International Journal of Technology (2016) 2: 227-234
ISSN 2086-9614

OPTIMIZATION OF THE FRICTION FACTOR AND FRICTIONAL PRESSURE DROP OF R22 AND R290

Normah Ghazali[1*], Qais Abid Yousif[1], Agus S. Pamitran[2], Sentot Novianto[2], Robiah Ahmad[3]

[1] *Faculty of Mechanical Engineering, Universiti Teknologi Malaysia 81310 Skudai, Johor, Malaysia*
[2] *Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus UI Depok, Depok 16424, Indonesia*
[3] *UTM Razak School of Engineering and Advanced Technology, Universiti Teknologi Malaysia 54100 JalanSemarak, Kuala Lumpur, Malaysia*

(Received: October 2015 / Revised: December 2015 / Accepted: January 2016)

ABSTRACT

Today, the air-conditioning and refrigeration industry is still searching for environmentally friendly refrigerants that could replace hazardous, ozone-depleting coolants – refrigerants that behave similarly, if not better, than the present ones. The present study examines optimization of the frictional pressure drop of R22 and R290 using genetic algorithm. Outcomes are compared against the measured pressure drop obtained from a horizontal 7.6 mm channel with a length of 1.07 meters. Three equations have been used for calculating the Darcy friction factor and two-phase flow pressure drop for both laminar and turbulent flow regimes in smooth and rough tubes. The effects of the different correlations for the friction factor and pressure drop utilized are demonstrated. The results illustrate that the differences between values of the Darcy friction factor are very small for the two refrigerants examined, with the frictional pressure of R-290 higher than R-22. Use of a smaller channel induced a much higher frictional pressure drop, as well.

Keywords: Darcy friction factor; Genetic algorithm; Optimization; Pressure drop

1. INTRODUCTION

The two-phase flow pressure drop in small diameter pipes has been the subject of research over the last few decades because of its importance in two-phase devices. It presents a main parameter in designing and determining the required pumping power in a forced system to transport the two-phase fluids, and also to control the recirculation rate in natural circulation systems. However, more accurate pressure data are needed to develop a reliable method for predicting pressure drops in small to micro tubes and in compact heat exchangers (Bergman et al., 2011).

The chlorofluorocarbon (CFC) refrigerants have been the indispensable component in refrigeration and air conditioning equipment for more than 50 years or so. Together with hydrochlorofluorocarbons (HCFCs) and other chemicals used in coolants, foaming agents, fire extinguishers, solvents and aerosols, these have been proven to be ozone depleting substances (ODS) (Molina & Rowland, 1974) responsible for causing the rise in the earth's temperature. The ozone layer exists in the stratosphere; it protects the earth`s atmosphere from the sun`s rays. In spite of the recognized hazardous effects of these refrigerants, R22 and HCFCs are still

*Corresponding author's email: normah@mail.fkm.utm, Tel. +607-5534577, Fax. +607-5566159
Permalink/DOI: http://dx.doi.org/10.14716/ijtech.v7i2.2989

widely used in the refrigeration and air-conditioning industry. In an attempt to find a replacement for R-22, HFCs and natural refrigerants like R-290 have been examined extensively because they do not hold chlorine. Zero or very low Global Warming Potential (GWP) is another advantage of these natural refrigerants.

To this day, numerous approaches have attempted to improve the performance of two-phase systems, i.e., increasing efficiency and decreasing the pressure drop. Genetic Algorithm (GA) is one of the optimization tools that have been proven to be particularly useful in determining the optimal pressure drop (Normah et al., 2015; Halelfadl et al., 2014). GA is a stochastic search procedure based on the mechanics of natural genetics and natural selection that can be used to obtain global and robust solutions to optimization problems (Gosselin et al., 2009). This paper reports optimization outcomes obtained from GA regarding minimization of (i) the friction factor, and (ii) frictional pressure drop under optimized mass flux and vapor quality. The frictional pressure drop is then compared with data obtained experimentally.

