UNIVERSITI PUTRA MALAYSIA

EXPERIMENTAL AND NUMERICAL INVESTIGATION ON THE OPTIMUM DISTANCE OF A REFRIGERATOR FROM ROOM WALL FOR MINIMUM ENERGY CONSUMPTION

ABDULLAH MOHAMED ABDULWAHAB

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By

ABDULLAH MOHAMED ABDULWAHAB

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Master of Science

March 2017

DEDICATION

Every challenging work needs self-efforts as well as guidance of elders especially those who were very close to our heart

My humble effort I dedicate to my sweet and loving

My Grand Father and Mother,

(**Mr. and Mrs. / ABDULWAHAB AL-FAKHREY**),

My Father and Mother,

(**Mr. and Mrs. / MOHAMED AL-FAKHREY**),

My Brothers and Sister,

(**MAHMOOD, NOORALDEEN, AND ZEINAB**)

Whose affection, support, encouragement, and love make me get much confidence in myself as well as their prayers for day and night make me able to get such success and honour

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement of the Degree of Master of Science

EXPERIMENTAL AND NUMERICAL INVESTIGATION ON THE OPTIMUM DISTANCE OF A REFRIGERATOR FROM ROOM WALL FOR MINIMUM ENERGY CONSUMPTION

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March 2017

Chairman : Associate Professor Nor Mariah Adam, PhD
Faculty : Engineering

In recent decades, the demand on saving energy and resources has risen to an important limit, in both the industrial and residential sectors. In Malaysia, refrigerators-freezers are considered to be among the largest consumers (26.3%) of residential electricity. The aim of this study was to carry out experimental and numerical investigations to determine optimum distance between the refrigerator and room wall for minimum energy consumption. Furthermore, the influence of air velocity (natural and forced air convection) around the compressor and condenser, frequency of door openings in residential and commercial cases, and different room (kitchen) temperatures, on the energy consumption of the refrigerator were investigated using experimental method. Experiments were carried out on a 150-liter Single-door refrigerator model iR-133C, manufactured in Malaysia. The influence of air velocity on the energy consumption of refrigerator was tested in three scenarios through the experiment. First, as the refrigerator comes from the factory, second by implementing a ventilation system with fan speed of 0.85 m/s, and third with fan speed of 1.65 m/s. Door opening was tested for 60 and 120 times/day in residential and commercial cases respectively through the experiment. In addition, the influence of room (kitchen) temperatures at 25 and 30 °C were also investigated. Distances between the back wall of the refrigerator and the room wall (3, 6, 9, 12, and 15 cm) were applied to the simulation with Malaysian kitchen temperature. The energy consumption was measured through all experiments using FLUKE 345 power quality clamp meter. 3D Computational Fluid Dynamic (CFD) geometries were created using Design Modeler software then, meshed with patch conforming tetrahedral mesh using ANSYS meshing. The simulation was performed using a commercial CFD code FLUENT (ANSYS workbench Version 16.1). The results showed an 8°C decrease in the temperature around compressor compartment within 332.2 Wh/day reduction in the energy consumption of refrigerator was recorded due to 1.65 m/s air velocity. Moreover, 28 % increases stated in the OFF compressor cycle time due to 1.65 m/s air velocity. The results of energy consumption of refrigerator showed 61.2% and 97.1% increases due to door openings for 60 and 120 times/day in residential and commercial scenarios, respectively. In addition, results demonstrated 42 Wh increases in the energy consumption of refrigerator for each 1°C increase in room (kitchen) temperature. The numerical results showed that 12 cm is the optimum distance of refrigerator from room wall for better air flow for the heat that rejected by compressor and condenser. Good agreement was achieved between the numerical and experimental results with 4 % of error. In addition, 26.6 Wh/day reduction in the energy consumption of refrigerator due to place the refrigerator at 12 cm from room wall.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Master Sains

KAJIAN EKSPERIMENTAL DAN BERNOMBOR KE ATAS JARAK OPTIMA SEBUAH PETI SEJUK DARI DINDING BILIK UNTUK PENGGUNAAN TENAGA YANG MINIMA

