

MINIMIZATION OF TWO-PHASE FLOW FRICTIONAL PRESSURE DROP IN
SMALL CHANNEL WITH ENVIRONMENTALLY
FRIENDLY REFRIGERANT

QAIS ABID YOUSIF

UNIVERSITI TEKNOLOGI MALAYSIA

MINIMIZATION OF TWO-PHASE FLOW FRICTIONAL PRESSURE DROP IN
SMALL CHANNEL WITH ENVIRONMENTALLY
FRIENDLY REFRIGERANT

QAIS ABID YOUSIF

A thesis submitted in fulfilment of the
requirement for the award of the degree of
Doctor of Philosophy (Mechanical Engineering)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

FEBRUARY 2018

I would like to thank my family for unlimited support with sympathetically aware of tolerance and understanding to complete my research despite the difficult conditions experienced by our dear. I hope they can forgive me for all the time that I spent far instead of being with them.

I have fully realized that the promise is to complete the study while you still capable and unrelated to other responsibilities and projects that prevent the focus on the study because the focus and time are the backbone to complete what you started and the most difficult is to find them, especially when the years pass.

Johor, Johor Bahru, Malaysia

DECEMBER 2017

Qais A. Yousif

ACKNOWLEDGEMENT

Praise be to Allah, the Cherisher and Sustainer of the World's; Most Gracious, Most Merciful; Master of the Day of Judgment. This study has been carried out under the supervision of Prof. Dr. Normah Mohd Ghazali. The project has been supported by the Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, which is gratefully acknowledged. Also, the project has been supported by the Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia which are gratefully acknowledged for the facilities of doing experiment.

I would like to thank Prof. Dr. Normah for her advices and guidance and giving me the opportunity and motivation to undertake this research. All the time she was available for fruitful research discussions and her guidance and encouragement during the period were of a great benefit of contribution to this study.

I would also like to thank my co-supervisor Assoc. Prof. Dr. Robiah for the discussions and for encouraging me always, and to thank my co-supervisor Dr. Pamitran for the support and facilities provided by him in order to overcome all difficulties and to conduct experiments in the laboratories of the University of Indonesia

Finally, I must offer special thanks to my wife for her graciously support throughout my study.

ABSTRACT

Accurate prediction of the friction factor and consequently the pressure drop in small two-phase flow channels are still lacking with large disagreements. In addition, the environmental concerns associated with industrial refrigerants currently used have further posed a challenge to find thermally and hydrodynamically compatible and environmentally friendly alternatives. The goal of this study is to determine the optimal friction factor and frictional pressure drop using single-objective and multi-objective genetic algorithms. A total of 53 friction factor models/correlations have been reviewed from which eight were utilized to address discrepancies. Then, minimization of the frictional pressure drop by implementing single-objective genetic algorithm (SOGA) was carried out. In the multi-objective genetic algorithm (MOGA), the conflicting objectives of friction factor and pressure drop have been minimized simultaneously. Finally, the analysis was carried out on a small horizontal tube of 7.6 mm inner diameter utilizing experimental data for the refrigerant R-22 and the natural refrigerant R-290. It has been shown that the disagreements occur due to (i) the use of fluid data from different sources, (ii) utilization of different correlations on viscosity, and consequently on predicting the friction factor, and (iii) the applications of different friction factor correlations on predicting the frictional pressure drop. It has been proven that the Blasius friction factor correlation for turbulent flow in smooth pipe can be used by experimental researchers to determine their frictional pressure drop or/and matching of data and predicted values due to the coincidentally good agreement obtained. The optimal outcomes using MOGA are found to be closest to the experimental data. The percentage difference between the predicted and experimental frictional pressure drop is up to 1.93% and 0.25% when the Blasius friction factor equation is used with the McAdams and Dukler viscosity equations for R-22 and R-290 respectively.

ABSTRAK

Ramalan tepat tentang faktor geseran dan akibatnya penurunan tekanan dalam saluran kecil aliran dua fasa masih kurang dengan pencanggahan yang tinggi. Kebimbangan terhadap alam sekitar terus menjadi cabaran kepada industri penyejukan untuk mencari pengganti kepada bahan penyejuk yang mempunyai ciri-ciri haba dan hidrodinamik yang bersesuaian. Objektif kajian ini adalah untuk menentukan faktor geseran dan kejatuhan tekanan geseran optimum menggunakan algoritma genetik objektif tunggal dan berbilang objektif. Sejumlah 53 model/korelasi faktor geseran telah dikaji semula, lapan daripadanya digunakan untuk menganalisa pencanggahan. Seterusnya, pengurangan faktor geseran dan penurunan tekanan geseran menggunakan algoritma genetik objektif tunggal (SOGA) dilakukan. Dalam algoritma genetik berbilang objektif (MOGA), objektif yang bercanggah iaitu faktor geseran dan penurunan tekanan telah diminimumkan serentak. Analisis ini diakhiri dengan data eksperimen tiub mendatar kecil bergaris pusat 7.6 mm dengan penyejuk R-22 dan penyejuk semula jadi R-290. Analisis menunjukkan terdapat pencanggahan adalah disebabkan (i) penggunaan data bendalir daripada sumber yang berlainan, (ii) penggunaan korelasi kelikatan yang berbeza dan penggunaannya terhadap anggaran faktor geseran, dan (iii) penggunaan faktor geseran yang berbeza untuk mendapatkan penurunan tekanan geseran. Kajian membuktikan korelasi faktor geseran *Blasius* untuk aliran gelora dalam paip licin boleh digunakan untuk menyelidik eksperimen dalam menentukan penurunan tekanan geseran atau/dan padanan data dengan nilai ramalan berdasarkan keputusan baik yang diperolehi. Hasil pengoptimuman menggunakan algoritma genetik didapati hampir dengan data eksperimen. Peratusan perbezaan antara penurunan tekanan geseran yang diramalkan dan eksperimen adalah 1.93% dan 0.25% apabila persamaan faktor geseran *Blasius* digunakan dengan persamaan kelikatan *McAdams* dan *Dukler* untuk R-22 dan R-290 masing-masing.

TABLE OF CONTENTS

| CHAPTER | TITLE | PAGE |
|----------|---|----------|
| | DECLARATION | ii |
| | DEDICATION | iii |
| | ACKNOWLEDGMENTS | iv |
| | ABSTRACT | v |
| | ABSTRAK | vi |
| | TABLE OF CONTENTS | vii |
| | LIST OF TABLES | x |
| | LIST OF FIGURES | xiv |
| | LIST OF ABBREVIATIONS | xviii |
| | LIST OF SYMBOLS | xix |
| | LIST OF APPENDICES | xxii |
| 1 | INTRODUCTION | 1 |
| | 1.1 Introduction | 1 |
| | 1.2 Flow Patterns and Flow Pattern Maps | 2 |
| | 1.3 Pressure Drop in Two-Phase Flow | 3 |
| | 1.4 Background and Rational of the Research | 4 |
| | 1.5 Problem Statement | 5 |
| | 1.6 Research Objectives | 6 |
| | 1.7 Scope of the Research | 7 |

| | | |
|----------|--|-----------|
| 1.8 | Research Contributions | 8 |
| 1.9 | Research Systematic Stages | 9 |
| 1.10 | Research Significance | 12 |
| 1.11 | Thesis Organization | 13 |
| 2 | LITERATURE REVIEW | 14 |
| 2.1 | Introduction | 14 |
| 2.2 | Related Studies on Pressure Drop | 15 |
| 2.3 | Related Studies on Friction Factor | 26 |
| 2.3.1 | Laminar Flow Regime | 30 |
| 2.3.2 | Transition Flow Regime | 32 |
| 2.3.3 | Turbulent Flow Regime | 34 |
| 3.3.3.1 | Turbulent Flow in Smooth pipes | 34 |
| 3.3.3.2 | Turbulent Flow in Rough Pipes | 39 |
| 2.3.4 | Colebrook Equation Approximations | 41 |
| 2.3.5 | Void Fraction Correlations/Models | 57 |
| 2.4 | Genetic Algorithms and Pressure Drop | 72 |
| 2.5 | Summary of the Chapter | 81 |
| 3 | METHODOLOGY | 89 |
| 3.1 | Introduction | 89 |
| 3.2 | Refrigerants R-290 and R-22 | 91 |
| 3.3 | Experimental Approach | 92 |
| 3.3.1 | Data Reduction | 96 |
| 3.4 | Theoretical Approach | 98 |
| 3.4.1 | Mathematical Modeling | 99 |
| 3.4.2 | Parameters Affecting the Pressure Drop | 103 |

| | | |
|----------|---|------------|
| 3.5 | Genetic Algorithms | 109 |
| 3.5.1 | Genetic Algorithms Optimization | 111 |
| 3.5.2 | Optimization Procedure | 112 |
| 3.6 | Summary of the Chapter | 118 |
| 4 | RESULTS AND DISCUSSIONS | 120 |
| 4.1 | Introduction | 120 |
| 4.2 | Parametric Results | 120 |
| 4.2.1 | The Effect of Using Data from Different Sources | 121 |
| 4.2.2 | The Effect of Using Different Viscosity Equations | 123 |
| 4.2.3 | The Effect of Using Different Friction Factor Equations | 124 |
| 4.3 | Genetic Algorithm Analysis | 132 |
| 4.3.1 | Single-Objective Optimization (SOGA) | 133 |
| 4.3.2 | Multi-Objective Optimization (MOGA) | 157 |
| 4.3.2.1 | Analysis MOGA Results | 161 |
| 4.4 | Chapter Summary | 177 |
| 5 | CONCLUSIONS AND RECOMMENDATIONS | 179 |
| 5.1 | Introduction | 179 |
| 5.2 | Conclusions | 180 |
| 5.3 | Recommendations | 182 |
| | REFERENCES | 183 |
| | Appendices A – B | 204 –209 |

LIST OF TABLES

| TABLE NO. | TITLE | PAGE |
|------------------|---|-------------|
| 2.1 | The proposed equations for friction factor in laminar flow regime | 32 |
| 2.2 | The friction factor correlations for turbulent flow regime in smooth circular channels | 37 |
| 2.3 | The friction factor correlations and Colebrook`s equation approximations for turbulent flow in rough channels | 43 |
| 2.4 | The two-phase flow viscosity equations | 54 |
| 2.5 | The void fraction models/correlations | 60 |
| 2.6 | Summary of the investigation on two-phase boiling flow pressure drop in horizontal channel | 83 |
| 3.1 | Thermal physical properties and environmental and safety characteristics of R-22 and R-290 (Linde Gases AG) | 91 |
| 3.2 | Experimental conditions of measuring two-phase flow frictional pressure drop | 96 |
| 3.3 | Selected friction factor equations in present research | 101 |
| 3.4 | Physical properties of the refrigerants R-22 and R-290 used in present research at inlet saturation temperature of 10°C | 102 |
| 3.5 | Selected parameters in optimization tool box of MATLAB (2016a) | 112 |
| 3.6 | Parameters setup in optimization Toolbox of MOGA in MATLAB (2016a) | 115 |
| 3.7 | Upper and lower limits of the mass flux for refrigerants R-22 and R-290 | 116 |

| | | |
|-----|---|-----|
| 4.1 | The percentage of difference in viscosity values using different viscosity equations and data of the refrigerants R-22 and R-290 from different sources | 121 |
| 4.2 | The percentage of difference in viscosity values of refrigerants R-22 and R-290 when using different viscosity equations and data from different sources | 124 |
| 4.3 | The percentage of difference between the friction factor values determined using different friction factor and viscosity equations with experimental data of the refrigerants R-22 and R-290 and calculated experimental friction factor | 125 |
| 4.4 | The percentage of difference between the calculated experimental frictional pressure drop and frictional pressure drop determined using different friction factor and viscosity equations with experimental data of R-22 and R-290 | 127 |
| 4.5 | The percentage of difference between the two-phase flow viscosity, friction factor, and frictional pressure drop values using Blasius equation for estimating friction factor with different viscosity equations and experimental data of the refrigerants R-22 and R-290 | 129 |
| 4.6 | The percentage of difference between the two-phase frictional pressure drop values using different friction factor equations with the McAdams viscosity equation and experimental data of the refrigerants R-22 and R-290 | 130 |
| 4.7 | The percentage of difference between the optimal values of the friction factor using different friction factor and viscosity equations as well as data of the refrigerant R-22 from different sources utilizing SOGA optimization method | 135 |

| | | |
|------|--|-----|
| 4.8 | The percentage of difference between the optimal values of the friction factor using different friction factor and viscosity equations as well as data of the refrigerant R-290 from different sources utilizing SOGA optimization method | 137 |
| 4.9 | The percentage of difference between the optimal values of the friction factor using data of the refrigerant R-22 from different sources and different friction factor and viscosity equations utilizing SOGA optimization method | 140 |
| 4.10 | The percentage of difference between the optimal values of the friction factor using data of the refrigerant R-290 from different sources and different friction factor and viscosity equations utilizing SOGA optimization method | 142 |
| 4.11 | The percentage of difference between the optimal values of the friction factor using different friction factor and viscosity equations with data of the refrigerant R-22 from different sources utilizing SOGA optimization method, and calculated experimental friction factor | 145 |
| 4.12 | The percentage of difference between the optimal values of the friction factor using different friction factor and viscosity equations with data of the refrigerant R-290 from different sources utilizing SOGA optimization method, and calculated experimental friction factor | 148 |
| 4.13 | The minimum values of the frictional pressure drop in [Pa] using different friction factor and viscosity equations as well as data of the refrigerant R-22 from different sources utilizing SOGA optimization method | 152 |
| 4.14 | The minimum values of the frictional pressure drop in [Pa] using different friction factor and viscosity equations as well as data of the refrigerant R-290 from different sources utilizing SOGA optimization method | 153 |