2. THEORETICAL BACKGROUND

The two-phase flow pressure drop consists of the sum of three components: gravitational, acceleration and frictional. The relationship is described in Equation 1 below.

$$\left(\Delta P_{2ph}\right)_{total} = \left(\Delta P_{2ph}\right)_{static} + \left(\Delta P_{2ph}\right)_{acc} + \left(\Delta P_{2ph}\right)_{frict} \tag{1}$$

Previous studies have shown that the frictional component was dominant and the contribution of acceleration and gravitational losses were small. Thus, the most problematic component is the frictional component, which can be found by using the Darcy-Weisbach equation (Brown, 2002),

$$\left(\Delta P_{2ph}\right)_{frict} = f_{2ph} \cdot \frac{L}{D_h} \cdot \frac{G_{2ph}^2}{2\rho_{2ph}} \tag{2}$$

where D_h is the hydraulic diameter, for a circular tube the pipe diameter is D, and f_{2ph} or f_D, is the Darcy friction factor or the Darcy-Weisbach friction factor. L, G_{2ph}, and ρ_{2ph} are tube length, coolant mass flux and density, respectively.

2.1. Darcy Friction Factor Equations

The Darcy friction factor, f_D (also known as the Moody friction factor), is a dimensionless quantity, not constant, and depends on the parameters of the pipe and velocity of the fluid flow. It can be found from a Moody diagram (Moody, 1944) and thus the name, Moody friction factor (sometimes called the Blasius friction factor), according to the proposed approximate formula by Blasius. The Darcy friction factor and the Fanning friction factor, f, are often confused with one another. The former is related to the latter by Manning and Thompson (1991) as:

$$f_D = 4f \tag{3}$$

The Darcy factor is commonly used by civil and mechanical engineers, and the Fanning factor by chemical engineers.

The flow regimes most often studied are the laminar and turbulent conditions. The former is characterized by smooth, constant fluid motion because the viscous forces are dominant at low Reynolds numbers $(Re < 2320)$. The Darcy friction factor in smooth circular channels for the laminar region can be calculated with the Hagen–Poiseuille law, Poiseuille law or Poiseuille equation (Pfitzner, 1976; Sutera & Skalak, 1993):

$$f_D = \frac{64}{Re} \tag{4}$$

The Blasius equation is the simplest equation for calculating the Darcy friction factor in smooth pipes, but is sometimes used in rough pipes due to its simplicity and validity up to Reynolds number 100,000 (Hager, 2003), as follows.

$$f_D = \frac{0.3164}{Re^{0.25}} \tag{5}$$

where the Reynolds number, *Re*, is defined by:

$$Re = \frac{Inertial\,Forces}{Viscous\,Forces} = \frac{GD}{\mu} \tag{6}$$

with μ being the viscosity. The Darcy friction factor specific for fully turbulent flow $(Re > 4{,}000)$ in rough channels can be calculated by the Colebrook equation, which is also known as the Colebrook–White equation. It is an implicit equation combining the experimental results of turbulent flow in smooth and rough pipes (Colebrook & White, 1937; Colebrook, 1939), taking into account the roughness factor, ε. This equation solves for the Darcy friction factor, f_D, iteratively:

$$\frac{1}{\sqrt{f_D}} = -2log_{10}\left(\frac{\varepsilon/D_h}{3.7} + \frac{2.51}{Re\sqrt{f_D}}\right) \tag{7}$$

Since the Colebrook equation is an implicit equation, it has been solved numerically or by iteration using the Newton Raphson method. To avoid doing the iterations, new equations were developed, and one of them was the Serghides equations. It is an approximation of the implicit Colebrook–White equation, derived by using Steffensen`s method (Serghides, 1984). It can be used to directly calculate the Darcy-Weisbach friction factor, f_D, for a full-flowing circular pipe. This equation involves calculating three quantities and then substituting them into the main equation, as follows:

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

$$A = -2log_{10}\left(\frac{\varepsilon/D_h}{3.7} + \frac{12}{Re}\right) \tag{9}$$

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

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

The aim of this study is to compare the values of the minimized frictional pressure drop for R-22 and R-290, using the different correlations discussed earlier for laminar and turbulent flow in smooth and rough pipes to identify differences in the outcomes between the equations.