Oleh

ABDULLAH MOHAMED ABDULWAHAB

Mac 2017

Pengerusi : Profesor Madya Nor Nor Mariah Adam, PhD
Fakulti : Kejuruteraan

Dalam dekad terkini, keperluan untuk menyimpan tenaga dan sumber telah menjadi semakin penting, dalam kedua-dua sektor industri dan perumahan. Di Malaysia, peti sejuk- peti pembeku dianggap sebagai pengguna terbesar elektrik di rumah-rumah (26.3%). Tujuan kajian ini ialah untuk menjalankan kajian eksperimental dan numerikal untuk menentukan jarak optima di antara peti sejuk dan dinding bilik untuk penggunaan tenaga minima. Tambahan pula, pengaruh halaju udara (konveksi udara yang bersifat semulajadi dan dipaksa) di sekeliling pemampat dan kondenser, frekuensi bukaan pintu dalam kes kediaman dan komersial, dan suhu bilik (dapur) yang berbeza, ke atas penggunaan tenaga peti sejuk dikaji menggunakan metod eksperimen. Eksperimen dijalankan ke atas satu peti sejuk model iR-133C, 150-liter yang dikilang di Malaysia. Pengaruh halaju udara ke atas penggunaan tenaga peti sejuk diuji dalam tiga senario melalui eksperimen. Pertama, oleh kerana peti sejuk datang dari kilang, kedua dengan menjalankan satu sistem pengudaraan dengan laju kipas 0.85 m/s, dan ketiga denagn lajunya 1.65 m/s. Bukaan pintu diuji untuk 60 dan 120 kali/sehari dalam kes kediaman dan komersial masing-masing, melalui eksperimen yang dijalankan. Tambahan pula, pengaruh suhu bilik (dapur) pada 25 dan 30 °C turut dikaji. Jarak di antara dinding belakang peti sejuk dan dinding bilik (3, 6, 9, 12, dan 15 cm) diaplikasi kepada simulasi dengan suhu dapur Malaysia. Penggunaan tenaga disukat melalui semua eksperimen menggunakan FLUKE 345 meter kuasa pengapit berkualiti. Geometri Dinamik Bendalir Komputasional 3D (CFD) dihasilkan menggunakan perisian Pemodel Rekabentuk, dijaring dengan jaringan tetrahedral yang serasi dengan tompok menggunakan jaringan ANSYS. Simulasi dibuat menggunakan kod CFD komersial FLUENT (meja kerja ANSYS Versi 16.1). Keputusan menunjukkan penurunan 8°C dalam suhu di sekitar bahagian pemampat dalam pengurangan 332.2 Wh/ hari dalam penggunaan tenaga peti sejuk yang dilaporkan berikutan halaju udara 1.65 m/s. Tambahan pula, peningkatan 28 % yang dinyatakan dalam masa kitaran pemampat OFF adalah disebabkan oleh halaju udara 1.65 m/s. Keputusan penggunaan tenaga dalam peti sejuk menunjukkan peningkatan 61.2% dan 97.1% berikutan bukaan pintu untuk 60 dan 120 kali sehari

dalam senario kediaman dan komersial, masing-masing. Tambahan lagi, keputusan menunjukkan peningkatan 42 Wh dalam penggunaan tenaga peti sejuk untuk setiap peningkatan 1°C dalam suhu bilik (dapur). Keputusan bernombor menunjukkan bahawa 12 cm adalah jarak optima peti sejuk dari dinding bilik untuk mendapatkan aliran udara yang lebih baik untuk haba yang ditolak oleh pemampat dan kondenser. Persetujuan yang baik dicapai di antara keputusan numerikal (bernombor) dan eksperimental dengan ralat 4%. Seterusnya, pengurangan 26.6 Wh/hari dalam penggunaan tenaga peti sejuk adalah disebabkan kedudukan peti sejuk pada 12 cm dari dinding bilik.

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Last but not least, I would like to express my heartfelt gratitude to my parents, my brothers and sister for their support and motivation throughout this research work.