- 4.15 The optimized values of the variables at which the optimal minimum values of the friction factor and frictional pressure drop obtained using different friction factor and viscosity equations with experimental data of the refrigerants R-22 and R-290 and utilizing SOGA optimization method 154
- 4.16 The optimized values of the variables at which the optimal values of the friction factor and frictional pressure drop obtained using different friction factor and viscosity equations with experimental data of the refrigerants R-22 and R-290 utilizing MOGA optimization method 170
- 4.17 The results of the comparisons between the selected optimal values of the friction factor and frictional pressure drop using different friction factor and viscosity equations with experimental data of the refrigerants R-22 and R-290 utilizing MOGA optimization method and calculated friction factor and frictional pressure drop 173

LIST OF FIGURES

| FIGURE NO. | TITLE | PAGE |
|------------|--|------|
| 1.1 | Methodical stages of the study | 11 |
| 2.1 | Graphical representation of the Lockhart and Martinelli (1949) correlation | 16 |
| 3.1 | Schematic diagram of the closed loop in test rig | 93 |
| 3.2 | photograph of the test rig | 94 |
| 3.3 | The effect of mass flux on two-phase flow Pressure drop of the refrigerant R22 for different values of vapor quality | 103 |
| 3.4 | The effect of vapor quality on two-phase flow pressure drop of the refrigerant R-22 for different values of mass flux | 104 |
| 3.5 | The effect of inner diameter on two-phase flow pressure drop of the refrigerant R-22 for different values of mass flux | 105 |
| 3.6 | The effect of heat flux and saturation temperature on two-phase flow pressure drop of the refrigerant R-290 at mass flux of $150 \text{ kg/m}^2\text{s}$ inside tube of 3 mm inner diameter | 106 |
| 3.7 | The effect of the relative roughness Rr of the channel inner surface on (a) friction factor and (b) two-phase flow frictional pressure drop of the refrigerant R-22 inside pipe of 7.6 mm inner diameter at mass flux of $615.48 \text{ kg/m}^2\text{s}$ for different values of vapor quality using Fang <i>et al.</i> (2011) equation for friction factor in | |

| | | |
|-----|---|-----|
| | rough pipe with McAdams viscosity equation and experimental data | 108 |
| 3.8 | The procedure of the GA optimization process | 113 |
| 3.9 | Steps of performing the search | 117 |
| 4.1 | The two-phase flow viscosity values of the refrigerants R-22 from different data sources and different viscosity equations | 122 |
| 4.2 | The two-phase flow viscosity values of the refrigerants R-290 from different data sources and different viscosity equations | 122 |
| 4.3 | The two-phase flow frictional pressure drops values using different friction factor equations and McAdams viscosity equation with experimental data of the refrigerant R-22 | 128 |
| 4.4 | The two-phase flow frictional pressure drops values using different friction factor equations and McAdams viscosity equation with experimental data of the refrigerant R-290 | 128 |
| 4.5 | The two-phase flow frictional pressure drop values using different friction factor equations with the McAdams viscosity equation and experimental data of the refrigerants R-22 and R-290 | 131 |
| 4.6 | The best and mean values of the friction factor and frictional pressure drop of the refrigerant R-22 using Fang <i>et al.</i> (2011) friction factor equation in rough tube with (a) McAdams viscosity equations; (b) Cicchitti viscosity equations; and (c) Dukler viscosity equations | 134 |
| 4.7 | Pareto optimal points of solutions using different friction factor equations with McAdams <i>et al.</i> (1942) viscosity equation and experimental data of the refrigerants R-22 and R-290 | 158 |

| | | |
|------|--|-----|
| 4.8 | Pareto optimal points of solutions using different friction factor equations with Cicchitti <i>et al.</i> (1960) viscosity equation and experimental data of the refrigerants R-22 and R-290 | 159 |
| 4.9 | Pareto optimal points of solutions using different friction factor equations with Dukler <i>et al.</i> (1964) viscosity equation and experimental data of the refrigerants R-22 and R-290 | 160 |
| 4.10 | Pareto optimal points of solutions using Hagen-Poiseuille friction factor equation with different viscosity equations and experimental data of the refrigerants R-22 and R-290 | 162 |
| 4.11 | Pareto optimal points of solutions from Blasius friction factor equation with different viscosity equations and experimental data of the refrigerants R-22 and R-290 | 163 |
| 4.12 | Pareto optimal points of solutions from Fang <i>et al.</i> (smooth) friction factor equation with different viscosity equations and experimental data of the refrigerants R-22 and R-290 | 164 |
| 4.13 | Pareto optimal points of solutions from Colebrook friction factor equation with different viscosity equations and experimental data of the refrigerants R-22 and R-290 | 165 |
| 4.14 | Pareto optimal points of solutions from Swamee-Jain friction factor equation with different viscosity equations and experimental data of the refrigerants R-22 and R-290 | 166 |
| 4.15 | Pareto optimal points of solutions from Haaland friction factor equation with different viscosity equations and experimental data of the refrigerants R-22 and R-290 | 167 |

- 4.16 Pareto optimal points of solutions from Serghides friction factor equation with different viscosity equations and experimental data of the refrigerants R-22 and R-290 168
- 4.17 Pareto optimal points of solutions from Fang *et al.* (2011) (rough) friction factor equation with different viscosity equations and experimental data of the refrigerants R-22 and R-290 169

LIST OF ABBREVIATIONS

| | | |
|-----------|---|---|
| ADM | - | Adomian Decomposition Method |
| AGC | - | Automatic Generation Control |
| ANN | - | Artificial neural network |
| CFCs | - | Chlorofluorocarbons |
| CFD | - | Computational fluid dynamics |
| Ci | - | Cicchitti |
| CW | - | Colebrook-White equation |
| Du | - | Dukler |
| EA | - | Evolutionary Algorithm |
| GA | - | Genetic Algorithm |
| GWP | - | Global Warming Potential |
| HFCs | - | Hydrofluorocarbons |
| Mc | - | McAdams |
| MOGA | - | Multi-objective optimization Genetic Algorithm |
| NSGA-II | - | Non-Dominated Sorting Genetic Algorithm |
| NTU | - | Number of Heat Transfer Units |
| ODP | - | Ozone Depleting Potential |
| <i>PD</i> | - | Percentage of Difference |
| RADM | - | Restarted Adomian Decomposition Method |
| SOGA | - | single-objective optimization Genetic Algorithm |
| UI | - | Universitas Indonesia |

LIST OF SYMBOLS

| | | |
|------------------------|---|---|
| A, B, C, K, K_1, K_2 | - | Constants |
| D | - | Internal diameter, [m] |
| D_h | - | Hydraulic diameter, [m] |
| f | - | Fanning friction factor |
| f_D | - | Darcy friction factor |
| $f_{D,exp}$ | - | Experimental Darcy friction factor |
| g | - | Gravitational acceleration, [m/s ²] |
| G_{tp} | - | Two-phase flow mixture mass flux, [kg/m ² s] |
| He | - | Hedstrom number |
| h_f | - | Head loss, [m] |
| i | - | Two-phase flow mixture specific enthalpy, [J/kg] |
| i_l | - | Enthalpy of saturated fluid [J/kg], |
| $i_{l,i}$ | - | Enthalpy at the inlet temperature, [J/kg] |
| i_{lg} | - | Latent heat of vaporization [J/kg] |
| L | - | Length, [m], |
| \dot{m} | - | Mass flow rate, [kg/s] |
| q | - | Heat flux, [W/m ²] |
| Re | - | Reynolds number |
| Re_{mod} | - | Modified Reynolds number |

| | | |
|--------------------|---|--|
| Rr | - | Relative roughness |
| S | - | Slip ratio |
| v | - | Average flow velocity, [m/s] |
| v_{gj} | - | Drift velocity, [m/s] |
| v_l | - | Liquid-phase velocity, [m/s] |
| v_g | - | Gas-phase velocity, [m/s] |
| W | - | Electric power, [W] |
| X | - | Martinelli parameter |
| x | - | Vapor quality |
| x_o | - | Outlet vapor quality |
| Z_{sc} | - | Subcooled length, [m] |
| ΔP | - | Pressure drop [Pa] |
| ΔP_f | - | Frictional pressure drop [Pa] |
| $\Delta P_{f,exp}$ | - | Experimental frictional pressure drop [Pa] |

Greek symbols

| | | |
|-----------------|---|---|
| α_l | - | Liquid-phase void fraction |
| α_g | - | Gas-phase void fraction |
| α_{tp} | - | Two-phase flow mixture void fraction |
| $\alpha_{tp,H}$ | - | Homogeneous two-phase flow mixture void fraction |
| ε | - | Absolute roughness, [mm] |
| λ | - | Friction coefficient |
| μ_l | - | Liquid-phase viscosity, [$\mu\text{Pa}\cdot\text{s}$] |
| μ_g | - | Gas-phase viscosity, [$\mu\text{Pa}\cdot\text{s}$] |

| | | |
|-------------|---|--|
| μ_{tp} | - | Two-phase flow mixture viscosity, [Pa.s] |
| ρ_l | - | Liquid-phase density, [kg/m ³] |
| ρ_g | - | Gas-phase density, [kg/m ³] |
| ρ_{tp} | - | Two-phase flow mixture density, [kg/m ³] |

Subscripts

| | | |
|------|---|-----------------------------------|
| f | - | Friction |
| g | - | Gas-phase |
| l | - | Liquid-phase |
| t | - | turbulent |
| tt | - | Turbulent – turbulent flow regime |
| tv | - | Turbulent – viscous flow regime |
| v | - | Viscous (laminar) |
| vt | - | Viscous – turbulent flow regime |
| vv | - | Viscous – viscous flow regime |

LIST OF APPENDICES

| APPENDIX | TITLE | PAGE |
|-----------------|----------------------------|-------------|
| A | Optimization program codes | 204 |
| B | List of publications | 209 |

CHAPTER 1

INTRODUCTION

1.1 Introduction

Two-phase flow phenomenon has gotten increased interest in recent years, attracting researchers to conduct more studies due to their higher heat transfer coefficient in comparison with single-phase flow (Jacopo, 2010). In general, the rate of the heat transfer rate during phase change can be higher than four to twenty-five times compared to the single-phase equivalent convection (Incropera *et al.*, 2007). Contrasted with the flow inside traditional channels, the flow of the refrigerants during boiling in smaller channels has distinct characteristics as a result of the chemical and physical properties of the refrigerants and the measurements of the channels. Therefore, the accuracy of the pressure drop prediction is of a great importance and occupies the forefront place in design and improvement of the systems for its close association with the power required to drive fluid inside channels.

