DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

INVESTIGATION OF BLOWN MATERIAL EFFECTS ON THERMAL CONDUCTIVITY AND INSULATION THICKNESS ON REFRIGERATORS

by

Gizem DURU

August, 2020

İZMİR

INVESTIGATION OF BLOWN MATERIAL EFFECTS ON THERMAL CONDUCTIVITY AND INSULATION THICKNESS ON REFRIGERATORS

A Thesis Submitted to the
Graduate School of Natural and Applied Sciences of Dokuz Eylül University
In Partial Fulfillment of the Requirements for the Degree of Master of Science
in Mechanical Engineering, Energy Program

by
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August, 2020
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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"INVESTIGATION OF BLOWN MATERIAL EFFECTS ON THERMAL CONDUCTIVITY AND INSULATION THICKNESS ON REFRIGERATORS"** completed by **GİZEM DURU** under supervision of **PROF. DR. DİLEK KUMLUTAŞ** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ACKNOWLEDGEMENTS

First of all, I would like to thank my supervisor, Prof. Dr. Dilek KUMLUTAŞ, for her incomparable knowledge and moral support, valuable advises and guidance throughout this thesis study.

I also wish to express my gratitude to Dr. Özgün ÖZER and Res. Ass. Utku Alp YÜCEKAYA for their patience and help.

Additionally I would like to thank my business chef İsmail KIRBAŞ to support my academic carrier.

Finally, I would like to gratefully thanks to my family and Tezol EREL for their endless encouragement, patience and valuable support in every part of my life.

Gizem DURU

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ABSTRACT

As energy efficiency and sustainability become more important with each passing day, the expectations of the materials used for refrigerator insulation have increased. Polyurethane is one of the most common insulation materials today. The choice of blowing agent is a significant subject which is focused on polyurethane to increase the thermal insulation. The blowing agent is among important factors on the total heat transfer coefficient and insulation performance because of its effect on the air additive rate in the polyurethane foam.

In this study; the thermal design of a refrigerator and the effect of the blowing agents in the polyurethane on this design were investigated by the computational fluid dynamics. The blowing agents investigated in this study are pentane and LBA materials.

Keywords: Insulation, polyurethane, blowing agent, thermal conductivity, insulation thickness

BUZDOLAPLARINDA ŞİŞİRİCİ MALZEMENİN ISI İLETİM KATSAYISI VE YALITIM KALINLIĞI ÜZERİNDEKİ ETKİLERİNİN ARAŞTIRILMASI

ÖZ

Enerji verimliliğinin ve sürdürülebilirliğin her geçen gün daha da önem kazanması sebebiyle, buzdolabı yalıtımı için kullanılan malzemelerden beklentiler artmıştır. Poliüretan ise günümüzde en yaygın kullanılan yalıtım malzemelerindendir. Isı yalıtımını arttırmak için poliüretan üzerinde yoğunlaşan çalışmalardan biri de şişirici ajan seçimidir. Şişirici ajan, malzemenin içindeki hava katkı oranını etkilediği için toplam ısı geçiş katsayısını ve yalıtım performansını etkileyen en önemli faktörlerden biridir.

Bu çalışmada; bir buzdolabının ısıl tasarımı ve poliüretana eklenen şişirici ajanların bu ısıl tasarıma etkisi parametrik olarak hesaplamalı akışkanlar mekaniği kullanılarak incelenmiştir. Çalışmada incelenen şişirici ajanlar pentan ve LBA malzemeleridir.

Anahtar Kelimeler: Yalıtım, poliüretan, şişirici ajan, ısıl iletkenlik, yalıtım kalınlığı

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CHAPTER ONE
INTRODUCTION

1.1 Literature

The aim of this study is to reduce the insulation thickness of the domestic refrigerator that is determined by the experimental and the numerical investigations. It' s seen from the literature that there are so many investigation about insulation, optimum insulation thickness, alternative insulation materials and methods on the refrigerators. Some of them are below:

"Buzdolabı Tasarımında Vakum Yalıtım Paneli Uygulamasının Sayısal Olarak İncelenmesi" Kumlutaş, Avcı, & Karadeniz (2013) studied on a refrigerator model which polyurethane and VIP were compared as thermal insulation technique numerically. The numeric model which validated by experimental methods analyzed and thermal load on evaporator and temperature distribution of interior air volume was obtained. Results of both PU and PU+VIP were computed and all alternative thermal design solutions were presented for this model.

Similarly, Yılmaz (2008) investigated energy consumption of a tabletop freezer which had been manufactured by using polyurethane and VIP as insulation material. Experimental studies that defined in the standards and results of computer aided analysis were discussed. At the end of the study, suggestions were presented for energy efficiency for the tabletop freezer.

Another study is about the effect of blowing agents alternatives on energy consumption and also environmental problems. These alternatives are used in polyurethane for household refrigerators' and freezers' insulation. After Energy Crisis of 1973, energy efficiency of household refrigerators and freezers are improved at developing countries. The CFC, HCFC and Cyclopentane were investigated as blowing agent and Dutt (1995) has questioned how they influence the global warming, ozone depletion and energy efficiency.