I certify that a Thesis Examination Committee has met on 29 March 2017 to conduct the final examination of Abdullah Mohamed Abdulwahab on his thesis entitled "Experimental and Numerical Investigation on the Optimum Distance of a Refrigerator from Room Wall for Minimum Energy Consumption" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Master of Science.The members of the Supervisory Committee were as follow:

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Declaration by graduate student

I hereby confirm that:

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This is to confirm that:

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Name of Member of Supervisory Committee: Dr. Azizan As'arry

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C_{μ}	Function of the mean strain and rotation rates	
A	Area	m^2
C	Celsius	
$C_{1\varepsilon}$, C_2	Constants	
C_p	Specific heat capacity	J/kg.k
d	Diameter	m
D_H	Hydraulic diameter of the pipe	m
F	Fahrenheit	
g	Gravitational acceleration	m/s^2
G_b	Generation of turbulence kinetic energy due to buoyancy	
G_k	Generation of turbulence kinetic energy due to the mean velocity gradients	
Gr	Grashof number	
h	Heat transfer coefficient	W/m^2 K
K	Thermal conductivity	W/m K
k	Turbulent Kinematic Energy	J/kg
kWh	kilo Watt hour	
L	Characteristics traveled length	m
l	Tube length	m
L	Litre	
N	Number of wires	
Nu	Nusselt number	
P	Pitch	m
P	Pressure	N/m^2

Pr	Prandtl number	
Q	Heat rejected	W
Ra	Rayleigh number	
Re	Reynold number	
S_{ij}	Strain rate tensor	
S_k, S_ε	User-defined source terms	
T	Temperature	K
Tij	Viscous stress tensor	
u,v,w	Components of velocity in x, y, z direction	m/s
V	Velocity	m/ s
Y_M	Contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate	
σ_k, σ_ε	Turbulent Prandtl numbers for k and ε	
ΔT	Temperature difference between the two ends of the solid	K

Subscripts

f	Film
—	Average value
'	Fluctuation
Cond.	Conduction
Conv.	Convection
e	Equiangular cell
ele	Element
eq	Equivalent
H	Higher isotherm
i	Inner

L	Lower isotherm
max.	Maximum, largest angle
min.	Minimum, smallest angle
o	Outer
o,tube	Outer tube
rad.	Radiation
Ref	Refrigerant
t	Tube
w	Wall
wire	Wire of condenser

Greek letters

υ	Kinematic viscosity	m^2/s
ρ	Density	kg/m^3
β	Coefficient of expansion	1/K
μ	Dynamic viscosity	kg/m.s
∞	Ambient conditions	
ε	Thermal emittance, Turbulent dissipation rate	m^2/s^3
σ	Stefan Boltzmann constant (σ) is $5.67x10^{-8}$	W/m^2K^4
σ	Standard deviation	
T	Shear stress	pa
λ	Material constant	
θ	Angle of cell	degree
π	Pi	

LIST OF ABBREVIATIONS

AHAM	Association of Home Application Manufacturers
ANSI	American National Standards Institute
ANZS	Australian- New Zealand Standard
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CFD	Computational Fluid Dynamic
CNS	Chinese National Standard
COP	Coefficient of Performance
DOE	Department of Energy
EU	European Union
GWP	Global Warming Potential
IEA	International Energy Agency
ISO	International Standards Organization
JIS	Japanese Industrial Standard
MEPs	Minimum Energy Efficiency Standard
OQ	Orthogonal Quality
RH	Relative Humidity
USD	US Dollar
UPM	Universiti Putra Malaysia

CHAPTER 1

INTRODUCTION

1.1 Background of the Problem

In electrified houses in Malaysia and worldwide, the electrical appliances especially refrigerator-freezer, fan, television, rice cooker as well as lighting are basic household appliances. The increasing in the energy consumption of those appliances per year due to the population growth, as well as economic growth (Mahlia et al., 2004). Refrigerators-freezers have becoming mandatory equipment in every house, shop, restaurant and other places with many brands and types such as single door, double door, frost free, direct cool, single zone beverage, dual zone beverage, side by side door, bottom mounted, top mounted, and so many others. Figure 1-1 shows main types of refrigerator-freezer in the market (Nathanielberman, 2016).

Refrigerator-freezer is considered as the highest electrical consumer in the household in Malaysia. Residential sector of Malaysia consumes about 21% of total electricity, whereas every domestic refrigerator consumed about 26.3% of residential electricity demand (Agus et al., 1993; Reddy et al., 1993; Ahmed et al., 2011; Saidur et al., 2006).