3. METHODOLOGY

In general, there are two typical flow models for predicting a two-phase pressure drop: the homogeneous flow model and the separated flow model. The homogeneous flow model is the simplest technique for analyzing two-phase (or multiphase) flows, as it considers the two-phase flow as a single-phase flow having average fluid properties depending on quality. Both liquid and vapor phases move at the same velocity (slip ratio = 1), so it is also called the zero slip model. This is the model adopted in this study. The separated model treats each liquid and vapor phase individually with its own properties.

Table 1 lists the experimental data for R22 and R290 that was used in this study, obtained from a test section of stainless steel pipe length 1.07 meters long with a 7.6 mm inside diameter. The density of two-phase flow for the homogeneous model can be expressed as follows:

$$\rho_{2ph} = \left(\frac{x}{\rho_g} + \frac{1-x}{\rho_l}\right)^{-1} \tag{12}$$

The two-phase flow viscosity is expressed using the McAdams equation (Awad and Muzychka, 2008; McAdams et al., 1942):

$$\mu_{2ph} = \left(\frac{\mathrm{x}}{\mu_g} + \frac{1-\mathrm{x}}{\mu_l}\right)^{-1} \tag{13}$$

The experimental pressure drop was determined from the difference of the measured total pressure drop and the calculated accelerational pressure drop from a 7.6 mm diameter channel (Collier and Thome, 1994):

$$\Delta P_f = \Delta P_{tot} - \Delta P_a \tag{14}$$

where

$$\Delta P_a = G^2 \vartheta_{lg} x_o \tag{15}$$

3.1. Optimization Procedure

All three formula; Equations 4, 5, and 8, together with the related equations, are used to determine the minimum Darcy friction factor f_D, and then the minimum two-phase flow frictional pressure drop $(\Delta P_{2ph})_{frict}$. For the turbulent flow in a rough channel, the absolute roughness of stainless steel (ε = 0.03 mm) is used. To find the optimal value for the two parameters, the single objective Optimization Toolbox (Version 8, 3.0, 532) in MATLAB R2014a (MATLAB, 1994) is used. The operating process of the GA optimization process is shown in Figure 1.

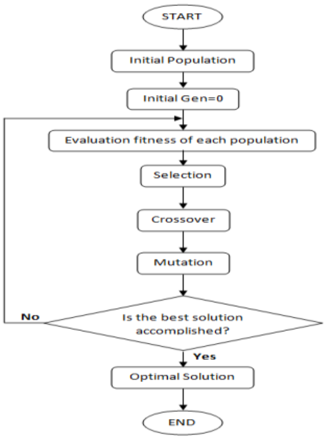


Figure 1 GA flow diagram

The evolution starts with a random population of individuals – solutions based on combination of parameters to be varied, and the initial population develops based on the selection, crossover and mutation operators with the objective to minimize $(\Delta P_{2ph})_{frict}$. The population size selected was 20, which means that for each generation, 20 best solutions proceeded to the next evolution (the rest being discarded). The crossover fraction of 0.8 means that the crossover operation will tolerate 80% of the solution for reproduction, and the iteration will continue until it stops at 200 generations as a default. In this study, the variable parameters are mass flux and vapor quality, which have been set as (G = 50–350 kg/m^{2}s and x = 0–1), and the objective function is first set to be the Darcy friction factor.