The 1950s were marked by the fact that air conditioners were available to almost every family, especially in developed countries. The makers of these gadgets supplanted poisonous refrigerant gasses with manufactured refrigerants called chlorofluorocarbons (CFCs). The 1970s were marked by the terrible discovery that CFCs, used in refrigeration units as well as various devices, were one of the factors leading to the depletion of the ozone layer responsible for reducing the harmful effects of solar radiation. The Montreal Protocol signed by most countries in 1987, a global agreement, attempts to replace the Chlorofluorocarbons (CFCs) products with other products such as Hydrofluorocarbons (HFCs) like R-410A and R-134a

(Mironov, 1968), that are environmentally friendly, natural, and have low or zero ozone depleting potential (ODP) and global warming potential (GWP). Currently, there are still inadequate studies on environmentally friendly natural refrigerants in small channels available in the literature. Preliminary results from these studies provided viable options but there is insufficient data on the properties of these refrigerants, especially with regard to heat transfer and pressure drop.

Appearance and disappearance of the phases during the two-phase flow makes the analysis of the flow systems very complex because of the characteristics of the intermittent fluids at the phase boundary, as well as the relative movement of the phases, mass and energy and the transfer of momentum between phases. Besides, void distribution in a two-phase channel has special importance. The flow patterns get more complex in small channels due to the increased frictional losses between the fluid layers as well as between the fluid and channel walls.

The advantages that can be found using small channels is the high heat transfer coefficient due to the high ratio between heat transfer surface and fluid flow volume. Also, their small size makes the need for less material and reduces the weight, fluid stock, installation costs and power reserve. However, despite these advantages, they are also characterized by an increase in wall friction which leads to increased pressure drop. Therefore, there is a need to understand the basic aspects of flow in two phases with regard to pressure reduction and heat transfer for accurate prediction leading to better design of compact heat exchangers and greater efficiency in industrial processes.

1.2 Flow Patterns and Flow Pattern Maps

The flow pattern in two-phase flow can be influenced by various parameters such as density and viscosity of the gas and liquid phases, surface tension, mass flow rate of each phase, and geometrical measurements of the flow channel. In addition, competition between forces such as inertia force, viscosity force, gravitational force, and surface tension force controls the order of specific flow patterns in the channel. It is, therefore, a necessary to predict these flow regimes as the basis for performing

arithmetic operations on two-phase flow. The usual procedure is to draw data in the form of a flow pattern map.

Thus, flow pattern maps can be defined as an operation of separating space into areas on a two-dimensional graph corresponding to the different flow patterns. They are a construct of two coordinates, where the liquid superficial velocity is plotted against the gas superficial velocity. The boundaries between the flow patterns are plotted by lines. Using these maps for predicting the local flow regime in both horizontal and vertical pipes are very useful. Additionally, most of the flow pattern maps have been developed for adiabatic two-phase flows, which may not yield reliable results when used in the case of diabatic.

1.3 Pressure Drop in Two-Phase Flow

The pressure drop is defined as the difference in pressure between two interesting points in the flow system. Total pressure drop usually occurs owing to friction because of the viscosity of the liquid and gas in motion. Where in the case of the laminar flow pressure loss occurs as a result of the momentum transfer between the particles, while in the turbulent flow occurs when the individual particles move at different velocities between the adjacent fluid layers. In addition, pressure losses also can be caused by the local pressure loss due to sudden changes in flow area, shape, and flow direction; and pressure losses due to acceleration, caused by changes in elevation (gravity effect), flow area or by changes in the fluid density.

In view of the design and operational issues caused due to the simultaneous flow of liquid and vapor and forming various two-phase flow patterns, makes the calculation of the pressure drop in these conditions a crucial in order to assist the piping designer to succeed in achieving the optimal line size and better design of the piping system. Most of the studies on pressure drop proved that the frictional component was dominant and the contribution of the accelerational and gravitational component is small (Saitoh *et al.*, 2005). Frictional pressure drop commonly comes from the friction between the flowing fluid and pipe wall. In two-phase flows, there

is an additional frictional pressure loss comes from the interphase friction between phases.

In general, calculation of the frictional pressure drop requires knowing either the two-phase friction factor or the two-phase frictional multiplier. Where, calculating friction factors can be done using implicit Colebrook equation which requires iterative procedure, an inconvenience and needs time for computation. Therefore, many explicit equations were developed to rid of the iterations. The main disadvantage of these explicit approximations is the relatively high percentage of error compared to the solution to the implicit Colebrook equation (Brkić, 2012).

In the past, five methods have been utilized in solving the Colebrook equation (Colebrook, 1939): (i) graphical method by finding the solution from the Rouse or Moody diagrams (Rouse, 1943; Moody and Princeton, 1944), (ii) implementing iterative process by using spreadsheet solvers, which gives accurate solutions to the Colebrook equation but requires long time (Excel is most suitable tool), (iii) using developed explicit equations of the Colebrook equation which requires less calculation but have higher error percentage (Genić *et al.*, 2011), (iv) make use of the Lambert W function to avoid the iterative calculations with less percentage error (Boyd, 1998; Barry *et al.*, 2000), and (v) applying trial – and – error method which is no longer used.

Today, Colebrook equations can be solved easily and accurately using the Newton-Raphson iterative procedure and common software tools such as Microsoft Excel and MATLAB.

1.4 Background and Rational of the Research

At present, the need for small channels in a variety of compact applications is widespread. Unfortunately, published reports indicate the significant increment in pressure drop to the detriment of heat transfer coefficient increment. Consequently,

there is a requirement for a dependable model with a high degree of accuracy for predicting two-phase flow frictional pressure drop in small channels.

To date, researchers have modified available correlations on pressure drop developed based on conventional systems. Meanwhile, other researchers have invested much time and funds in developing new correlations in search of better agreements across refrigerants, channel diameter, and flow regimes. The issue remains with the many different predicted friction factor correlations used in the determination of the frictional pressure drop. Besides, the different approaches in modelling the flow (homogeneous or separated) introduced further variations in the outcomes. Global concerns for natural and more environmentally friendly refrigerants in practical applications have added a new challenge to the study and investigation of the two-phase flow in small channels.

Experimental studies that have been conducted on boiling heat transfer and pressure drop of refrigerants during two-phase flow in small channels are few in comparison with those in conventional channels. Even less is the focus on optimized conditions for minimal pressure drop. The difficulty of effectively dealing with turbulent flow issues in pipes originates from the truth that friction factor is an intricate function of roughness and Reynolds number. With various correlations/models applicable and performance on alternative refrigerants, there is a need for a study and analyze available correlations/models proposed or modified (many) to identify and address causes of discrepancies. Optimized conditions such as inlet temperature, mass flux, heat flux, and vapor quality in small channels whereby the frictional pressure drop is minimized have to be investigated, with comparisons of the performance between current and environmentally friendly refrigerants as potential alternatives.

1.5 Problem Statement

Two-phase flow pressure drop is a major parameter in designing two-phase flow systems and takes precedence over any other consideration. Past empirical

correlations come with various degrees of disagreements with experimental data, up to and above 100% (Xu and Fang, 2012; Xu *et al.*, 2012; Xu and Fang, 2013). The use of data from different sources and various equations in calculating the viscosity value had a clear effect on the viscosity value estimation. This effect is clearly shown in the calculation of the value of the number of Reynolds, which is a critical element in estimating the friction factor. In addition, the use of various equations for calculation of the friction factor has had a considerable effect on the accuracy of the predicted value of the friction factor and consequently on predicting frictional pressure drop.

In addition, the enormous ecological harm that has happened because of the utilization of halogens pushed the researchers to look for and examine natural refrigerants as replacements to the current used. Thus, in this study the propane (R-290) has been examined simultaneously with HCFC (R-22) as an alternative natural environmentally friendly refrigerant.

Current research investigated the effect of using data from various sources and various viscosity and friction factor equations on estimating viscosity and friction factor values. As well as, this research inspects the effect of the predicted viscosity and friction factor values on predicting frictional pressure drop. Examination has been performed utilizing the genetic algorithm (GA) as a convenient optimization method. The optimal outcomes were compared with experimental data collected from the experiments conducted at the Universitas Indonesia.

1.6 Research Objectives

The objectives of this study are:

- i. Perform a critical review of the available implicit and explicit equations for a wide range of Reynolds numbers and relative pipe roughness to establish the accuracy.

- ii. Examine the natural environmentally friendly refrigerant R-290 parametrically and under optimized conditions as an alternative refrigerant to the refrigerant R-22 using Genetic Algorithm Optimization.
- iii. Show the effects of using data from various sources on estimating the viscosity value and thus on evaluating the friction factor value.
- iv. Illustrate the effects of using the different equations on the viscosity value estimate and the effect of this on the value estimation of the friction factor.
- v. Demonstrate the effect of using various correlations on estimating the friction factor value and its impact on the accuracy of the prediction of the frictional pressure drop in two-phase flow.
- vi. Evaluate the magnitude of all the above-mentioned effects by comparing the results obtained with experimental data to increase the accuracy of the analysis.

1.7 Scopes of the Research

Theoretical and experimental approaches were involved in this research. The research focuses on study and evaluation of the effect of using data from different sources and different equations in calculating the value of viscosity on which the Reynolds is dependent on. The Reynolds number is a key element in the calculation of the friction factor which is a critical factor in the evaluation of the frictional pressure drop. In addition, examination of the effect of using various viscosity equations as well as various equations on estimating the friction factor is completed. Consequently, the impact of all these effects on predicting the frictional pressure drop is analyzed. Some of the most commonly used equations were selected to assess the magnitude of all these effects.

An examination of a natural and environmentally friendly refrigerant as a replacement to the currently used refrigerants was accomplished. Genetic algorithm

has been utilized as an effective and convenient optimization method with the aim to identify the source of inconsistency between the predicted frictional pressure drop and experimental results previously reported from a large number of researchers. Comparison of the numerical and optimal outcomes of the measured pressure drop and calculated experimental friction factor from the experiment conducted for this purpose, has made it possible to assess the selected viscosity and friction factor correlations and their effect on the accuracy of the predicted frictional pressure drop. Thus, utilizing these correlations and applying the homogeneous flow model, pressure drop can be more effectively predicted in the design of compact two-phase flow systems.

1.8 Research Contributions

- i. A critical review of the implicit and explicit friction factor correlations due to the large number of them that can be found in literature to determine which of them gives results consistent with the experimental results and with high accuracy.
- ii. At the same manner, a critical review of the two-phase flow void fraction and viscosity models/correlations that can be found in literature to determine which of them gives results compatible with the experimental results and with high accuracy when substitute in correlation of friction factors.
- iii. Demonstrate the effect of using data from various sources and various viscosity correlations on calculating viscosity and friction factor and corresponding on prediction of the frictional pressure drop. Where, the experimental data from published paper of Pamitran *et al.* (2010), experimental data from Universitas Indonesia (UI), and available data from the National Institute of Standards and Technology (NIST) chemistry webbook (Eric *et al.*, 2013) were used.

- iv. Examining natural environmentally friendly refrigerant as an alternative to the one currently in use in order to follow the instructions of the Montreal Conference for the Protection of the Environment.
- v. Utilizing genetic algorithm (GA) optimization tools as a convenient optimization method which has not been applied before in the field of the two-phase flow in small channels, to examine the effects mentioned in (iii) in order to reduce the large inconsistency with the experimental results already reported from a large number of researchers to less than what can be.

1.9 Research Systematic Stages

The major steps of this research can be briefed in the following:

- i. Critical review on the studies and research available in literature related to the pressure drop prediction methods and correlations in small channels.
- ii. Critical review on the studies and research available in literature related to the void fraction and viscosity models/correlations.
- iii. Critical review on the studies and research available in literature related to the friction factor implicit and explicit correlations for a wide range of Reynolds numbers and relative pipe roughness to establish the accuracy.
- iv. Critical review on the studies and research available in literature related to the pressure drop optimization methods that apply Genetic algorithms.
- v. Describing and analyzing the behavior and performance of the two-phase system in small channels through applying homogeneous flow models in laminar and turbulent flow regimes methodically and parametrically.