A chemical blowing agent (CBA) called HCOOH is investigated at another study to use other than water, which can replace phsyical blowing agents (Modesti, Baldoin, & Simioni, 1998). Researchers have underlined benefits and deficits after investigating the reaction of isocyanate±formic acid. Lots of occasions and challenges are came up by renewed reactions at the polyurethane chemistry.

Another important point is about formic acid usage in this study:

> Another important effect produced by using formic acid is the delay action on the reactivity profile that causes a prolonged gel time; this can be very important in applications where the flowability of PU systems is an important parameter. On the other hand, the employment of HCOOH and the generation of CO during the polymerization phase, with problems associated to corrosion of the devices and toxicological aspects are evident drawbacks that must be take into account. Its use with n-pentane would be more convenient, due to the fact that this compound requires already suitable safety measures (Modesti et al., 1998, p. 1240).

Polymer foams which are used in energy saving applications like wrapping or thermal isolation materials are investigated by Frerich (2015). To understand and predict the quality and material properties of polymer foams, concise knowledge of the factors influencing the foaming behaviour, especially pressure and temperature is required. Therefore, three biodegradable polyesters, namely poly (lactide) (PLA), poly (butylene succinate) (PBS) and a blend of poly (lactide) and poly (hydroxy butyrate) (PLA-PHB), have been subjected to a direct foaming procedure using compressed carbon dioxide as blowing agent, studying the influence of saturation temperature (ranging from 95 ◦ C to 175 ◦ C) and applied pressure (ranging from atmospheric pressure to 30 MPa) on the resulting foam material. These results depends on the melting attitude of the polymers. Calorimetric analysis in a screening transitiometer which has range to apply pressure levels up to 45 MPA is applied to all three polymers. The created porous materials were characterized by determining their density, porosity and morphology, using SEM analysis. Their mechanical behaviour was investigated by using compressive strength tests. It is shown that the quality of the produced foam structures and its properties is strongly depending on the foaming conditions. In order to obtain foams with a high quality, the saturation temperature and pressure have to be adapted to the phase transition liquid–solid of the polymer–gas system. The results obtained via scanning transitiometer represent the SLG-line of the binary systems polymer and CO2 , and their influence on the foaming behaviour enabled the identification of ideal foaming conditions for the three polymers regarded in this study.

At another study, Kuranska & Prociak (2012) investigated rigid polyurethane foams which modified with oil-based polyol and natural. At that study, the aim was providing cellular polyurethane composites which have similar better heat insulation and mechanical properties than reference material. The density of obtained polyurethane composites were about 40 kg/m3. Biodegradable components of prolongable raw materials are included in the modified composites. Compression strength and thermal conductivity of the rigid polyurethane composites are analyzed by the effect of the rapeseed oil-based polyol, flax and hemp fibres of different length on the cell structure, closed cells content, apparent density The highest compressive strength and the lowest thermal conductivity were acquired at the foam composites when include fibre in the amount of 5% php (per hundred polyols).

Kwon, Jang, Jung, & Song (2009) investigated three thermal transport mechanisms of different loading materials for Vacuum Insulation Panels (VIPs). At the beginning, foam, powder, staggered beam and fiber which are solid conductivities of porous materials anda re exposed to atmospheric compression are reproduced.

Because of the different lenght of thermal path, fiber and staggered beam insulation have inferior solid conductivities than powder and foam. Gaseous conductivity, the second mechanism, demonstrates that fine powder has the lowest because of its smallest stoma size. At last the radiative conductivity is determined by diffusion approximation. Negligible radiation effect occurs at staggered beam when radiation shield are installed. The fiber and staggered beam are appropriate filling materials for VIPs due to total effective conductivites.

In the literature, the investigations of blowing agent which affects the heat transfer coefficient of polyurethane foam are generally made by experimental methods with polyurethane samples. Five polyurethane samples are prepared with various blowing agents of CP, CP + IP, CP + 245fa, CP + 245fa lower gas pressure and CP + 245fa + LBA by Zhang, Fang, Li, & Tao (2017). Thermal conductivities were measured using transient plane source method under various environmental conditions like long time storage, high & low temperature and humidity. End of the study, effect of thermal performance of all types of blowing agents on PU foam samples were revealed (Zhang et al., 2017).

Another study is about the devoloping a strategy for optimum insulation thickness of domestic refrigerators. Trias et al., (2018) studied an analytical approach based on the Lagrange multipliers method. This mathematical model determined the optimum insulation solutions for one and two compartmented refrigerators. In this study, while analyzing the distribution of insulation thickness, heat loss, energy efficiency and internal volume value parameters were discussed.

Johnson (2004) investigated the performance of two different blowing agents which are used in a household refrigerator, in terms of energy efficiency and global warming effect comparatively. The agents he studied are pentane (a blend formulation) and HFC-245fa. Three combi model (bottom freezer) refrigerators were produced by foaming with pentane, three similar in all respects refrigerators were produced by foaming with HFC-245fa agent. The energy tests of the manufactured cabinets were conducted according to ISO standards and the results were presented in this study.

In the literature, there is no study investigating how different blowing agents affect the thermal performance of a whole refrigerator thermal system. In this study, a single door refrigerator model consisting only a cooling part has been studied numerically. The parametric analysis was carried out on a numerical model which was validated by applying the experimental methods. Considering the thermal uniformity and minimization of heat losses, the effect of the blowing agent on optimum insulation design for the refrigerator was investigated.

