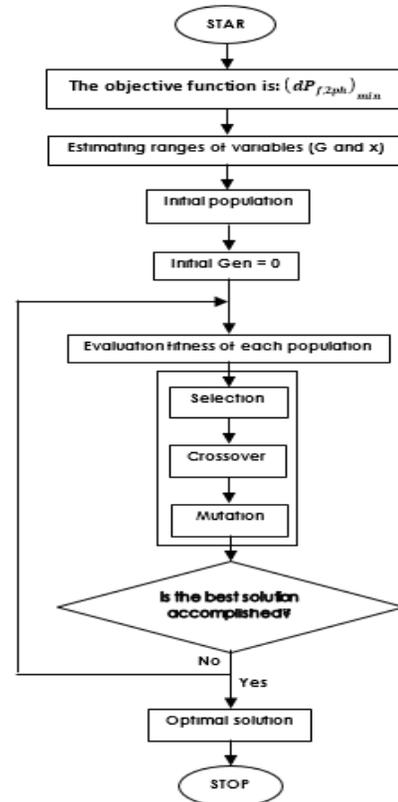


Figure 1 Genetic Algorithm Flow Diagram

3.0 RESULTS AND DISCUSSION

Figures 2 through 4 show the fitness function obtained from sample runs of the GA optimization of the friction factor and frictional pressure drop based on the correlations of Hagen-Poiseuille, Blasius, and Swamee-Jain.

Figure 5 and 6 show the comparison of the minimized friction factor (f_D) and pressure drop ($dP_{f,2ph}$) for the 3 mm and 7.6 mm diameter tube for

the friction factor correlations of laminar flow from Hagen – Poiseuille (H-P), and turbulent flow from Swamee-Jain (S-J), Haaland (Ha), Serghides (Se) and Blasius (Bl). The diameter of 3 mm is the upper limit for a mini-channel beyond which the tube is considered as small, not mini. Although the experimental data was obtained for a 7.6 mm diameter tube, optimization has been completed for the 3 mm channel as well to look at the effects of channel reduction on the frictional

factor and pressure drop of two-phase flow of R22. It has been generally accepted that the behavior of fluids, particularly liquids, are different in small pipes due to the magnified effects of frictional forces and wall effects. Thus, data of properties in analysis of small channels should be taken from those performed under similar conditions.