- vi. Applying genetic algorithm optimization based on the homogeneous flow model for optimization the objective functions which are minimum friction factor and minimum frictional pressure drop in small channel of 7.6 mm inner diameter.
- vii. Conducting experiments on two-phase flow pressure drop of the refrigerant R-22 and R-290 which significantly added to the available data of pressure drop measurements taken in a horizontal pipe of 7.6 mm inner diameter and length of 1070 mm for two-phase flow.
- viii. Analyze and compare the numerical results with experimental data to demonstrate the effect of use different friction factor and viscosity correlations/models as well as data from different sources on prediction of the two-phase flow frictional pressure drop.
- ix. Examining the refrigerant R-290 as an alternative natural environmentally friendly refrigerant simultaneously with refrigerant R-22 in laminar and turbulent flow regimes, parametrically and under optimized conditions.

The steps of this research are shown in Figure 1.1.

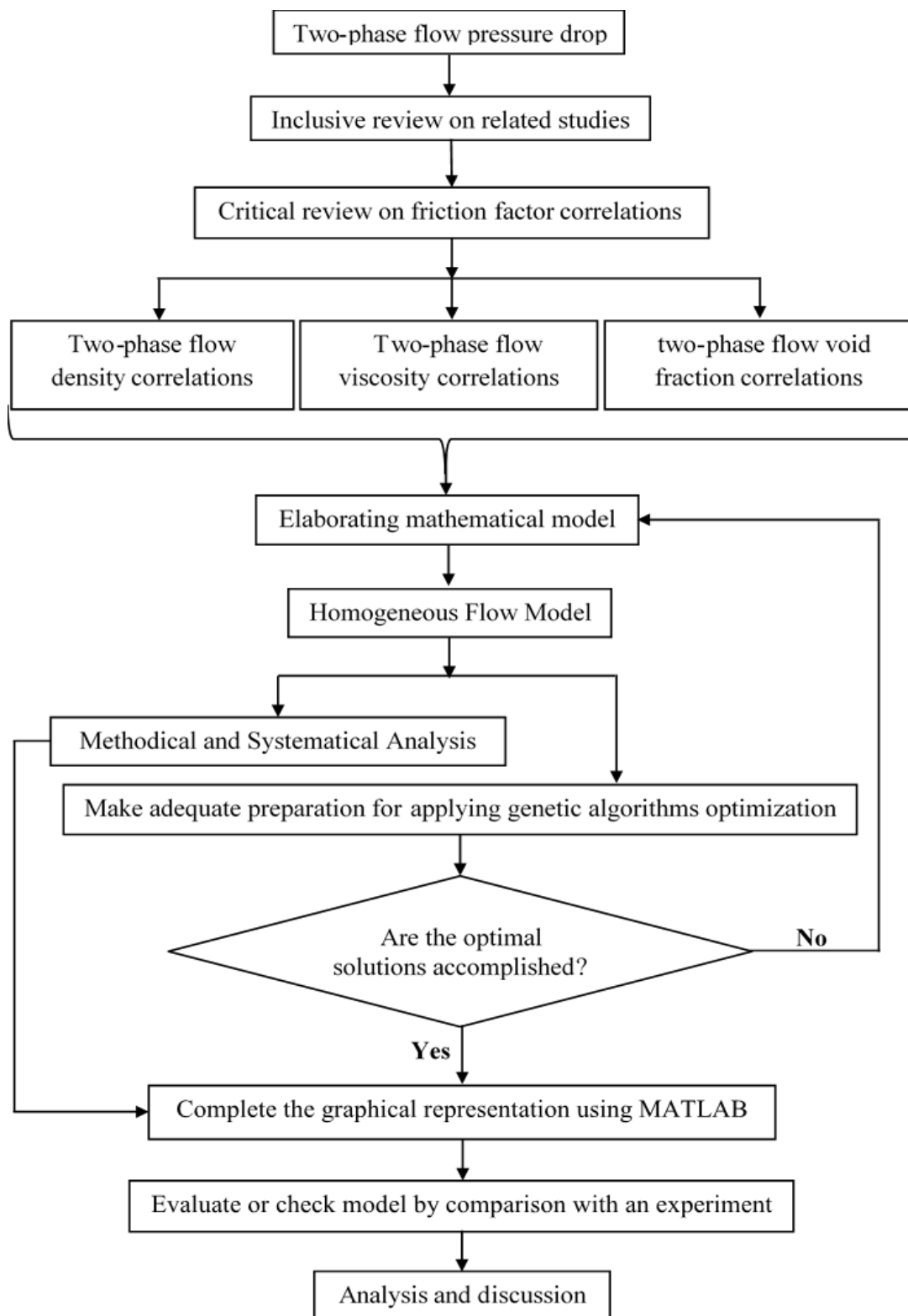


Figure 1.1 Methodical stages of the current study

1.10 Research Significance

The importance of the research lies in the critical review of the huge number of the void fraction, viscosity, and friction factor correlations available in the literature used for laminar and turbulent flow regimes. In addition to that, the effect of using data from different sources on the viscosity value, the effect of using different viscosity equations in calculating the viscosity value and the subsequent effect on the predicted friction factor has been demonstrated. Furthermore, genetic algorithm optimization tool to optimize the friction factor and frictional pressure drop in a small channel that has not been used previously has been utilized. Thus, the research significance can be summarized in the following points:

- i. This research is an effort to comprehend the effect of the frictional pressure drop on two-phase flow boiling in small channels including experiments and applying of different friction factor and viscosity equations.
- ii. Demonstrate the effect of using data from various sources in evaluating friction pressure drop and correspondingly on predicting pressure drop.
- iii. The critical review discovered some correlations that have not been mentioned before, in addition to the presence of some of the misconceptions about the original developers of these correlations.
- iv. Applying genetic algorithms optimization gave a methodical optimization program with less limiting conditions, and can be used by the designers without difficulty or effort.
- v. Examination of a natural environmentally friendly refrigerant as a replacement to the currently HCFC used in order to protect the environment, preserve the ozone layer and avoid global warming.

1.11 Thesis Organization

The manuscript is arranged in a systematic way as follows:

Chapter 1 – Introduction: Presents a brief description of two-phase flow and pressure drop issues in small channels and the background of the problem. In addition, offers the objectives, scopes, as well the significance of this study.

Chapter 2 – Review of the Literature: Provides a critical review of the related studies on the two-phase viscosity, void fraction, friction factor, and frictional pressure drop. The review includes correlations, geometries, refrigerants, materials as well the employed genetic algorithms optimization techniques.

Chapter 3 – Methodology: Displays the viscosity and friction factor correlations applied in the study. Offers parametric and genetic algorithms optimization analysis with the assumption of liquid-gas flow into pipes. Homogeneous flow model has been applied using the selected correlations. Genetic Algorithm Optimization and the procedures of implementation of the single and multi-objective genetic algorithms optimization in the present study were discussed and explained.

Chapter 4 – Results and Discussions: displays the outcomes of the parametric analysis and optimization operations, comparisons between the outcomes themselves, and comparisons with experimental data. All outcomes of the comparisons were discussed and explained.

Chapter 5 – Conclusions and Recommendations: Gives the conclusion depending on the analysis and discussion of the comparisons outcomes as well proposes the recommendations.

REFERENCES

- Abdel-Magid, Y. L. and Dawoud, M. M. (1995). Tuning of AGC of Interconnected Reheat Thermal Systems with Genetic Algorithms. *Proceedings of IEEE International Conference on Systems, Man, and Cybernetics* 3: 2622 – 2627.
- Abdullah, K., David W. C. and Alice E. S. (2006). Multi-Objective Optimization Using Genetic Algorithms: A Tutorial. *Journal of Reliability Engineering and System Safety* 91: 992 – 1007.
- Abdulmagid, A. K., Ahmed, A. H, and Mofied M. E. (2015). The Relation Between the Coefficient of Friction and Pressure Drop by Using the Different Reynolds Number in a Circular Tube. *Open Journal of Fluid Dynamics* 5: 99 – 105.
- Akagawa, K., Sekoguchi, K. Sakaguchi, T. and Kobayashi, S. (1969). *Transactions of the Japan Society of Mechanical Engineering* 35 (276): 1714 – 1722.
- Ali, R., Palm, B. and Maqbool, M.H. (2011). Experimental Investigation of Two-Phase Pressure Drop in a Microchannel. *Heat Transfer Engineering* 32 (13 – 14): 1126 – 1138.
- Allred, L. G. and Kelly, G. E. (1992). Modified Genetic Algorithm for Extracting Thermal Profiles From Infrared Image Data. *SPIE Proceedings*, Vol. 1766, Neural and Stochastic Methods in Image and Signal Processing, 77 (December 16, 1992).
- Altshul, A. D. (1952). Generalized Formula of Resistance in Pipelines. *Hydraulic construction* 6.
- Androulakis, I. P. and Venkatasubramanian, V. (1991). A Genetic Algorithmic Framework for Process Design and Optimization. *Computers and Chemical Engineering* 15(4): 217 – 228.
- Arora, J. S. (2004). *Introduction to Optimum Design*, Second Edition, Elsevier Academic Press, San Diego.
- ASHRAE. (1993). Handbook: *Fundamentals*. American Society of Heating, Refrigerating and Air-conditioning Engineers, Atlanta.

- ASHRAE 15-2016 (packaged w/ 34-2016). Standard 15-2016 (packaged w/ Standard 34-2016) -- Safety Standard for Refrigeration Systems and Designation and Classification of Refrigerants (ANSI Approved).
- Autee, A. T., Rao, S. S., Ravikumar, P. and Shrivastava, R. K. (2012). Two-Phase Pressure Drop Calculations in Small Diameter Inclined Tubes. *International Journal of Engineering and Technology* 1 (3): 168 – 181.
- Awad, M. M. and Muzychka, Y. S. (2007). Bounds on Two-Phase Frictional Pressure Gradient in Mini-channels and Micro-channels. *Heat Transfer Engineering* 28 (8-9): 720 – 729.
- Awad, M. M. and Muzychka, Y. S. (2010). Two-Phase Flow Modeling in Microchannels and Minichannels. *Heat Transfer Engineering* 31(13):1023 – 1033.
- Azzopardi, B. J. and Hills, J. H. (2003). One-Dimensional Models for Pressure Drop, Empirical Equations for Void Fraction and Frictional Pressure Drop and Pressure Drop and other Effects in Fittings. In: V. Bertola (Ed.), *Modelling and Experimentation in Two-phase Flow*, New York, 157 – 220.
- Bäck, T., Hammel, U. and Schwefel, H. P. (1997). Evolutionary Computation: Comments on the History and Current State. *IEEE Transactions on Evolutionary Computation* 1: 3 – 17.
- Bagley, J. D. (1967). *The Behavior of Adaptive Systems Which Employ Genetic and Correlation Algorithms*. Ph.D. thesis, University of Michigan, Ann Arbor.
- Baker, J. E. (1987). Reducing Bias and Inefficiency in the Selection Algorithm. In: Genetic Algorithms and Their Applications: *Proc. 2nd Int. Conf. Genetic Algorithms*, 14 – 21.
- Baroczy, C.J. (1966). A Systematic Correlation for Two-Phase Pressure Drop. *Chemical Engineering Progress* 62(64): 232 – 249.
- Barr, D. I. H. (1975). New Forms of Equation for the Correlation of Resistance Data. *Proceedings of the Institution of Civil Engineers* 59 (2): 827 – 835.
- Barry, D. A., Parlange, J. Y., Li, L., Prommer, H., Cunningham, C. J. and Stagnitti, F. (2000). Analytical Approximations for Real Values of the Lambert W-Function. *Mathematics and Computers in Simulation* 53(1–2): 95 – 103.
- Batchelor, G. (2000). *Introduction to Fluid Mechanics*. Published by the Press Syndicate of the University of Cambridge, Cambridge, United Kingdom.