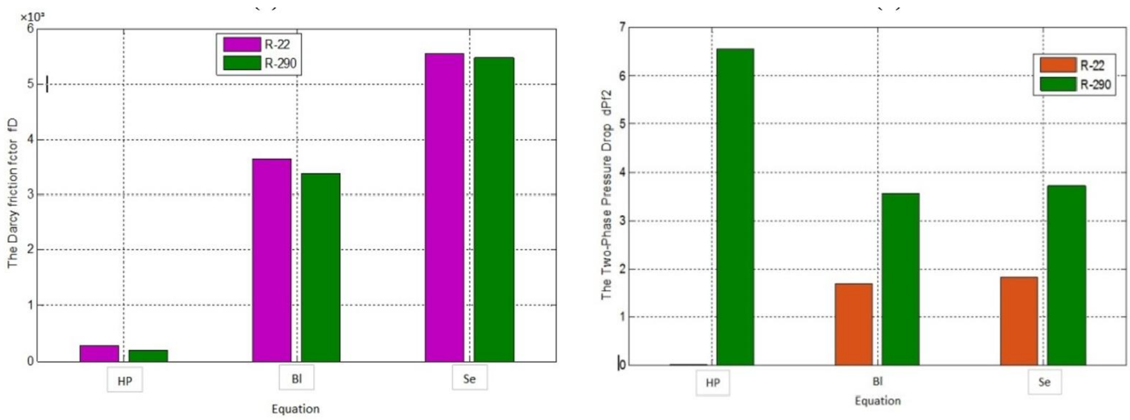
Table 1 Experimental data of R-22 and R-290

Experimental parameters of refrigerant R-22			
T_{in}	9.88 °C	q	380 Watt
P_{in}	0.682 MPa	G	282.4 kg/m²‧s
P_{out}	0.68 MPa	ṁ	0.013 kg/s
ΔP_{tot}	1131 Pa	x	0.15
ρ_l	1246.59 kg/m^3	μ_l	193.64 µPa.s
ρ_g	28.84 kg/m^3	μ_g	11.799 µPa.s
Experimental parameters of refrigerant R-290			
T_{in}	9.672 °C	q	640 Watt
P_{in}	0.629 MPa	G	336.78 kg/m²‧s
P_{out}	0.626 MPa	ṁ	0.012 kg/s
ΔP_{tot}	4681 Pa	x	0.131
ρ_l	515.33 kg/m^3	μ_l	113.84 µPa.s
ρ_g	13.621 kg/m^3	μ_g	7.7409 µPa.s

GA optimization was performed for the three equations for the Darcy friction factor, and in all the runs the process started with a uniformly random population, and all the parameters values are equally represented in the initial population. Although a single run can give as good a solution as multiple runs (Cantú-Paz et al., 2003), five runs were completed for repeatability and reliability of outcomes. Thus, five runs were performed for each equation, for each refrigerant, and for each diameter. The most frequent outcomes of the optimum Darcy friction factor and correspondingly the minimized two-phase frictional pressure drop were selected and presented in this study.

4. RESULTS AND DISCUSSION

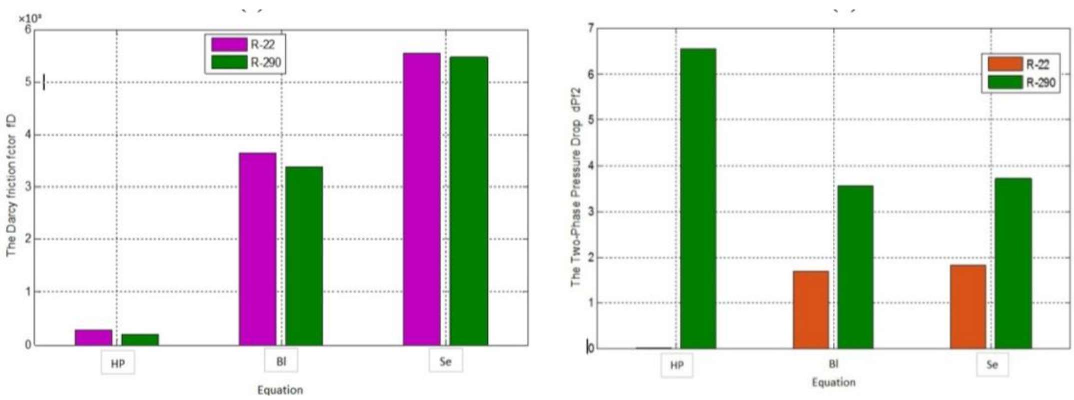
Figures 2 and 3 show huge differences between the outcomes of the equations used. The differences in Equations 4, 5, and 8 are insignificant between the refrigerants themselves for the minimized friction factor. These figures demonstrate the minimized Darcy friction factor and two-phase frictional pressure drop under optimized conditions of mass flux and vapor quality. The lowest friction factor and frictional pressure drop is obtained from the Hagen-Poiseuille equation in comparison with results from the Blasius and Serghides equations. The friction factor and frictional pressure drop is indeed lower for laminar flow. These results indicate the importance of selecting the appropriate equation to determine the friction factor and subsequently the frictional pressure drop. It is also observed here that the pressure drop for R-290 is much higher than refrigerant R22 for the smaller diameter channel compared to the 7.6 mm channel, which is expected, as smaller tubes induce a higher pressure drop due to frictional losses.