CHAPTER TWO

INSULATION FOR REFRIGERATION

2.1 History of Insulation for Refrigerators and Freezers

According to report of Safeguarding the ozone layer and the global climate system (2005), "The appliance market is highly competitive in all regions of the world and subject to stringent energy regulations in some places. The cost and performance characteristics of the insulating material are therefore both important parameters." (p. 322). Additionally, while precluding the emplacement which could take place with further non-foam insulation types, to maximize interior area and decrease wall thickness the finest feasible insulation amount is indicated. Decreasing energy depletion and reform at production is started by the utilization of polyurethane foam as an another possibility to mineral fibre to insulate household appliances in Europe on 1950s. As a key factor in succeeding impressive developments in device efficiency, this technology is now globally used.

The IPCC reports that today, despite the depletion of energy resources (especially fossils), the need for energy increases exponentially and energy unit prices rise rapidly. This leads to new searches for the efficient use of energy in many countries with limited resources. Refrigerators and freezers (R-F) are a major technological interest due to their great benefits, common use, energy spending and additive to ecological corruption (Little et al., 1993).

To reduce the heat gain of the R-F which is using polyurethane foam currently, insulation must be increased. For this, the thickness of the cabinet must be increased that means either the outer dimensions should be increased or the internal volume reduced [Advanced Insulations for Refrigerator/Freezers, www.osti.gov]. Decreasing interior volume of refrigerator dimensions reduces the advantage of the product for users, on the other hand increasing external dimensions may be difficult for built-in spaces in kitchens.. Thermal insulation and general assembly designs that provide a high level of thermal resistance can have a significant value for a given thickness, especially in larger model R-Fs (Griffith, & Arasteh, 1995).

Polyurethane is an extremely efficient insulation for use in household refrigeration devices.

2.2 Alternative Material for Refrigerator Insulation

Refrigerators and freezers perform non-stop in a day. The energy efficiency of these devices, which consume energy continuously, is very important. Therefore, the performance of the refrigerator insulation has the fundamental role for the consumption of energy.

Limits of energy classes are regulated according to energy efficiency strategy. Therefore, the household refrigerators and freezers which have upper than A+ energy class have been exported/imported since 2012 (Kumlutaş et al., 2013).

2.2.1 Vacuum Inslation Panels (VIPs)

The global energy crisis and the risk of ODP forced the development of thermal insulation technology. In recent years, one of the most important progress in insulation industry is Vacuum Insulation Panels (VIP). VIPs occur of a filling material coated with a thin, super barrier film. The system which is closed to atmosphere, is discharged to a vacuum to very low pressure and sealed. the applied vacuum depends on the characteristic of the core material and the required thermal capacity of the finished panel. When VIPs are replaced with a portion of polyurethane rigid foams as insulation material, they can save energy without a significant volume decrease in household refrigerators. The capacity of thermal resistance of VIPs is directly related to the vacuum degree. when the pressure inside the panel exceeds 1 mbar, the thermal conductivity increases sharply. Diagram of thermal conductivity of some materials as a function of glass (air) pressure is shown in Figure 2.1 (Yang, Li, Gao, & Xu, 2012).

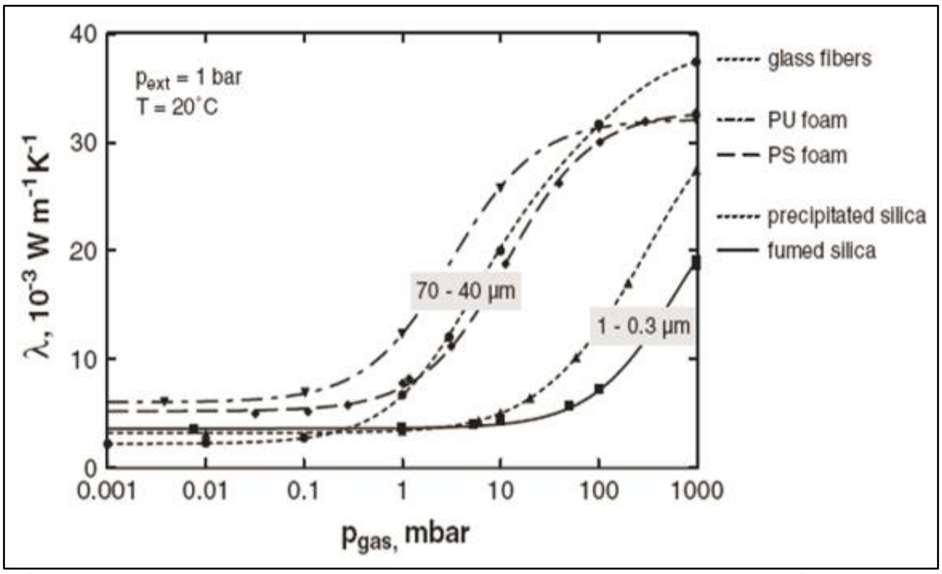

Figure 2.1 Thermal conductivity of fibers, powders and foams as a function of glass (air) pressure (Yang et al., 2012)

The VIPs are envelope shaped insulation materials which consist of multilayer laminate films as shown in Fig. 2.2. The inside of this structure is filled with a core material that constituents panel thickness. Then the filled envelope is discharged to the required vacuum pressure. Finally edges of envelope shaped panel is sealed by heat (Araki, Kamato, & Matsuoka, 2009).