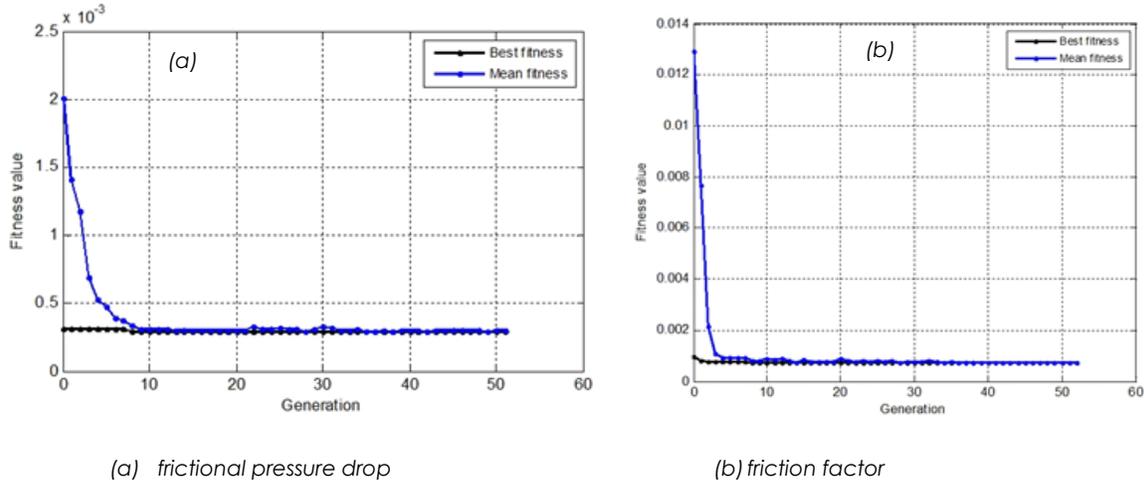


Figure 2 Hagen-Poiseuille Equation

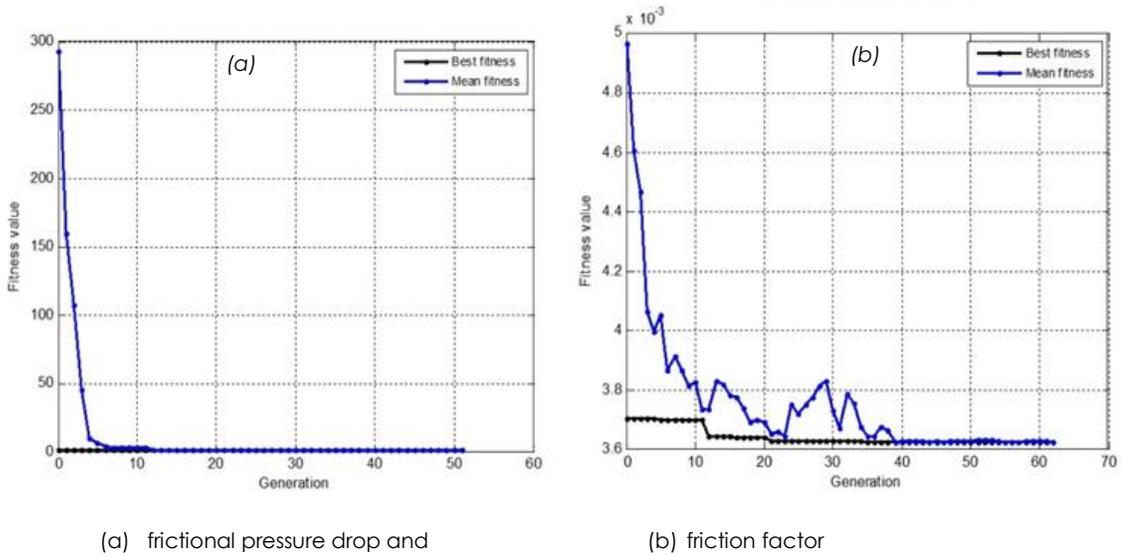


Figure 3 Blasius Equation

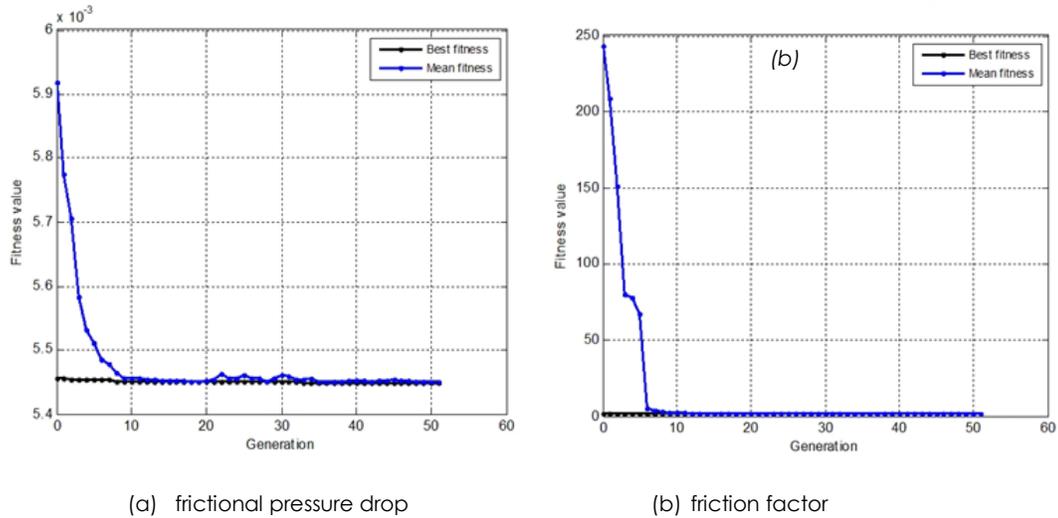


Figure 4 Swamee-Jain Equation

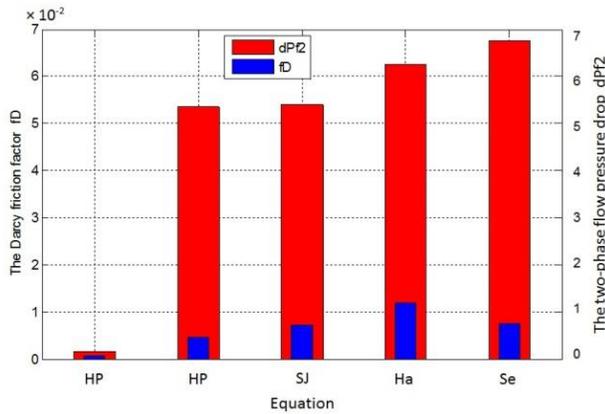


Figure 5 Minimized friction factor and frictional pressure drop inside tube of 3 mm inner diameter

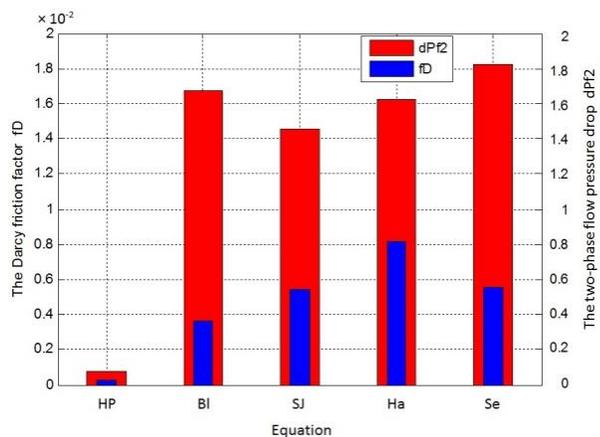


Figure 6 Minimized friction factor and frictional pressure drop inside tube of 7.6 mm inner diameter

Optimization with GA has been completed for five runs each for consistency and repeatability, and to obtain the average. The laminar friction factor and

frictional pressure drop are very much lower than those for the turbulent condition which is of course due to the higher degree of interactions caused by turbulence and mixing. It is interesting though that the friction factor outcome from the Blasius equation which is just a modified version of the Hagen-Poiseuille equation for laminar condition, is almost similar to that from the Colebrook solution with Swamee-Jain equation for the 3 mm diameter channel. The latter developed specifically for turbulent flow in rough channels. The Haaland and Serghides prediction of the frictional pressure drop are 20-30% higher than that of the Blasius equation. The trend in decreasing pressure drop with smaller diameter tube is as expected; the pressure drops more than twice for the 3 mm tube compared to the 7.6 mm mini-channel. However, at the 7.6 mm diameter case study, it is the Haaland correlation that is closest to the modified simplified Hagen-Poiseuille correlation. For optimized conditions, the behavior of the predicted frictional pressure drop differs between correlations as well as for different diameters. It is not surprising then; disagreements occur between correlations developed even under controlled conditions in different laboratories where experimental data collected may also differ.