(a) (b)

Figure 2 Optimization results of: (a) the Darcy friction factor; and (b) the two-phase pressure drop from three different equations inside a test section of 7.6 mm inside diameter

The figures also show that the values of the two-phase flow pressure drop are higher when using alternative refrigerant R-290. Tables 2 and 3 present the optimization outcomes from GA and the frictional pressure drop obtained experimentally. These experimental values were based on the smooth channel assumption using the Blasius equation. Future calculations could possibly utilize the experimental data to determine the frictional pressure drop using the Serghides equation. Table 4 presents the comparisons between results that have been obtained when R-22 and R-290 are used, where the differences are under 6%.



(a) (b)

Figure 3 Optimization results of: (a) the Darcy friction factor; and (b) the two-phase pressure drop from three different equations inside a test section of 3 mm inside diameter

Table 2 Differences between GA outcomes and experimental results of refrigerant R-22

Equation	dP_{f2ph}	$dP_{f2,exp}$	Difference
Hagen-Poiseuille	57.5193		0.92
Blasius	187.6094	726.153	0.74
Serghides	209.9696		0.71

Table 3 Differences between GA outcomes and experimental results of refrigerant R-290

Equation	dP_{f2ph}	$dP_{f2,exp}$	Difference
Hagen-Poiseuille	54.33991		0.9848
Blasius	178.1321	3576	0.9501
Serghides	199.5169		0.9442

Table 4 Differences between the GA outcomes of refrigerants R-22 and R-290

Equation	$dP_{f,2ph}$		Difference
	R-22	R-290	
Hagen-Poiseuille	57.5193	54.33991	0.0585
Blasius	187.6094	178.1321	0.0532
Serghides	209.9696	199.5169	0.0523

Tabulated results indicate the potential presented by R290 as a replacement for R22 in terms of its hydrodynamic performance. The large discrepancies noted between the minimized frictional pressure drop and that obtained experimentally could be attributed to the non-optimized operations of the tests and the reality of experimental conditions, which are never ideal.

5. CONCLUSION

The prediction of the minimized Darcy friction factor and frictional pressure drop for two refrigerants, R22 and R290, in channels of two different diameters have been completed. Some conclusions that can be drawn are: (1) The use of different equations, laminar or turbulent, in smooth or rough channels produced different outcomes even under optimized conditions; (2) The Darcy friction factor and the frictional pressure drop in a smaller diameter are higher than in the large diameter channel, which was expected; (3) The difference between the measured frictional pressure drop and the optimized frictional pressure drop is large, possibly due to the different equations utilized; (4) It is important to select the most appropriate equation in predicting the frictional pressure drop when comparing with the experimental frictional pressure drop, since the development of the correlations have been based on different experimental conditions; although similar conditions have been attempted as closely as possible, the differences cannot be ignored.