As shown in Figure 2.2, VIP structere consists of respectively, the outer surface layer, two middle layers, gas barrier film, inner layer and finally film layerwith heat-sealing properties (Araki et al., 2008).

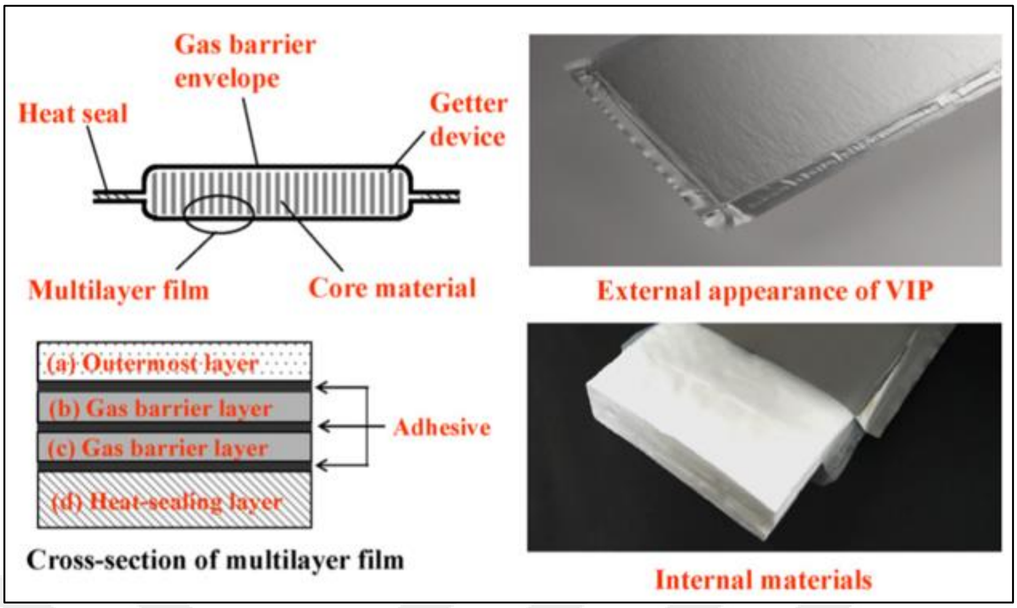

Figure 2.2 VIP structure (Araki et al., 2008)

2.3 Characteristics of Polyurethane

The most common material used in refrigerator insulation is rigid polyurethane foam (PUR and PU). Polyurethane is a polymer composed of an organic unit chain joined by urethane linkages. In addition, thermoplastic polyurethanes are also available. Polyurethane polymers are generally formed by reacting a di- or poly-isocyanate with a polyol. Polyurethanes are formed between alcohols with least two reactive hydroxyl (-OH) groups per molecule and isocyanates that have more than one reactive isocyanate group (-NCO) per molecule as shown in Figure2.3. (Polyurethanes, nd).

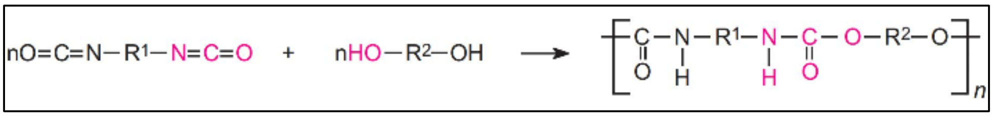

Figure 2.3 Diisocyanate reaction (Polyurethanes, n.d.)

2.3.1 Isocyanates

Diisocyanates is one of the essential reactive materials required to produce polyurethanes. Diisocynates are characterized by an (NCO) group that is highly reactive alcohols. Isocyanates are divided into three groups which are aromatic, aliphatic and cycloaliphatic (Çalış, 2007).

Polymeric isocyanates (Figure 2.4) are the most common isocyanates (PMDI) used in the production of polyurethane.

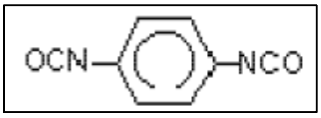

Figure 2.4 P-phenylene diisocyanate (PPDI, C8H4O2N2) (Çalış, 2007)

2.3.2 Polyols

Another raw material used in polyurethane production is polyol. Polyols are compounds having at least two and more hydroxyl groups in their structure. Polyether and polyester bases are mostly used as polyols. The molecular weight of polyols used in polyurethane production ranges from 200-10,000 g / mol (Çalış, 2007). High quality polyurethane foams and elastomers are produced with polyether-based polyols. The most important polyether polyols are; 1.4-polybutanediol (polyBD), polytetramethylene ether glycol (PTMEG), propylene oxide glycol (PPO) and polybutylene oxide glycol (Çalış, 2007).

2.4 Blowing Agents

Such as metals, polymers and plastics, the blowing agent can be able to produce cellular construction by induration or phase transition. Blowing agents are implemented while they are in fluid phase. Density reduces, acoustic and thermal insulation increases by the cellular construction as the notional hardness of actual polymer increases.