- Bazin, H. (1902). Experiences nouvelles sur la distribution des vitesses dans les tuyaux (Experiences News on the Velocity Distribution in Pipes). *Memoires a l'Academie d. Sciences de l'Institute de France* 32 (6) (in French).
- Bergles, A. E. and Dormer, T. J. (1969). Subcooled Boiling Pressure Drop with Water at Low Pressure. *International Journal of Heat Mass Transfer* 12: 459 – 470.
- Bhave, P. R. (1991). Analysis of Flow in Water Distribution Networks. *Technomic Publication Company, Inc., USA*.
- Blasius, H. (1913). Das Aehnlichkeitsgesetz bei Reibungsvorgängen in Flüssigkeiten. *Mitteilungen über Forschungsarbeiten auf dem Gebiete des Ingenieurwesens* 131: 1 – 39, (In German). English. Translation (The Law of Similarity in Friction Processes in Liquid operations). *communications research in the fields of engineering* 131: 1 – 39.
- Bonne, U., Patani, A., Jacobson, R. D. and Mueller, D. A. (1980). Electric-Driven Heat Pump Systems: Simulations and Controls II. *ASHRAE Transactions* 86, Part I.
- Bradshaw, P. (2000). A Note on 'Critical Roughness Height' and 'Transitional Roughness'. *Physics of Fluids* 12(6): 1611 – 1614.
- Brkić, D. (2011). Review of Explicit Approximations to the Colebrook Relation for Flow Friction. *Journal of Petroleum Science and Engineering*, 77(1): 34 – 48.
- Brkić, D. (2012). Comparison of the Lambert W-function Based Solutions to the Colebrook Equation. *Engineering Computations* 29 (6): 617 – 630.
- Brown, G. O. (2002). The History of the Darcy-Weisbsch Equation for Pipe Flow Resistance. *Environmental and Water Resources History* 38 (7): 34 – 43.
- Brownlie, W. R. (1981). Reexamination of Nikuradse Roughness Data. *Journal of Hydraulics Engineering-American Society of Civil Engineers ASCE* 107(1): 115 – 119.
- Buckingham, E. (1921). On Plastic Flow Through Capillary Tubes. *ASTM Proceeding* 21: 1154 –1161.
- Cantú-Paz, E. (2001). Are Multiple Runs Better Than One?. *Genetic and Evolutionary Computation Conference*, San Francisco.
- Cavazzuti, M. and Corticelli, M. A. (2008). Optimization of Heat Exchanger Enhanced Surfaces Through Multi-Objective Genetic Algorithms. *Numerical Heat Transfer, Part A*, 54, 603 – 624.

- Chen, J.J.J. (1984). A Simple Explicit Formula for the Estimation of Pipe Friction Factor. *Proceedings of the Institution of Civil Engineers* 77: 49 – 55.
- Chen, J. J. J. (1985). Systematic Explicit Solutions of the Prandtl and Colebrook-White Equations for Pipe Flow. *Proceedings of the Institution of Civil Engineers* 79 (2): 383 – 389.
- Cheng, N. S. (2008). Formulas for Friction Factor in Transitional Regions. *Journal of Hydraulic Engineering*, American Society of Civil Engineers (ASCE) 134 (9): 1357 – 1362.
- Cheng, N. S. and Chiew, Y. M. (1998). Modified Logarithmic Law for Velocity Distribution Subjected to Upward Seepage. *Journal of Hydraulic Engineering-American Society of Civil Engineers ASCE* 124(12): 1235 – 1241.
- Chexal, B., Horowitz, J. and Lellouche, G. S. (1991). An Assessment of Eight Void Fraction Models. *Nuclear Engineering and Design* 126: 71 – 88.
- Chipperfield, A. (1997). *Introduction to genetic algorithms*. In Genetic Algorithms in Engineering Systems, (Eds.) A.M.S. Zalzal, P.J. Fleming, Institute of Electrical and Electronics Engineers, New York.
- Chisholm, D. (1967). A Theoretical Basis for the Lockhart-Martinelli Correlation for Two-Phase Flow. *International Journal of Heat and Mass Transfer*, vol. 10 (12), pp. 1767 – 1778.
- Chisholm, D. (1967-1968). The Influence of Mass Velocity on Friction Pressure Gradients During Steam-Water Flow. *Proc Instn Mech Engrs.*, 182(3H): 336 – 341.
- Chisholm, D. (1973). Pressure Gradients Due to Friction during the Flow of Evaporating Two-Phase Mixtures in Smooth Tubes and Channels. *International Journal of Heat and Mass Transfer*, vol. 16 (2), pp. 347 – 358.
- Cho, J. M. and Kim, M. S. (2007). Experimental Studies on the Evaporative Heat Transfer and Pressure Drop of CO₂ in Smooth and Micro-Fin Tubes of the Diameters of 5 and 9.52 mm. *Int. J. Refrigeration* 30: 986 – 994.
- Choi, K. I., Pamitran, A. S., Oh, C. Y., and Oh, J. T. (2008). Two-Phase Pressure Drop of R-410A in Horizontal Smooth Mini-Channels. *International Journal of Refrigeration*, 31: 119 – 129.
- Choi, K. I., Pamitran, A. S., Oh, J. T., and Saito, K. (2009). Pressure Drop and Heat Transfer During Two-Phase Flow Vaporization of Propane in Horizontal Smooth Mini-Channels. *International Journal of Refrigeration* 32: 837 – 845.

- Churchill, S. W. (1973). Empirical Expressions for the Shear Stress in Turbulent Flow in Commercial Pipe. *American Society of Chemical Engineers Journal AIChE* 19 (2): 375 – 376.
- Churchill, S. W. (1977). Friction Factor Equation Spans All Fluid Flow Regimes. *Chemical Engineering* 84 (7): 91 – 92.
- Cicchitti, A., Lombardi, C., Silversti, M., Soldaini, G., and Zavattarlli, R. (1960). Two-Phase Cooling Experiments Pressure Drop, Heat Transfer, and Burnout Measurements. *Energia Nucleare*, 7 (6): 407 – 425.
- Coelho, P. M. and Pinho, C. (2007). Considerations About Equations for Steady State Flow in Natural Gas Pipelines. *Journal of Brazilian Society Mechanical Sciences Engineers* 29(3): 262 – 273.
- Ćojbašić Ž. and Brkić, D. (2013). Very Accurate Explicit Approximations for Calculation of the Colebrook Friction Factor. *International Journal of Mechanical Sciences* 67: 10 – 13.
- Colebrook, C. F. and White, C. M. (1937). Experiments with Fluid Friction in Roughened Pipes. *Proceedings of the Royal Society of London, Series A, Mathematical and Physical Sciences*: 367 – 381.
- 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 Institution of Civil Engineers* 11(4): 133 – 156.
- Coleman, J. W. and Krause, P. E. (2004). Two Phase Pressure Losses of R134a in Microchannel Tube headers with Large Free Flow Area Ratios. *Experimental Thermal and Fluid Science* 28 (2-3): 123 – 130.
- Collier, J. G. (1981). *Convective Boiling and Condensation*. Second Edition, McGraw-Hill Book Company, New York.
- Copetti, J. B., Macagnan, M. H., Zinani, F. and Kunsler, N. L. F. (2011). Flow Boiling Heat Transfer and Pressure Drop of R-134a in a Mini Tube: An Experimental Investigation. *Experimental Thermal and Fluid Science* 35: 636 – 644.
- Cvornjek, N., Brezocnik, M., Jagric, T. and Papa, G. (2014). Comparison Between Single and Multi-Objective Genetic Algorithm. *Fifth International Conference on Bioinspired Optimization Methods and their Applications (BIOMA 2014)*, Ljubljana, Slovenia.

- Dalkilic, A.S. and Wongwises, S. (2010). A Performance Comparison of Vapor-Compression Refrigeration System Using Various Alternative Refrigerants. *International Communications in Heat and Mass Transfer* 37: 1340 – 1349.
- Daniels, T. C. and Davies, A. (1975). The Relationship Between the Refrigerant Charge and the Performance of a Vapor Compression Refrigeration System. *ASHRAE Transactions*, Vol. 81, Part I.
- Danish, M., Kumar, S. and Kumar, S. (2011). Approximate Explicit Analytical Expressions of Friction Factor for Flow of Bingham Fluids in Smooth Pipes Using Adomian Decomposition Method. *Communications in Nonlinear Science and Numerical Simulation* 16 (1): 239 – 251.
- Darby, R. and Melson, J. (1981). How to Predict the Friction Factor for Flow of Bingham Plastics. *Chemical Engineering* 28: 59 – 61.
- Darcy, H. (1858). Recherches Experimentales Relatives au Mouvement de L'eau Dans les Tuyaux (Experimental Research on the Water Pipe Movement). *Memoires a l'Academie d. Sciences de l'Institute imperial de France* 15: 141 (in French).
- Davalos, R. V. and Rubinsky, B. (1996). An Evolutionary-Genetic Approach to Heat Transfer Analysis. *American Society of Mechanical Engineers ASME Journal of Heat Transfer* 118(3): 528 – 531.
- Davis, L. (1991). *Handbook of Genetic Algorithms*. Van Nostrand Reinhold, New York.
- De Jong, K. A. (1975). An Analysis of the Behavior of a Class of Genetic Adaptive Systems. *Dissertation Abstracts International* 36 (10), 5140B (University Microfilms No. 76-9381).
- Dhar, M. and Soedel, W. (1979). Transient Analysis of a Vapor Compression Refrigeration System: Part I-The Mathematical Model. *XV International Congress of Refrigeration*, Venice, Italy.
- Diener, R. and Friedel, L. (1998). Reproductive Accuracy of Selected Void Fraction Correlations for Horizontal and Vertical Up Flow. *Forschung im Ingenieurwesen* (Research in engineering) 64 (4-5): 87.
- Dukler, A. E., Moye, W. and Cleveland, R. G. (1964). Frictional Pressure Drop in Two-Phase Flow. Part A: A Comparison of Existing Correlations for Pressure Loss and Holdup, and Part B: *An Approach through Similarity Analysis* *AIChE Journal*, 10 (1): 38 – 51.

- Dukler, A. E., Wicks, M. and Cleaveland, R. G. (1964). Pressure Drop and Hold Up in Two-Phase Flow. *Journal of American Society of Chemical Engineers AIChE* 10: 38 – 51.
- Eric, W. Lemmon, E. W., Huber, M. L. and McLinden, M. O. (Ed.). (2013). NIST Standard Reference Database 23, April 2013. NIST Reference Fluid Thermodynamic and Transport Properties, REFPROP Version 9.1. National Institute of Standards and Technology, Boulder, Colorado 80305 (<http://webbook.nist.gov>).
- European Commission. (1994). *Non-Nuclear Energy-Joze II-Project Synopses*. European Commission, Brussels. 1018 – 5593.
- Fabbri, G. (1997). A Genetic Algorithm for Fin Profile Optimization. *International Journal of Heat and Mass Transfer* 40(9): 2165 – 2172.
- Falkovich, G. (2011). *Fluid Mechanics*. Cambridge University Press.
- Fang, X., Xua, Y., Zhou, Z. (2011). New Correlations of Single-Phase Friction Factor for Turbulent Pipe Flow and Evaluation of Existing Single-Phase Friction Factor Correlations. *Nuclear Engineering and Design* 241, 897 – 902.
- Farshad, F., Rieke, H. and Garber, J. (2001). New Developments in Surface Roughness Measurements, Characterization, and Modeling Fluid Flow in Pipe. *Journal of Petroleum Science and Engineering* 29: 139 – 150.
- Filonenko, G. K. (1948). Formula dlya koefitsienta gidravlicheskiy soprotivlenie gladkikh trub (Formula for the Coefficient of Fluid Resistance of Smooth Pipes). - *Izvestiya VTI*, No. 10 (162). (In Russia).
- Finnicome, J. R. (1950). The Friction Coefficient for Circular Pipes at Turbulent Flow. *Mechanical W/d Engineering Rec.*, Manchester and London, 127(331): 725 – 739.
- Foli, K., Okabe, T., Olhofer, M., Jin, Y. and Sendhoff, B. (2006). Optimization of Micro Heat Exchanger: CFD, Analytical Approach and Multi-Objective Evolutionary Algorithms. *International Journal of Heat and Mass Transfer* 49: 1090 – 1099.
- Friedel, L. (1979). Improved Friction Pressure Drop Correlations for Horizontal and Vertical Two-Phase Pipe Flow. In: *European Two-Phase Flow Group Meeting*, Ispra, Italy, pp. 485 – 492.
- Friedel, L. (1980). Pressure Drop During Gas/Vapor–Liquid Flow in Pipes. *International Journal of Chemical Engineering* 20: 352 – 367.