Although GA has again proven its capability in predicting the optimized frictional pressure drop, reliable and acceptable experimental data must be utilized particularly when dealing with small channels and new refrigerants when the behavior of the coolants have yet to be established.

6. ACKNOWLEDGEMENT

The authors wish to thank the Ministry of Education for the Research University Grant (Vot 08H29), Universiti Teknologi Malaysia for the facilities to complete this research, and the University of Indonesia for the facilities that provided the experimental data.

7. REFERENCES

Awad, M.M., Muzychka, Y.S., 2008. Effective Property Models for Homogeneous Two-Phase Flows. *Experimental Thermal and Fluid Science*, Volume 33(1), pp. 106–113

Bergman, T.L., Lavine, A.S., Incropera, F.P., DeWitt, D.P., 2011. *Fundamentals of Heat and Mass Transfer*, John Wiley & Sons, Inc., Hoboken, New Jersey, USA

Brown, G.O., 2002. Henry Darcy and the Making of A Law. *Water Resources Research*, Volume 38(7), pp. 11-1–11-12

Colebrook, C.F. 1939, Turbulent Flow in Pipes, with Particular Reference to the Transition Region between the Smooth and Rough Pipe Laws. *Journal of the ICE*, Volume 11(4), pp. 133–156

Colebrook, C.F., White, C.M., 1937. Experiments with Fluid Friction in Roughened Pipes. In: *the Proceedings of the Royal Society of London, Series A, Mathematical and Physical Sciences*, pp. 367–381

Collier, J.G., Thome, J.R., 1994. *Convective Boiling and Condensation*, Oxford Engineering Science Series, Book 38, *Oxford University Press Inc*. New York, USA

Gosselin, L., Tye-Gingras, M., Mathieu-Potvin, F., 2009. Review of Utilization of Genetic Algorithms in Heat Transfer Problems. *International Journal of Heat and Mass Transfer*, Volume 52(9), 2169–2188

Hager, W.H., 2003. Blasius: A Life in Research and Education. *Experiments in Fluids*, Volume 34(5), pp.566–571

Halelfadl, S., Adham, A.M., Mohd-Ghazali, N., Maré, T., Estellé, P., Ahmad, R., 2014. Optimization of Thermal Performances and Pressure Drop of Rectangular Microchannel Heat Sink using Aqueous Carbon Nanotubes Based Nanofluid. *Applied Thermal Engineering*, Volume 62(2), pp. 492–499

Manning, F.S., Thompson, R.E., 1991. *Oilfield Processing of Petroleum Volume One: Natural Gas*. Pennwell Publishing Company, Tulsa, Oklahoma, USA

McAdams, W.H., Woods, W.K., Heroman, L.C., 1942. Vaporization inside Horizontal Tubes-II-Benzene-Oil Mixtures. *Transactions of the A.S.M.E.*, Volume 64(3), pp. 193–200

Molina, M.J., Rowland, F.S., 1974. Stratospheric Sink for Chlorofluoromethanes–Chlorine Atom Catalyzed Destruction of Ozone. *Nature*, Volume 249(5460), pp. 810–812

Moody, L.F., 1944. Friction Factors for Pipe Flow. *Transactions of the A.S.M.E.*, Volume 66, pp. 671–684

Normah, G.M., Oh, J.T., Chien, N.B., Choi, K.I., Robiah, A., 2015. Comparison of the Optimized Thermal Performance of Square and Circular Ammonia-Cooled Microchannel Heat Sink with Genetic Algorithm. *Energy Conversion and Management*, Volume 102, pp. 59–65

Pfitzner, J., 1976. Poiseuille and His Law. *Anaesthesia*, Volume 3(2), pp. 273–275

Serghides, T.K., 1984. Estimate Friction Factor Accurately. *Chemical Engineering*, Volume 91(5), pp. 63–64

Sutera, S.P., Skalak, R., 1993. The History of Poiseuille's Law. *Annual Review of Fluid Mechanics*, Volume 25(1), pp. 1–20