Blowing agents which generate holes in a matrix bringing out cellular materials, have been categorized as physical blowing agents e.g. CFCs, HCFCs, hydrocarbons (e.g. pentane) and liquid CO2. Heat is needed at the buble/foam producing, which is bilateral and endothermic process, to fugacious a fluid blowing agent. In addition to this a bilateral process occurs when the blowing agent condenses.

Sodium bicarbonate, which is also called aka baking soda and takes part in thermoplastic foams, water and isocyanate, nitrogen-based materials, which are used in thermoplastic and elastometric foams, are all chemical blowing agents.

In 1987, the Montreal Protocol was signed to prevent the ozone layer depletion by phasing out the usage of some agents such as CFCs (chlorofluorocarbons) and HCFCs (hydrochlorofluorocarbons). CFCs have been phased out since 1996 in industrialised countries, and recently in developing countries.

Because of their lower ODP (Ozone Depletion Potential), HCFCs have been an established intermediate alternative to CFCs. In foam productions HCFC141b is prohibited in the European Union or the United States of America, (Polyurethanes; Blowing agent options for insulation foamafter HCFC phase out, nd) HCFC141b has been the preferential blowing agent in most countries at last decade. Nations signed the 19th protocol of the Montreal protocol in 2007 for the rapid end of HCFCs. The usage of HCFC141b peaked at 2013 and started to reduce by 2015 until to 2030 at developing countries. (Polyurethanes; Blowing agent options for insulation foamafter HCFC phase out, n.d.)

A decade ago the transition from HCFC141b to alternative blowing agents took place in most industrialized countries. (Polyurethanes; Blowing agent options for insulation foamafter HCFC phase out, nd) Different blowing agent options are showned in Figure 2.5. Pentane is prefered with a wide range for its' reliable usage and foam performance in Europe. Global warming potential is one of the important parameter when looking for alternative to HCFC141b. The development of HFOs began with the definition of HFCs in the Kyoto Protocol as industrial gases requiring emission control due to high GWP. HFOs with very low GWPs are expected to last a few years in industry.

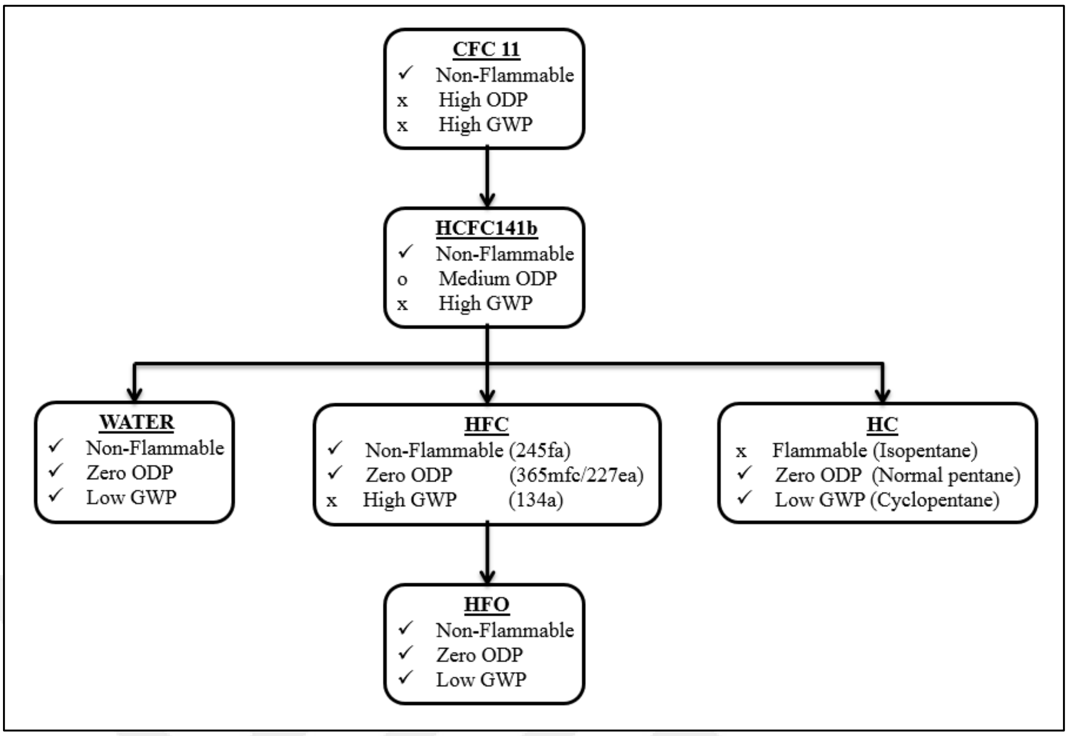

Figure 2.5 Properties of alternative blowing agents

2.4.1 LBA

In response to global warming potential (GWPs) and energy efficiency, new blowing agents have been developed in the polyurethane industry. Liquid Blowing Agent (LBA) is the latest development in technology of blowing agent foam. It's based on hydrofluoro-olefin (HFO) chemical structure.

Some commercial refrigerator manufacturers have initiated studies on the LBA instead of pentane which is the most common blowing agent. LBA offers almost 99.9% advantage over global warming potential, especially when compared to HFC-245fa.

LBA has also better thermal insulation capacity than other blowing materials of past generation. The use of LBA instead of pentane as blowing agent has advantages such as reducing the energy consumption and insulation thickness of refrigerator.