- Furutera, M. (1986). Validity of Homogeneous Flow Model for Instability Analysis. *Nuclear Engineering and Design* 95: 65 – 74.
- Geankoplis, C. J. (2003). *Transport Processes and Separation Process Principles*. Fourth Edition, p. 475. Prentice Hall Professional Technical Reference. ISBN 978-0-13-101367-4.
- Genić, S., Arandjelović, I., Kolendić, P., Jarić, M., Budimir, N. and Genić, V. (2011). A Review of Explicit Approximations of Colebrook's Equation. *FME Transactions* 39: 67 – 71. Faculty of Mechanical Engineering, Belgrade University.
- Ger, A. M. and Holly, E. R. (1976). Comparison of Single Point Injections in Pipe Flow. *Journal of Hydraulic Engineering*, American Society of Civil Engineers (ASCE), 102 (HY6), pp. 731 – 746.
- Ghosh, S., Ghosh, I., Pratihar, D. K., Maiti, B. and Das, P. K. (2011). Optimum Stacking Pattern for Multi-Stream Plate – Fin Heat Exchanger Through a Genetic Algorithm. *International Journal of Thermal Sciences* 50: 214 – 224.
- Godbole, P. V., Tang, C. C. and Ghajar, A. J. (2011). Comparison of Void Fraction Correlations for Different Flow Patterns in Upward Vertical Two-Phase Flow, *Heat Transfer Engineering* 32: 843 – 860.
- Goldberg, D. E. (1989). *Genetic Algorithms in Search, Optimization, and Machine Learning*. Addison-Wesley Publishing Co. Inc., Berkshire, UK.
- Goldberg, D. E., Deb, K. and Clark, J. H. (1992). Genetic Algorithms, Noise, and the Sizing of Populations. *Complex System*. 6: 333-362.
- Gosselin, L., Tye-Gingras, M. and Mathieu-Potvin, F. (2009). Review of Utilization of Genetic Algorithms in Heat Transfer Problems. *International Journal of Heat and Mass Transfer* 52: 2169 – 2188.
- Grefenstette, J. J. (1986). Optimization of Control Parameters for Genetic Algorithms. *IEEE Transactions on Systems, Man and Cybernetics*, 122 – 128.
- Grønnerud, R. (1972). Investigation of Liquid Hold-Up, Flow Resistance and Heat Transfer in Circulation Type Evaporators, Part IV: Two-Phase Flow Resistance in Boiling Refrigerants. *Bulletin*, The Institute of Refrigeration, Appendix 1972-1.

- Haaland, S. E. (1983). Simple and Explicit Formulas for the Friction Factor in Turbulent Pipe Flow. *Journal of Fluids Engineering, American Society of Mechanical Engineers (ASME)* 105: 89 – 90, New York.
- Hajabdollahi, H., Tahani, M. and Shojaee Fard, M. H. (2011). CFD Modeling and Multi-Objective Optimization of Compact Heat Exchanger Using CAN Method. *Applied Thermal Engineering* 31: 2597 – 2604.
- Hammad, M. (1999). Product Performance: Energy Performance of Plastic Pipes. *Polymer Testing* 18 (2): 111 – 122.
- Hanks, R. W. and Pratt, D. R. (1967). On the Flow of Bingham Plastic Slurries in Pipes and Between Parallel Plates. *Journal of Society of Petroleum Engineers* 1: 342 – 346.
- Halimic, E., Ross, D., Agnew, B., Anderson, A. and Potts, I. (2003). A Comparison of the Operating Performance of Alternative Refrigerants. *Applied Thermal Engineering* 23: 1441–1451.
- He, M. G., Song, X. Z., Liu, H. and Zhang, Y. (2014). Application of Natural Refrigerant Propane and Propane/Isobutene in Large Capacity Chest Freezer. *Applied Thermal Engineering* 70: 732 – 736.
- Hilbert, R., Janiga, G., Baron, R. and Thevenin, D. (2006). Multi-Objective Shape Optimization of a Heat Exchanger Using Parallel Genetic Algorithms. *International Journal of Heat and Mass Transfer* 49: 2567 – 2577.
- Hinze, J. O. (1975). *Turbulence*. McGraw-Hill, New York.
- Holland, J. H. (1975). *Adaptation in Natural and Artificial Systems*. University of Michigan Press, Ann Arbor, Michigan; re-issued by MIT Press (1992).
- Holland, J. H. (1992). Genetic algorithms. *Scientific American* 267 (1): 66 – 72.
- Hopf, L. (1923). Die Messung der hydraulischen Rauigkeit (The measurement of the hydraulic roughness). *ZAMM - Zeitschrift für Angewandte Mathematik und Mechanik (Journal of Applied Mathematics and Mechanics)* 3: 329. (In German).
- Huo, X., Shiferaw, D., Karayiannis, T.G., Tian, Y. S. and Kenning, D.B.R. (2006). Boiling Two-Phase Pressure Drop in Small Diameter Tubes. Aspen Tech Inc., Berkshire, UK.
- Hwang, Y. W. and Kim, M. S. (2006). The pressure drop in microtubes and the correlation development. *International Journal of Heat and Mass Transfer* 49: 1804 – 1812.

- IAEA-TECDOC-1203. (2001). *Thermohydraulic Relationships for Advanced Water-Cooled Reactors*. Nuclear Power Technology Development Section, International Atomic Energy Agency IAEA, Vienna, Austria.
- Incropera, F.P. and Dewitt, D.P. (2001). *Fundamentals of Heat and Mass Transfer*. 5th Edition, LTC, Guanabara Dois, Rio de Janeiro.
- Incropera, F.P., DeWitt, D.P., Bergman, T. and Lavine, A. (2007). *Fundamentals of Heat and Mass Transfer*. John Wiley Sons, Jefferson City.
- Ishibuchi, H., Nojima, Y. and Doi, T. (2006). Comparison Between Single-Objective and Multi-Objective Genetic Algorithms: Performance Comparison and Performance Measures. *IEEE Congress on Evolutionary Computation*: 1143 – 1150, Vancouver, BC..
- Jacopo, B. (2010). Notes on Two-Phase Flow Boiling Heat Transfer and Boiling Crises in PWRs and BWRs. 22.06 *Engineering of Nuclear Systems*, MIT Department of Nuclear Science and Engineering. <http://ocw.mit.edu/terms>.
- Jain, A. K. (1976). Accurate Explicit Equation for Friction Factor. *Journal of Hydraulic Engineering*, American Society of Civil Engineers (ASCE)102: 674 – 677.
- James, R. W. and Marshall, S. A. (1973). Dynamic Analysis of a Refrigeration System. *Proceedings Institute of Refrigeration* 70: 13 – 24, London.
- Jimenez, J. (2004). Turbulent Flows Over Rough Walls. *Annual Review of Fluid Mechanics* 36: 173 – 196.
- Joda, F., Tahouni, N. and Panjeshahi, M. H. (2013). Application of Genetic Algorithms in Design and Optimization of Multi-Stream Plate-Fin Heat Exchangers. *The Canadian Journal of Chemical Engineering* 91: 870 – 881.
- Johnson, S. P. (1934). A Survey of Flow Calculation Methods. Preprinted Paper for Summer Meeting, ASME.
- Judy, J., Maynes, D. and Webb, B.W. (2002). Characterization of Frictional Pressure Drop for Liquid Flows Through Micro-Channels. *International Journal of Heat and Mass Transfer* 45: 3477 – 3489.
- Jürgensen, H. (2016). *Propane as R22-Replacement in Commercial Appliances*. Danfoss Compressors GmbH D-24939 Flensburg.
- Kandlikar, S. G. (2002). Two-Phase Flow Patterns, Pressure Drop and Heat Transfer During Boiling in Mini-Channel and Micro-Channel Flow Passages of Compact Evaporators. *Heat Transfer Engineering* 23: 5 – 23.

- Kandlikar, S. G. (2010). Scale Effects on Flow Boiling Heat Transfer in Microchannels: A fundamental perspective. *International Journal of Thermal Sciences* 49: 1073 – 1085.
- Kim, S. M. and Mudawar, I. (2013). Universal Approach to Predicting Two-Phase Frictional Pressure Drop for Mini/Micro-Channel Saturated Flow Boiling. *International Journal of Heat and Mass Transfer* 58: 718 – 734.
- Kim, S. M. and Mudawar, I. (2014). Review of Databases and Predictive Methods for Pressure Drop in Adiabatic, Condensing and Boiling Mini/Micro-Channel Flows. *International Journal of Heat and Mass Transfer* 77: 74 – 97.
- Kureta, M., Kobayashi, T., Mishima, K. M. and Nishihara, H. (1998). Pressure Drop and Heat Transfer for Flow Boiling of Water in Small-Diameter Tubes: *JSME International Journal, Series B*, Vol. 41(4): 871 – 879.
- Lamont, P. (1969). The Choice of the Pipe Flow Laws for Practical Use. *Water and Water Engineering*, pp. 55 – 63.
- Lazarek, G. M. and Black, S. H. (1982). Evaporative Heat Transfer, Pressure Drop and Critical Heat Flux in a Small Diameter Vertical Tube with R-113. *International Journal of Heat and Mass Transfer* 25: 945 – 960.
- Lee, H. J. and Lee, S. Y. (2001). Pressure drop correlations for two-phase flow within horizontal rectangular channels with small heights. *International Journal of Multiphase Flow* 27: 783 – 796.
- Ligrani, P. M. and Moffat, R. J. (1986). Structure of Transitionally Rough and Fully Rough Turbulent Boundary-Layers. *Journal of Fluid Mechanics* 162: 69 – 98.
- Lin, S., Kwok, C. C. K., Li, R. Y., Chen, Z. H. and Chen Z. Y. (1991). Local Friction Pressure Drop During Vaporization of R-12 Through Capillary Tubes. *International Journal of Multiphase Flow* 17(1): 95 – 102.
- Linde Gases AG, Gases Division. Refrigerants Environmental Data. Ozone Depletion and Global Warming Potential. Seitnerstrasse 70, 82049 Pullach, Germany.
- Liu, Z. and Cheng, H. (2008). Multi-Objective Optimization Design Analysis of Primary Surface Recuperator for Microturbines. *Applied Thermal Engineering* 28: 601 – 610.
- Lockhart, R. W. and Martinelli, R. C. (1949). Proposed Correlation of Data for Isothermal Two-Phase, Two-Component Flow in Pipes. *Chemical Engineering Progress* 45: 39 – 48.

- MacArthur, J. W. (1984). Transient Heat Pump Behavior: A Theoretical Investigation. *International Journal of Refrigeration* 7(2): 123 – 132.
- Manning, F. S. and Thompson, R. E. (1991). *Oilfield Processing of Petroleum*. Vol. 1: Natural Gas, PennWell Books 420 pages, See page 293. ISBN 0-87814-343-2.
- Manzan, M., Nobile, E, Pieri, S. and Pinto, F. (2008). *Multi-Objective Optimization for Problems Involving Convective Heat Transfer, in Optimization and Computational Fluid Dynamics*. Chapter 8. Thévenin D, Janiga G, Editor. Springer-Verlag: Berlin.
- Martin, H. (1999). Economic Optimization of Compact Exchangers. In: R.K. Shah (Ed.), *First International Conference on Compact Heat Exchangers and Enhancement Technology for the Process Industries*, Banff, Canada, pp. 75 – 80.
- Martinelli, R. C., Boelter, L. M. K., Taylor, T. H. M., Thomsen, E.G. and Morrin, E. H. (1944). Isothermal Pressure Drop for Two-Phase, Two-Component Flow in a Horizontal Pipe. *Transactions of ASME* 66(2): 139 – 151.
- Martinelli, R. C. (1947). Heat transfer to molten metals. *Transaction of ASME* 69: 947 – 959.
- Martinelli, R. C. and Nelson, D. B. (1948). Prediction of Pressure Drop During Forced-Circulation Boiling of Water. *Transaction of ASME* 70: 695 – 702.
- Mishima, K. and Hibiki, T. (1996). Some Characteristics of Air-Water Two-Phase Flow in Small Diameter Vertical Tubes. *International Journal of Multiphase Flow* 22(4): 703 – 712.
- MATLAB R2016a Version (9.0.0.341360) 64 Bit (win64), License Number 123456.
- Matsunaga, K. (2002). Comparison of Environmental Impacts and Physical Properties of Refrigerants. *Fu Foundation of Engineering and Applied Science*, Research by the Earth Engineering Centre, Columbia University.
- McAdams, W. H., Woods, W. K. and Bryan, R. L. (1942). Vaporization Inside Horizontal Tubes-II- Benzene–Oil Mixtures. *Trans. ASME* 64 (3): 193 – 200.
- McKeon, B. J., Zagarola, M. V., and Smits, A. J. (2005). A New Friction Factor Relationship for Fully Developed Pipe Flow. *Journal of Fluid Mechanics* 538: 429 – 443.
- Michalewicz, Z. (1992). *Genetic Algorithms + Data Structures = Evolution Programs*. Springer-Verlag.