Meanwhile, the lowest friction factor is found to be very close to the saturated vapor state for all correlations attempted, with the optimized mass flux between 341 to 350 kg/m²s for the 7.6 mm tube and between 316 to 350 kg/m²s for the 3mm mini-channel. Discrepancies in the friction factor and pressure drop can be seen between the different correlations used, under optimized conditions; the Serghides equation producing the highest friction factor and frictional pressure drop among them. Except for the Blasius, the other three correlations take into consideration the surface roughness factor which has been taken to be 0.03 mm here for general stainless steel pipes. However, except for the

Swamee-Jain, the difference between the later three correlations is interestingly at a lesser degree, under 15%, with the larger diameter tube. The results here are encouraging since these were obtained using the evolutionary algorithm which lately has found wide applications in design, transportation and medicine [22]. The fast output produced show promise in investigation of the hydrodynamic performance of potential new refrigerants. However, GA as a stochastic search tool does not recognize the physics of the flow and thus had to be cautiously applied in any optimization process, perhaps best with some preliminary data available with some knowledge of the flow itself. Then, further exploration of the hydrodynamic performance of the new refrigerants may be investigated.

Comparison with experimental data for the 7.6 mm pipe is shown in Table 2, though the experimental pressure drop provided had been based on the Blasius correlation for the friction factor which was developed for laminar flow in smooth pipes but modified for turbulent flow as given by equation (7). The properties evaluated were determined using the McAdams equation [14]. No roughness factor was considered. The parameters that produced the experimental pressure drop are taken and substituted into equations (2) to (14) to obtain the frictional pressure drop according to the predicted correlations. The differences are clearly huge and this could only be attributed to the in situ conditions which besides being not optimized, was susceptible to the environment at the particular instant the experiments were completed. Furthermore, it was the total pressure drop that was measured directly, at the pipe inlet and exit, the frictional pressure drop was then determined by subtracting the calculated accelerational pressure drop from that quantity with the drop assumed to be linear.

Table 2 Comparison between the predicted and experimental results

Equation	$\Delta P_{frict.}$	$\Delta P_{f.exp}$	RE
Hagen-Poiseuille	57.58		0.9207
Blasius	188.48		0.7404
Swamee-Jain	195.32	726.153	0.7413
Haaland	191.91		0.7447
Serghides	210.64		0.7282

Figure 7 show the predicted frictional pressure drop based on the five correlations investigated in this study with all parameters taken associated with the experimental frictional pressure drop of 726.153 Pa. The laminar correlation gives much lower magnitude compared to the turbulence ones and the difference between the correlations for turbulent conditions is small.

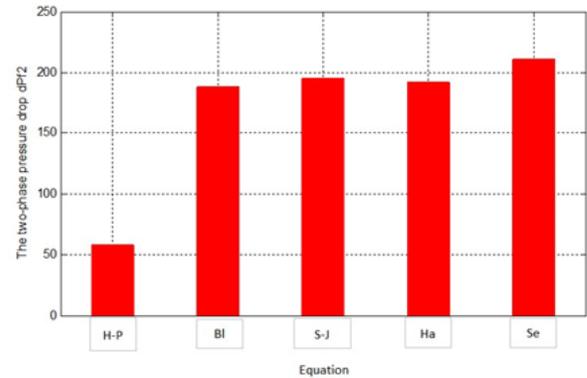


Figure 7 Predicted frictional pressure drop based on experimental conditions

4.0 CONCLUSION

An evolutionary algorithm, genetic algorithm (GA), based on a random search for a minimized two-phase friction factor as well as frictional pressure drop has been utilized based on different correlations, for laminar and turbulent flow in a small tube. The GA optimization scheme has not been utilized in the study of two-phase flow in small tubes. Results have shown that different correlations used produced different outcomes, as has been reported previously though in the present study, the differences under optimized conditions have been obtained quickly with genetic algorithm.

As expected the pressure drop is less with a larger diameter tube. The outcome from this optimization has shown promise due to the quick output obtained in this investigation of the hydrodynamic performance of refrigerant R22, as well as points to the expected disagreements even under optimized conditions. Even with correlations that have been developed to consider the pipe roughness, discrepancies still exist.

The application of this optimization tool is possible with new potential refrigerants to replace the current hazardous refrigerants though initial experimental data is still needed because GA as an optimization tool does not consider the physical phenomena that governs the transient two-phase flow behavior.

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