CHAPTER THREE

EXPERIMENTAL MEASUREMENT

3.1 Thermal Conductivity Measurement

The thermal conductivity coefficient of the insulation materials is measured by two methods: steady state and transition. The common method is the heated plate method in steady state. For this method, the average thermal conductivity of a plate-shaped test sample is determined, which is placed symmetrically on both sides of a heated plate. The measuring devices, in case of transition, can detect the thermal conductivity of smaller size materials in a shorter time.

The main transition methods are Angstrom Method, Flash Method, and Hot Wire Method (Gönenlioğlu, & Avcı, 2007). Thermal conductivity coefficient measuring device (Shotherm QTM-D2) was developed at our laboratory via using Hot Wire method, and it is able to measure the thermal conductivity coefficient between 0.02-10 W/m.K.

The thermal conductivity coefficient at customary Hot Wire Method is approximately determined by below formula:

$$k = \frac{q.\ln(\frac{t_2}{t_1})}{4.\pi \Delta T} \tag{3.1}$$

q: Heat flux of wire which is passing through the center of the sample material, [kcal/h.m]

t: Time, [h]

ΔT: Temperature Difference, [ºC]

With some transformations in the formula, (q=0.85 R.I^2 ve V= η.T), below new formula is obtained.

$$k = \frac{K.I^2\ln({t_2}/{t_1})}{V_2 - V_1} - H \tag{3.2}$$

V1, V2 : Voltage, [mv]

I : Current [amp]

K, H : Constants of device

In the Hot Wire method, the heating wire is placed between two samples. If one of the samples is a well insulated material with known thermal conductivity coefficient, the thermal conductivity coefficient of the other plate is determined by the equation (3.2). Each standard QTM probe has different K and H constants. When these constants are replaced, the thermal conductivity coefficient is calculated by the formula (3.2) with a microcomputer inside the device. Within a few seconds, the thermal conductivity coefficient for a given temperature value of the material is numerically displayed on the screen. Thermal conductivity coefficient is measured by SHOTHERM QTM – D2 device (Figure 3.1) in Heat Laboratory at DEU Mechanical Engineering Department.

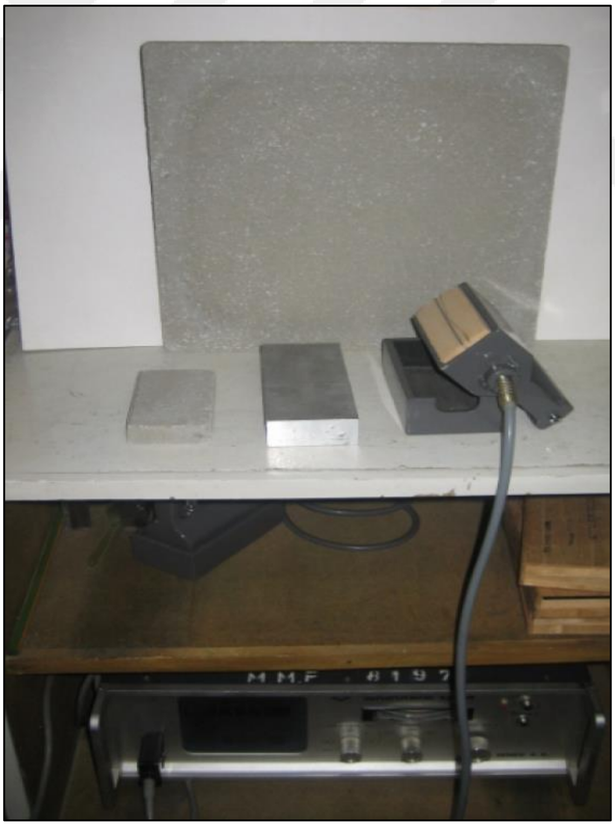

Figure 3.1 Shotherm QTM – D2 (Personal archive, 2015)

5 pcs sample were prepared to the suitable size (Figure 3.2) for measurement. The refrigerator cabinet was produced using polyurethane foam with blowing agent LBA.

After producing, 5 pcs samples were cut of and taken from the refrigerator cabinet and following this, the measurements were carried out in the laboratory. Results of experimental measurements are shown in Table 3.1.

Figure 3.2 A sample view of a LBA - PU foam (Personal archive, 2015)

Table 3.1 Results of experimental measurements

Sample No	**Initial Temp. (°C)**	**Final Temp. (°C)**	**Measurement Temp. (°C)**	**Thermal Conductivity Coefficient (W/m.K)**
1	26	37	32	0.0188
2	26	39	33	0.0174
3	27	39	33	0.0176
4	28	40	34	0.0176
5	28	40	34	0.0169
			Average:	0.01766

CHAPTER FOUR

NUMERICAL STUDY

4.1 Preparing the Cad Model For Numerical Study

The CAD data of interior air volume for numerical study was obtained from a commercial household refrigerator model of white goods manufacturer. The internal volume dimensions of refrigerator model are 170cm x 48cm x 45cm. is a single doored without freezer zone (Figure 4.1). The evaporator of the model is positioned on inner side of rear wall, and its dimensions are 44.5x91 cm^2. The WOT (wire on tube) condenser is placed on the outer side of the rear wall. The interior volume has gaps of cabinet and door shelves, crispers, a light and fan box (Figure 4.1).