- Mironov, O. G. (1968). Hydrocarbon Pollution of the Sea and Its Influence on Marine Organisms. *Helgoländer Wissenschaftliche Meeresuntersuchungen* 17: 335 – 339.
- Mishima, K. and Hibiki, T. (1996). Some Characteristics of Air-Water Two-Phase Flow in Small Diameter Vertical Tubes. *International Journal of Multiphase Flow* 22 (4): 703 – 712.
- Mishra, M., Das, P. K. and Sarangi, S. (2004). Optimum Design of Crossflow Plate-Fin Heat Exchangers Through Genetic Algorithm. *International Journal of Heat Exchangers* 5(2): 379 – 401.
- Mitchell, M. (1996). *An Introduction to Genetic Algorithms*. MIT Press, Cambridge, MA.
- Moody, L. F. and Princeton, N. J. (1944). Friction Factor for Pipe Flow. *Transactions of American Society of Mechanical Engineers (ASME)* 66: 671 – 684.
- Moody, L. F. (1947). An Approximate Formula for Pipe Friction Factors. *Mechanical Engineering*, New York, 69: 1005 – 1006.
- Morel, M. A. and Laborde, J. P. (1994). *Exercices de Mécanique des Fluides*. Volume 1, Chihab-Eyrolles Editions, Algeria.
- Morini, G. L., Yang, Y., Chalabi, H. and Lorenzini, M. (2011). A Critical Review of the Measurement Techniques for the Analysis of Gas Microflows through Microchannels. *Experimental Thermal and Fluid Science* 35: 849–865.
- Muralifrishna, K. and Shenoy, U.V. (2000). Heat Exchanger Design Targets for Minimum Area and Cost. *Transactions of the Institution of Chemical Engineers* 78: 161 – 167.
- Najafi, H., Najafi, B. and Hoseinpoori, B. (2011). Energy and Cost Optimization of a Plate and Fin Heat Exchanger Using Genetic Algorithm. *Applied Thermal Engineering* 31: 1839 – 1847.
- Nekrasov, B. (1968). *Hydraulics*. Peace Publishers, Moscow, (Translated by V. Talmy), 95 – 101.
- Nikuradse, J. (1930). Widerstandsgesetz und Geschwindigkeitsverteilung von turbulenten Wasserströmungen in glatten und rauhen Rohren (Resistance formula and velocity distribution of turbulent water currents in smooth and rough pipes). *Verh. d. 3. Intern. Kongr. f. techn. Mech.*, Stockholm (Stockholm 1931) Vol. 1, pp. 239. (In German).

- Nikuradse, J. (1932). Gesetzmäßigkeiten der turbulenten Strömung in glatten Röhren (Regularities of turbulent flow in smooth Pipes). VDI – Forsch. – Heft 356. (In German).
- Nikuradse, J. (1933). Laws of Flow in Rough Pipes (Stromungsgesetze in Rauhen Röhren), VDI-Forschungsheft, Vol. 361. Beilage zu: Forschung auf dem Gebiete des Ingenieurwesens, Ausgabe B Band 4; English Translation NACA Tech. Mem. 1292, 1937.
- NIST 2013. NIST Thermodynamic Properties of Refrigerants and Refrigerant Mixtures. Version 9.1: Computer software, National Institute of Science and Technology, Gaithersburg, MD.
- Noakes, C. and Sleight, A. (2009). *An Introduction to Fluid Mechanics*. School of Civil Engineering, University of Leeds. Retrieved 23 November 2010.
- Oh, H. K., Ku, H. G., Roh, G. S., Son, C. H. and Park, S. J. (2008). Flow Boiling Heat Transfer Characteristics of Carbon Dioxide in a Horizontal Tube. *Appl. Therm. Eng.* 28: 1022 – 1030.
- Oh, J. T., Choi, K. I., and Chien, N. Ba. (2015). Pressure Drop and Heat Transfer during a Two-phase Flow Vaporization of Propane in Horizontal Smooth Minichannels. Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education.
- Oh, J.-T., Oh, H.-K. and Choi, K.-Il. (2011). Two-Phase Flow Boiling Heat Transfer for Evaporative Refrigerants in Various Circular Mini-Channels. Heat Transfer-Theoretical Analysis, Experimental Investigations and Industrial Systems, Prof. Aziz Belmiloudi (Ed.), ISBN: 978-953-307-226-5. InTech, available from: [http://www.intechopen.com/books/Heat Transfer Theoretical Analysis Experimental Investigations and Industrial Systems/Two-Phase Flow Boiling Heat Transfer for Evaporative Refrigerants in Various Circular Mini-Channels](http://www.intechopen.com/books/Heat_Transfer_Theoretical_Analysis_Experimental_Investigations_and_Industrial_Systems/Two-Phase_Flow_Boiling_Heat_Transfer_for_Evaporative_Refrigerants_in_Various_Circular_Mini-Channels).
- Ould, D. M. B., Kattan, N. and Thome, J. R. (2002). Prediction of Two-Phase Pressure Gradients of Refrigerants in Horizontal Tubes. *International Journal of Refrigeration* 25: 935 – 947.
- Ozkol, I. and Komurgoz, G. (2005). Determination of the Optimum Geometry of the Heat Exchanger Body Via a Genetic Algorithm. *Numerical Heat Transfer Part A – Applications* 48 (3): 283 – 296.

- Pacheco-Vega, A., Sen, M., Yang, K.T., and McClain, R.L. (1998). Genetic-Algorithm Based Prediction of a Fin-Tube Heat Exchanger Performance, *Proceedings Eleventh International Heat Transfer Conference 6*: 137 – 142.
- Pamitrana, A. S., Choi, K. I., Oh, J. T. and Oh, H. K. (2008). Two-Phase Pressure Drop during CO₂ Vaporization in Horizontal Smooth Minicanals. *international journal of refrigeration* 31: 1375 – 1383.
- Pamitran, A.S., Choi, K.I., Oh, J.-T. and Hrnjak, P. (2010). Characteristics of Two-Phase Flow Pattern Transitions and Pressure Drop of Five Refrigerants in Horizontal Circular Small Tubes. *International Journal of Refrigeration* 33: 578 – 588.
- Panjeshahi, M. H., Joda, F. and Tahouni, N. (2010). Pressure Drop Optimization in an Multi-Stream Heat Exchanger using Genetic Algorithms. *Chemical Engineering Transaction* 21: 247 – 252.
- Park, C. Y. and Hrnjak, P. S. (2007). CO₂ and R410A Flow Boiling Heat Transfer, Pressure Drop, and Flow Pattern at Low Temperatures in a Horizontal Smooth Tube. *Int. J. Refrigeration* 30: 166 – 178.
- Pfitzner, J. (1976). Poiseuille and His Law. *Anaesthesia* 31(2): 273 – 275.
- Pigott, R. J. S. (1933). The Flow of Fluids in Closed Conduits. *Mechanical Engineering* 55: 497 – 515.
- Ponce, J. M., Serna, M., Rico, V. and Jimenez, A. (2006). Optimal Design of Shell-and-Tube Heat Exchangers Using Genetic Algorithms. *Computer Aided Chemical Engineering* 21: 985 – 990.
- Powell, R.W. (1968). The Origin of Manning Formula. *Journal of Hydraulic Engineering*, American Society of Civil Engineers (ASCE), pp. 1179 – 1181.
- Prandtl, L. (1930). Turbulenz und ihre Entstehung (Turbulence and Its Origin). Tokyo – Vortrag 1929, *J. Aeronaut. Res. Inst.*, Tokyo Imperial University, No. 65. (In German).
- Prandtl, L. (1932). Zur turbulenten strömung in Rohren und längs Platten(turbulent flow in pipes and along plates). *Ergeb. d. Aerodyn. Versuchsanst. zu Gottingen*, 4. Lief., p. 18. (In German).
- Prandtl, L. (1933). Neuere Ergebnisse der Turbulenzforschung (Recent Results of Turbulence Research). *Z. Ver. Deutsch. Ing.* 77, 105. (In German).
- Prandtl, L. (1935). The Mechanics of Viscous Fluids. In: W.F, D. (ed.) *Aerodynamic Theory III*. Berlin: Springer.

- Rechenberg, I. (1973). *Evolutionsstrategie: Optimierung Technischer Systeme nach Prinzipien der Biologischen Evolution* (German Edition). Paperback. Frommann-Holzboog Verlag, Stuttgart, German.
- Revellin, R. and Thome, J.R. (2007). Adiabatic Two-Phase Frictional Pressure Drops in Microchannels. *Experimental Thermal and Fluid Science* 31: 673 – 685.
- Rice, C. K. (1987). The Effect of Void Fraction Correlation and Heat Flux Assumption on Refrigerant Charge Inventory Predictions, *ASHRAE Transactions* 93: 341 – 367.
- Richard V. M. (1914). Elemente der Technischen Thermodynamik (Elements of technical thermodynamics). *Leipzig, B. G. Teubner* (in German).
- Rosenberg, R. S. (1967). *Simulation of Genetic Population with Biochemical Properties*. Ph.D Thesis, University of Michigan, Ann Harbor, Michigan.
- Round, G. F. (1980). An Explicit Approximation for the Friction Factor-Reynolds Number Relation for Rough and Smooth Pipes. *The Canadian Journal of Chemical Engineering*, Ottawa 58: 122 – 123.
- Rouse, H. (1943). Evaluation of Boundary Roughness. *Proceedings of the 2nd Hydraulics Conference* 27: 105 – 116, New York.
- Sadeghzadeh, H., Aliehyaei, M. and Rosen, M. A. (2015). Optimization of a Finned Shell and Tube Heat Exchanger Using a Multi-Objective Optimization Genetic Algorithm. *Sustainability* 7: 11679 – 11695.
- Saisorn, S., Kaew-On, J., and Wongwises, S. (2010). Flow Pattern and Heat Transfer Characteristics of R-134a Refrigerant During Flow Boiling in a Horizontal Circular Mini-Channel. *International Journal of Heat and Mass Transfer* 53: 4023 – 4038.
- Saitoh, S., Daiguji, H. and Hihara, E. (2005). Effect of Tube Diameter on Boiling Heat Transfer of R-134a in Horizontal Small-Diameter Tubes. *International Journal of Heat and Mass Transfer* 48: 4973 – 4984.
- Sanaye, S. and Hajabdollahi, H. (2010). Thermal-Economic Multi-Objective Optimization of Plate Fin Heat Exchanger Using Genetic Algorithm. *Applied Energy* 87: 1893 – 1902.
- Saphier, D., Grimm, P. (1992). Bypass Channel Modelling and New Void Correlations for the BWR Option of the SILWER Code. PSI – Bericht No. – 119.