The total electricity in the residential sector is shown in Figure 1-2 (Agus et al., 1993) and the electricity pattern for a single household is shown in Figure 1-3 (Saidur et al., 2006).

Figure 1.1 : Different types of refrigerator (Nathanielberman, 2016)

Modifications in shape and design on each refrigerator allow it to keep up with the development of more efficient equipment. A survey was carried out by Agus (1993) found that 76% of Malaysian houses have one refrigerator, and 9 out of 100 households own more than one refrigerators. The refrigerator size range from 148–600 litre and consume about 2–3 kWh; a small number consume more than 4 kWh (Saidur et al., 2008).

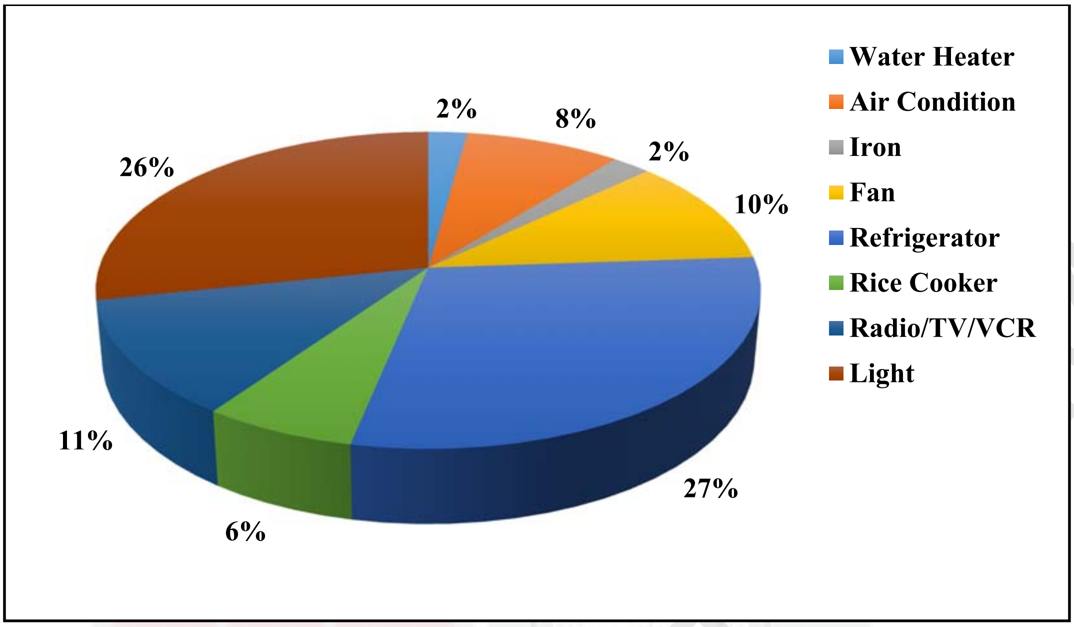

Figure 1.2 : Overall residential electricity share (Agus et al., 1993)