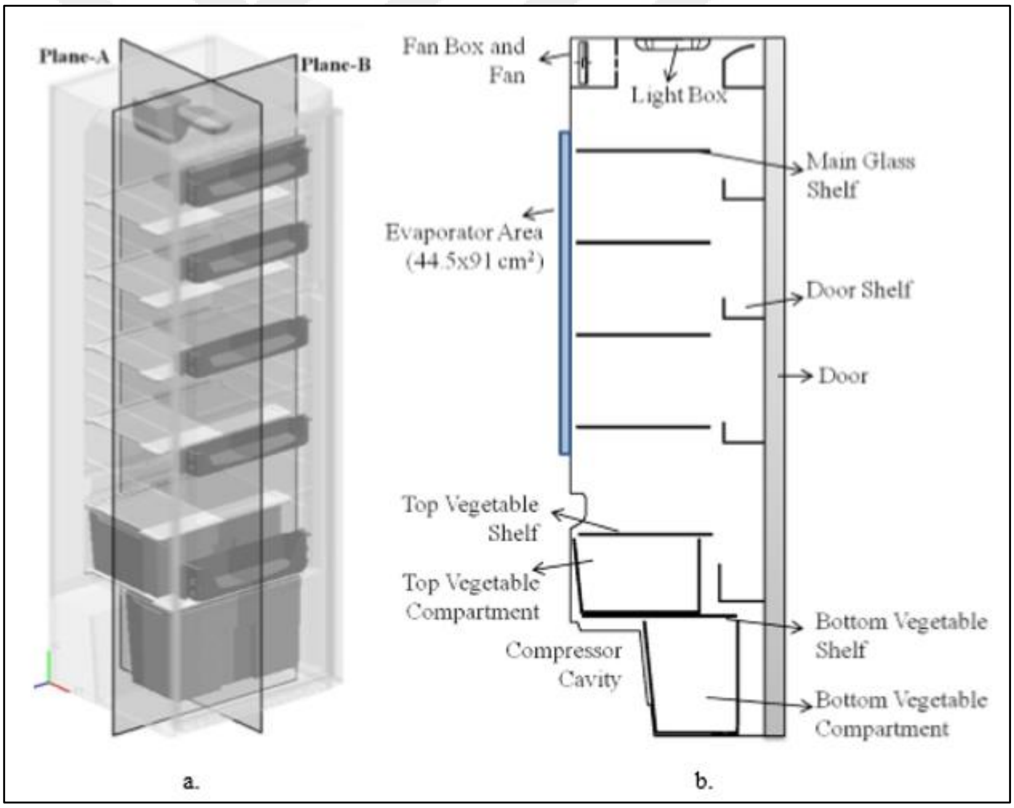

Figure 4.1 Refrigerator isometric view (a), inner configuration (b)

These internal configurations, regarded as a geometric barrier to flow, were defined as a cavity within the volume of air generated. Some neglectable details in the air volume, fan box, and outer walls of the refrigerator (interior cabinet plastic, polyurethane foam and metal panel) were not designed for simplification. This step was taken in order to have a high mesh quality and decrease the time of numerical analysis. (Figure 4.2).

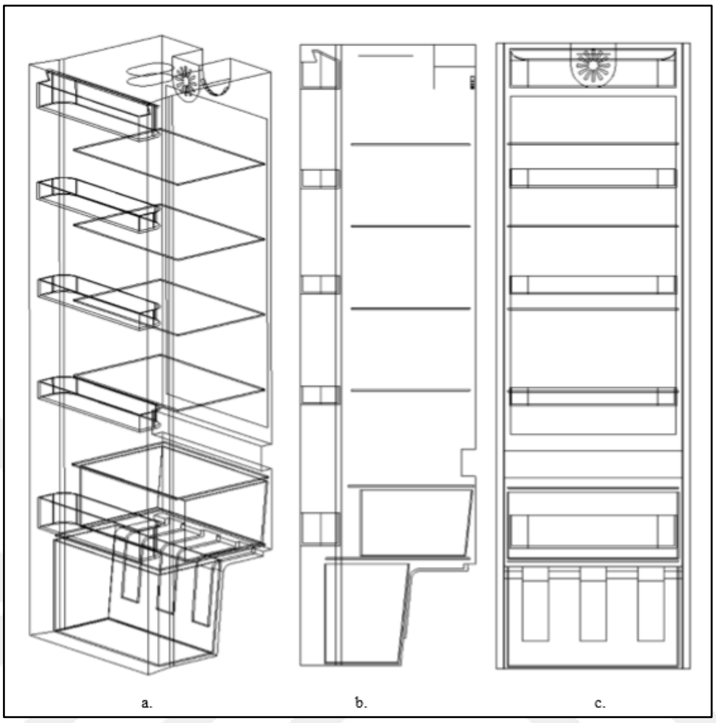

Figure 4.2 3D view of the cad model (a), left view (b), front view (c)

4.2 Meshing

The most essential steps to achieve near-real consequences in CFD analysis are creating an appropriate numerical grid model and accurately defining boundary conditions. A commercial CFD analysis program was used for the numerical study. The 3D design is transferred to the mesh process of the package program. Then, the names of the regions of the inner air volume model were defined for step of boundary condition.