- Schmit, T. S., Dhingra, A. K., Landis, F., and Kojasoy, G. (1996). Genetic Algorithm Optimization Technique for Compact High Intensity Cooler Design. *Journal of Enhanced Heat Transfer* 3(4): 281 – 290.
- Schmitt, L. M. (2001). Theory of genetic algorithms. *Theoretical Computer Science* 259 (1–2): 1 – 61.
- Selbas, R., Kizilkan, O. and Reppich, M. (2006). A New Design Approach for Shell-and-Tube Heat Exchangers Using Genetic Algorithms from Economic Point of View. *Chemical Engineering and Processing* 45 (4): 268 – 275.
- Sen, M. and Yang, K. T. (2000). *Applications of Artificial Neural Networks and Genetic Algorithms in Thermal Engineering*. CRC Handbook of Thermal Engineering: 620 – 661.
- Serghides, T. K (1984). Estimate Friction Factor Accurately. *Chemical Engineering* 91 (5): 63 – 64.
- Shah, R. K. and London, A. L. (1978). *Laminar Flow Forced Convection in Ducts*. New York: Academic Press.
- Shrivastava, A. P. and Chandrakishor, S. C. (2016). Evaluation of Refrigerant R290 as a Replacement to R22. *International Journal of Research in Science and Engineering* 2(3): 739 – 747.
- Sivanandam, S. N. and Deepa, S. N. (2008). *Introduction to Genetic Algorithms*. Springer, Berlin Heidelberg.
- Smith, R. V. (1990). *Practical Natural Gas Engineering*. PennWell Books.
- Soupremanien, U., Person, S. L., Favre, EM. M. and Bultel, Y. (2011). Influence of the Aspect Ratio on Boiling Flows in Rectangular Mini-Channels. *Experimental Thermal and Fluid Science* 35: 797 – 809.
- Staub, F. W. and Wallet, G. E. (1970). The Void Fraction and Pressure Drop in Subcooled Flow Boiling. *Heat Transfer 1970, Fourth International Heat Transfer Conference* 5.
- Stoecker, W. F., Smith, L. D. and Emde, B. N. (1981). Influence of the Expansion Device on the Seasonal Energy Requirements of a Residential Air Conditioner. *ASHRAE Transactions* 87, Part I.
- Sun, L. and Mishima, K. (2009). Evaluation Analysis of Prediction Methods for Two-Phase Flow Pressure Drop in Mini-Channels. *International Journal of Multiphase Flow* 35: 47 – 54.

- Swamee, P. K. and Aggarwal, N. (2011). Explicit Equations for Laminar Flow of Bingham Plastic Fluids. *Journal of Petroleum Science and Engineering* 76: 178 – 184.
- Swamee, P. K. and Jain, A. K. (1976). Explicit Equations for Pipe Flow Problems *Journal of Hydraulic Engineering*, American Society of Civil Engineers (ASCE) 102 (HY5): 657 – 664.
- Tang, M. C. and Carothers, J. D. (1996). Multichip Module Placement with Heat Consideration. *Proceedings Ninth Annual IEEE International ASIC Conference and Exhibit*, pp. 175 – 178.
- Tayal, M. C., Fu, Y. and Diwekar, U. M. (1999). Optimal Design of Heat Exchangers: A Genetic Algorithm Framework. *Industrial Engineering and Chemical Research* 38: 456 – 467.
- Taylor, J. B., Carrano, A. L., Kandlikar, S. G. (2006). Characterization of the Effect of Surface Roughness and Texture on Fluid Flow-Past, Present, and Future. *International Journal of Thermal Sciences* 45(10): 962 – 968.
- Techo, R., Tichner, R.R. and James, R.E. (1965). An Accurate Equation for the Computation of Friction Factor for Smooth Pipes from the Reynolds Number. *Journal of Applied Mechanics* 32: 443.
- Tong, W., Bergles, A. E. and Jensen, M. K. (1997). Pressure Drop with Highly Subcooled Flow Boiling in Small-Diameter Tubes. *Experimental Thermal and Fluid Science* 15:202 – 212.
- Tran, T. N., Wambsganss, M. W., France, D. M. and Jendrzejczyk, J. A. (1993). Boiling Heat Transfer in a Small, Horizontal, Rectangular Channel. *Heat Transfer-Atlanta 1993, AIChE Symposium Series*, Vol. 89: 253 – 261.
- Tran, T. N., Wambsganss, M. W., and France, D. M. (1996). Small Circular and Rectangular Channel Boiling with Two Refrigerants. *International Journal of Multiphase Flow* 22(3): 485 – 498.
- Tran, T. N., Chyu, M. C., Wambsganss, M. W. and France, D. M. (2000). Two-Phase Pressure Drop of Refrigerants During Flow Boiling in Small Channels: An Experimental Investigation and Correlation Development. *International Journal of Multiphase Flow* 26: 1739 – 1754.
- Vijayan, P. K., Patil, A. P., Pilkhawal, D. S., Saha, D. and Raj, V. V. (2000). An Assessment of Pressure Drop and Void Fraction Correlations with Data from Two-Phase Natural Circulation Loops. *Heat and Mass Transfer*, 36: 541 – 548.

- Von Karman, T. (1930). Mechanische Ähnlichkeit und Turbulenz (Mechanical Similarity and Turbulence). In: Ossen, C.W., Weibull, W. (Eds.), *Proceeding Third International Congress for Applied Mechanics*, Stockholm, vol. 1, pp. 79 – 93. (In German).
- Von Kármán, T. (1934). Turbulence and Skin Friction. *Journal of the Aeronautical Sciences* (Institute of the Aeronautical Sciences, Inc.) 1 (1): 1 – 20.
- Von Wolfersdorf, J., Achermann, E., and Weigand, B. (1997). Shape Optimization of Cooling Channels Using Genetic Algorithms. *American Society of Mechanical Engineers ASME Journal of Heat Transfer* 119(2): 380 – 388.
- Wambsganss, M. W., Jendrzejczyk, J. A., France, D. M., and Obot, N.T. (1990). Two-Phase Flow Patterns and Frictional Pressure Gradients in a Small, Horizontal, Rectangular Channel. Argonne National Laboratory Report ANL-90.
- Wambsganss, M. W., Jendrzejczyk, J. A., France, D. M. and Obot, N.T. (1991). Frictional Pressure Gradients in Two-Phase Flow in a Small, Horizontal, Rectangular Channel. *Experimental Thermal and Fluid Science Journal*.
- Wambsganss, M. W., Jendrzejczyk, J. A., France, D. M. (1992). Two-Phase Flow and Pressure Drop in Flow Passages of Compact Heat Exchangers. Argonne National Laboratory, Report ANL/CP-74646.
- Wang, J. J., Jing, Y. Y. and Zhang, C. F. (2010). Optimization of Capacity and Operation for CCHP System by Genetic Algorithm. *Applied Energy* 87: 1325 – 1335.
- Wang, Q. W., Zhang, D. J. and Xie, G. N. (2009). Experimental Study and Genetic-Algorithm – Based Correlation on Pressure Drop and Heat Transfer Performances of a Cross – Corrugated Primary Surface Heat Exchanger. *Journal of Heat Transfer* 131(6): 061802 – 061808.
- Wang, Q. W., Xie, P. B. T. and Zeng, M. (2007). Experimental Study and Genetic-Algorithm-Based Correlation on Shell-Side Heat Transfer and Flow Performance of Three Different Types of Shell-and-Tube Heat Exchangers. *American Society of Mechanical Engineers ASME Journal of Heat Transfer* 129, in press.
- Warrier, G. R., Dhir, V. K. and Momoda, L. A. (2002). Heat Transfer and Pressure Drop in Narrow Rectangular Channels. *Experimental Thermal and Fluid Science* 26: 53 – 64.

- Wildi-Tremblay, P. and Gosselin, L. (2007). Minimizing Shell-and-Tube Heat Exchanger Cost with Genetic Algorithms and Considering Maintenance. *International Journal of Energy Research* 31 (9): 867 – 885.
- Williams, G.S. and Hazen, A. (1933). *Hydraulic Tables*. 3rd Edition, John Wiley & Sons Inc., USA.
- Williams, G. P. (1970). Manning Formula-A Misnomer? *Journal of Hydraulic Engineering*, American Society of Civil Engineers (ASCE), pp. 193 – 200.
- Winkler, J., Killion, J., Garimella, S. and Fronk, B. M. (2012). Void Fractions for Condensing Refrigerant Flow in Small Channels: Part I literature review. *International journal of refrigeration* 35:219 – 245.
- Woldesemayat, M. A. and Ghajar, A. J. (2007). Comparison of Void Fraction Correlations for Different Flow Patterns in Horizontal and Upward Inclined Pipes. *International Journal of Multiphase Flow* 33: 347 – 370.
- Wolfersdorf, J., Achermann, E. and Weigand, B. (1997). Shape Optimization of Cooling Channels Using Genetic Algorithms. *Journal of Heat Transfer* 119(2): 380 – 388.
- Wood, D. J. (1972). An Explicit Friction Factor Relationship. *Civil Engineering*, American Society of Civil Engineers (ASCE), pp. 383 - 390.
- Xie, G. N., Sunden, B. and Wang, Q. W. (2008). Optimization of Compact Heat Exchangers by a Genetic Algorithm. *Applied Thermal Engineering* 28 (8 – 9), 895 – 906.
- Xu, Y. and Fang, X. (2012). A New Correlation of Two-Phase Frictional Pressure Drop for Evaporating Flow in Pipes. *International. Journal of Refrigeration*, 35 (7): 2039 – 2050.
- Xu, Y., Fang, X., Su, X., Zhou, Z., Chen, W. (2012). Evaluation of Frictional Pressure Drop Correlations for Two-Phase Flow in Pipes. *Nuclear engineering design* 253: 86 – 97.
- Xu, Y. and Fang, X. (2013). A New Correlation of Two-Phase Frictional Pressure Drop for Condensing Flow in Pipes. *Nuclear Engineering and Design* 263: 87–96.
- Xu, Y. and Fang, X. (2014). Correlations of Void Fraction for Two-Phase Refrigerant Flow in Pipes. *Applied Thermal Engineering* 64 (1–2): 242 – 251.

- Xu, Y., Fang, X., Li, D., Li, G., Yuan, Y. and Xu, A. (2016). An Experimental Study of Flow Boiling Frictional Pressure Drop of R134a and Evaluation of Existing Correlations. *International Journal of Heat and Mass Transfer* 98:150 – 163.
- Yalin, M. S. and Da Silva, A. M. A. F. (2001). *Fluvial processes*. IAHR, Delft, Netherlands.
- Yamaguchi, K., Sasaki, C., Tsuboi, R., Atherton, M., Stolarski, T. and Sasaki, S. (2014). Effect of Surface Roughness on Friction Behavior of Steel under Boundary Lubrication. *Journal of Engineering Tribology* 228 (9): 1015 – 1019.
- Yen, B. C. (2002). Open Channel Flow Resistance. *Journal of Hydraulic Engineering- American Society of Civil Engineers ASCE* 128(1): 20 – 39.
- Yoon, S. H., Cho, E. S., Hwang, Y. W., Kim, M. S., Min, K. and Kim, Y. (2004). Characteristics of Evaporative Heat Transfer and Pressure Drop of Carbon Dioxide and Correlation Development. *Int. J. Refrigeration* 27: 111 – 119.
- Yu, W., France, D. M., Wambsganss, M. W. and Hull, J. R. (2002). Two-Phase Pressure Drop, Boiling Heat Transfer, and Critical Heat Flux to Water in a Small Diameter Horizontal Tube. *International Journal of Multiphase Flow* 28: 927 – 941.
- Zagarola, M. V. and Smits, A. J. (1998). Mean Flow Scaling in Turbulent Pipe Flow. *Journal of Fluid Mechanics* 373: 33 – 79.
- Zakaria, M. Z., Jamaluddin, H., Ahmad, R. and Loghmanian, S. M. (2012). Comparison Between Multi-objective and Single-Objective Optimization for the Modeling of Dynamic Systems. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering* 226 (7): 994 – 1005.
- Zhang, W., Hibiki, T. and Mishima, K. (2010). Correlations of Two-Phase Frictional Pressure Drop and Void Fraction in Minichannel. *International Journal of Heat and Mass Transfer* 53 (1 – 3): 453 – 465.
- Zhao, Y., Molki, M., Ohadi, M. M. and Dessiatoun, S.V. (2000). Flow Boiling of CO₂ in Microchannels. *ASHRAE Trans*: 437 – 445.
- Zigrang, D. J. and Sylvester, N. D. (1982). Explicit Approximations to the Solution of Colebrook Friction Factor Equation. *American Institute of Chemical Engineers (AIChE) Journal* 28 (3): 514 – 515.