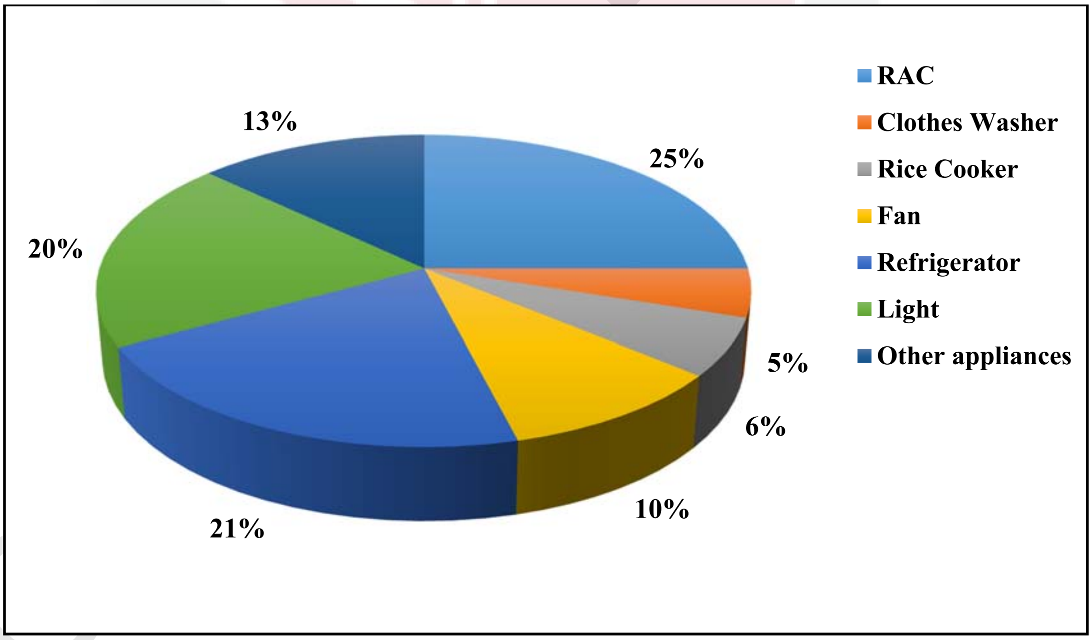

Figure 1.3 : Electricity pattern for a single household (Saidur et al., 2006)

The energy consumption of domestic refrigerators-freezers appliances in each household becomes one of the most important things that has attracted significant attention; as a result, the energy efficiency standards and green labels have been achieved by some governments like in Malaysia and worldwide, in order to replace inefficient stock (Mahlia and Saidur, 2010, Harrington, 2009). Implementing the standards and green labels are very useful for all countries, to give them the ability to motivate users to use energy efficient appliances (Masjuki et al., 2001). The relevant and common standards that applied to the refrigerators-freezers are ISO 8187, ISO

8561, and ISO 7371. The standards have shown applicability and acceptability to apply the ISO energy for the refrigerator-freezer and the respect to Malaysian climatic conditions (Mahlia et al., 2002).

Many researchers studied different variables to improve the efficiency and energy consumption of refrigerator. Technical components influenced the efficiency and energy consumption of refrigerator were studied such as the refrigerant type, amount of charging refrigerant, compressor cooling capacity, capillary tube diameter, condenser air cooling increment, and the insulation. Moreover, factors such as ambient temperature, internal temperature, the number of door openings, load and placing of warm products have been studied by several researchers (Boeng and Melo, 2014; Hasanuzzaman et al., 2008; Hasanuzzaman et al., 2009; D. Liu et al., 2004; D.-Y. Liu et al., 2004; Masjuki et al., 2001; Mastrullo et al., 2014; Mohanraj, 2013; Rasti et al., 2013; Saidur et al., 2002).

1.2 Problem statement

The refrigerator-freezer is the highest consumer of electricity in a household (Agus et al., 1993; Mahlia et al., 2004). It consume about 26.3% of residential electricity demand (Agus et al., 1993; Reddy et al., 1993; Ahmed et al., 2011; Saidur et al., 2006). Many researchers studied the influence of different variables to improve the efficiency and the energy consumption of a domestic refrigerator. They show that, it is possible to increase the efficiency and reduce the energy consumption of refrigerator by investigating many parameters such as refrigerant type, the amount of charging refrigerant, compressor cooling capacity, capillary tube diameter, condenser air cooling increment, and the insulation. Environmental factors such as ambient temperature, internal temperature, the number of door openings, load and placing of warm products. (Hasanuzzaman et al., 2008; Hasanuzzaman et al., 2009; Mohanraj, 2013; Rasti et al., 2013; Saidur et al., 2002; Afonso, 2013; Afonso and Matos, 2006; Alissi, 1987).

An experimental studies on the influence of room temperature and door openings of the refrigerator in a household on the energy consumption of refrigerator without including air velocity effect around the compressor and condnser were conducted by Hasanuzzaman (2009); Hasanuzzaman (2008); Saidur (2002) and Masjuki (2001). Moreover, those studies were not conducted in Klang Valley area / Malaysia.

An experimental and numerical studies conducted by Bassiouny (2009) were to investigate the effect of the space surrounding the condenser of the household refrigerator on the heat rejected only. The study did not included the effect of air velocity around compressor and condenser tube, number of door opening, kitchen temperature of Malaysia and load level on the energy consumption of refrigerator. In addition, it was not conducted or repeated in Malaysia.

