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

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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.

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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 percanggahan. Seterusnya, pengurangan faktor geseran dan penurunan tekanan geseran menggunakan algoritma genetik objektif tunggal (SOGA) dilakukan. Dalam algoritma genetik berbilang objektif (MOGA), ojektif 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 percanggahan 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 penyelidik 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.

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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
PD	-	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, [µPa.s]
μ_{g}	-	Gas-phase viscosity, [µPa.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

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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.

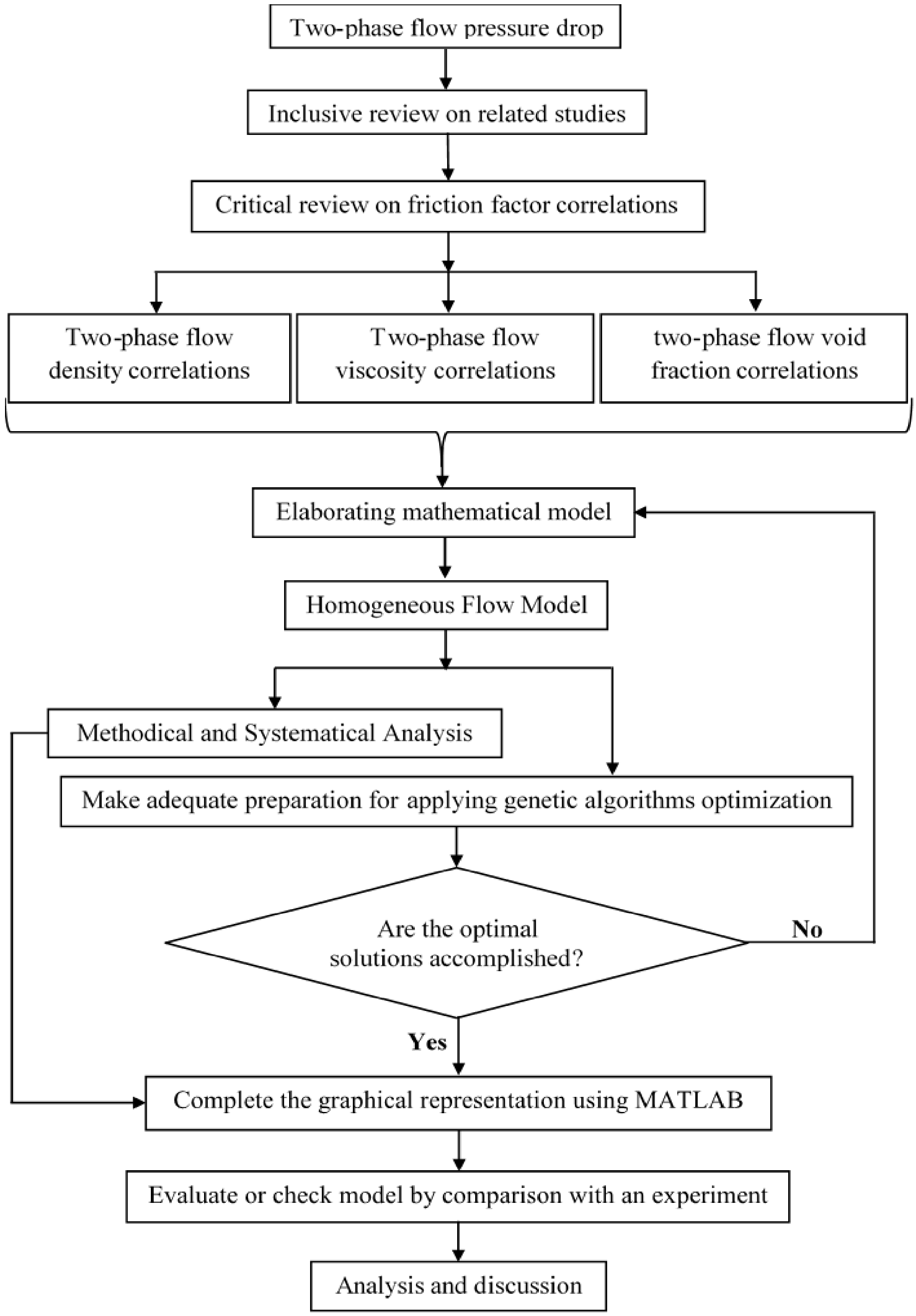

Figure 1.1 Methodical stages of the current study

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.

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