Therefore, there is a need to improve the energy efficiency and reduce wastage through a passive method in Malaysia .This study focuses on the refrigerator and the factors affecting the energy consumption. The study describes an experimental work to determine the influence of some factors such as air velocity, frequency of door openings in both residential and commercial cases and different room (kitchen) temperatures on the energy consumption of a domestic refrigerator. In addition, experimental and numerical simulation works to determine the optimum distance of refrigerator from the room wall for minimum energy consumption.

1.3 Study Objectives

The aim of this research is to determine the optimum distance of the refrigerator from room wall for minimum energy consumption of the refrigerator using experimental and numerical methods.

The specific objectives are as follows:

1. To determine the influence of air velocity, frequency of door openings and room (kitchen) temperatures on the energy consumption of refrigerator also to use some of them as input parameters into the numerical analysis.
2. To determine the optimum distance (gap) of the refrigerator from room wall.
3. To compare the numerical results that have been conducted in the second objective using experimental method.

1.4 Scope and Limitations

Improving refrigerator efficiency and reducing the wastage is achieved through experimental and numerical methods. The current study is focused on some parameters that can help to improve the efficiency and reduce the energy consumption of domestic refrigerator.

The limitation of study are:

1. Selected refrigerator of 150 litre single-door, model iR-133C, manufactured in Malaysia used as a test unit through the experimental sections of this study.
2. Field data on residential (houses) and commercial places are in Klang Valley / Malaysia for door openings of refrigerator and room (kitchen) temperatures.
3. In the CFD analysis, the viscous model used is Realizable k-ε turbulence model as well as, the other schemes are chosen based on the ANSYS FLUENT Theory Guide (Kayne and Agarwal, 2013; ANSYS FLUENT 13 User's Guide, 2013; Boonloi and Jedsadaratanachai, 2016; Rakhsha et al., 2015).
4. The refrigerator distance (gap) is taken as (3, 6, 9, 12 and 15 cm) from the wall.
5. Using theoretical calculation for the heat transfer coefficient of compressor and condenser.
6. A verification case study was conducted to make sure the accuracy of ANSYS-FLUENT Version 16.1 used based on the study by Bassiouny (2009).

7. The output parameters of the experimental sections are the energy consumption based on the reading of FLUKE 345 power quality clamp meter, and the temperature at different points of refrigerator using thermocouple wires type K. On the other hand, the temperature distribution and velocity profile around the compressor, condenser and at the optimum distance between the refrigerator and the room wall were from the numerical simulation section.

The hypothesis of study is the distance (gap) between the refrigerator and the room wall which is taken as (3, 6, 9, 12 and 15 cm), is the dominant factor for the energy consumption of domestic refrigerator to improve the energy efficiency and reduce wastage in Malaysia. In addition, the wood plenum as a ventilation system has fabricated to vary the air velocity at the base of the refrigerator through the experimental sections.

The study scope is to present a passive method to improve the energy efficiency of the refrigerator and reduce the wastage in Malaysia. Further, determination the optimum distance (gap) of refrigerator from the room wall for minimum energy consumption.

1.5 Thesis Outline

This thesis involves five chapters, the thesis starts with an introduction in chapter one. The second chapter is the literature review that contains the review of previous studies related to the subject of the research. Material and methods are the subject of the third chapter. This chapter is divided into three main sections. First is an experimental method that covers the fabrication processes of the ventilation system used at the base of the domestic refrigerator. Test procedures and methods are also presented in this section. The second section is numerical simulation method that contains creating geometries, meshed domains, CFD approaches and governing equations and boundary conditions used in this simulations. The third section is an experimental (validation) method that covers the process of validating the numerical results for the optimum distance of the domestic refrigerator from room wall. Furthermore, the method for measuring the energy consumption of the refrigerator, as well as the equipment's used through all experimental sections of this study. Chapter four is the Results and Discussion. In this chapter, detailed results of experimental and numerical simulations studies are presented, as well as the validation of the numerical and experiment results. The main core of this chapter is to determine the optimum distance of the refrigerator from the room wall. In addition, the effects of various parameters on the energy consumption of domestic refrigerator. Discussions around results especially the comparison between effects of different variables are carried out to meet the thesis objectives and targets. Finally, Chapter five presents the conclusion of this study and recommendations for future work.

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