High grade meshes is required for computational fluid dynamics to analyse properly. Therefore, advanced meshing options are used for mesh process. The inflation mesh control is available for the evaporator wall As shown in Figure 4.3, the size growth rate of mesh is 1.01 and inflation has five layers. Totaly 192616 nodes and 853637 elements are used in the CFD model.

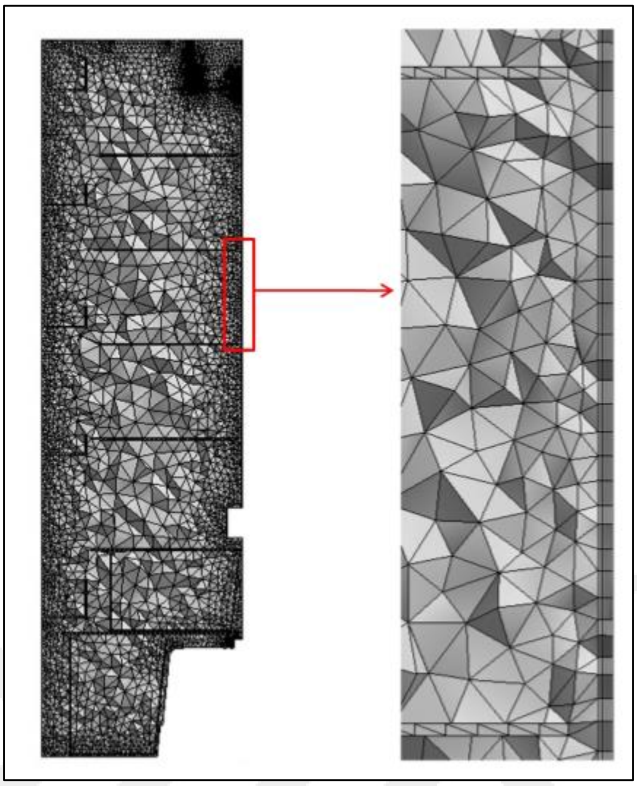

Figure 4.3 Mesh structure on the left view and inflation layer detail

4.3 Boundary Conditions

The model after mesh process was imported to the CFD program. This inner air volume model was defined as fluid (air) domain to the program.

Due to the effect of the compressor cycle process, which results with the oscillation of temperatures in the inner air volume, household refrigerator analysis must be considered as a transient problem. The average temperatures of the refrigerator under equilibrium conditions are considered in terms of standarts and studies int he literature. Thus, steady-state analyzes were performed to facilitate the analysis. In order to determine boundary conditions and the verify of numerical results, average temperatures under equilibrium conditions are considered.

The refrigerator wall occurs by interior plastic, polyurethane and metal panel respectively. The heat transfer is continuously transferred to the refrigerator from outside to inside. Due to simulate this heat transfer, the overall heat transfer coefficient based on thermal resistances and the measurement of the outer surface avarage temperatures from experimental studies are used. Only the thermal resistance of the insulating material is considered for calculating the coeffient due to the negligible thickness of the other layers of the wall.

The heat which is acquired in household refrigerators, is removed from the evaporator surface that contacts with inner volume air. Temperature of evaporator oscillates between the maximum and minimum values. For this reason, the temperature of the evaporator surface gets change by the time of progress. According to the numerical studies, the surface of the evaporator was assumed to be a constant wall. As a result, the temperature of the evaporator was considered as constant, which is gained the average value from the measurement of thermocouples on the evaporator surfaces in the experiment.

In the numerical model, insulation thickness and the thermal conductivity coefficient of the polyurethane foam are set as boundary conditions. Boundary conditions from experiments are given in Table 4.1

Table 4.1 Boundary conditions

SURFACE	**PU BOUNDARY CONDITIONS**	
	PENTAN BLOWING AGENT	**LBA BLOWING AGENT**
Evaporator Surface	Constant Temp -3.16 ^{o}C	Constant Temp -3.16 ^{o}C
Door (Front) Surface	T=24.82 ^{o}C	T=24.82 ^{o}C
	U=0.619 W/m^2K	0.405 W/m^2K
Compressor Top Surface	T=26 ^{o}C	T=26 ^{o}C
	U=0.416 W/m^2K	0.272 W/m^2K
Compressor Side Surface	T=26 ^{o}C	T=26 ^{o}C
	U=0.327 W/m^2K	0.214 W/m^2K
Back Surface	T=25.47 ^{o}C	T=25.47 ^{o}C
	U=0.331 W/m^2K	0.216 W/m^2K
Side Surfaces	T=24.9 ^{o}C	T=24.9 ^{o}C
	U=0.466 W/m^2K	0.305 W/m^2K
Top Surface	T=25 ^{o}C	T=25 ^{o}C
	U=0.353 W/m^2K	0.231 W/m^2K
Bottom Surface	T=26.1 ^{o}C	T=26.1 ^{o}C
	U=0.420 W/m^2K	0.274 W/m^2K
Flow Restrictors	Adiabatic	Adiabatic

Heat is transferred by natural and forced convection effects in interior air volume in static type household refrigerators with installed fan. Natural convection creates a bouncy effect and forced convection obtains in measured inlet velocities by the fan holder zone (Figure 4.4)

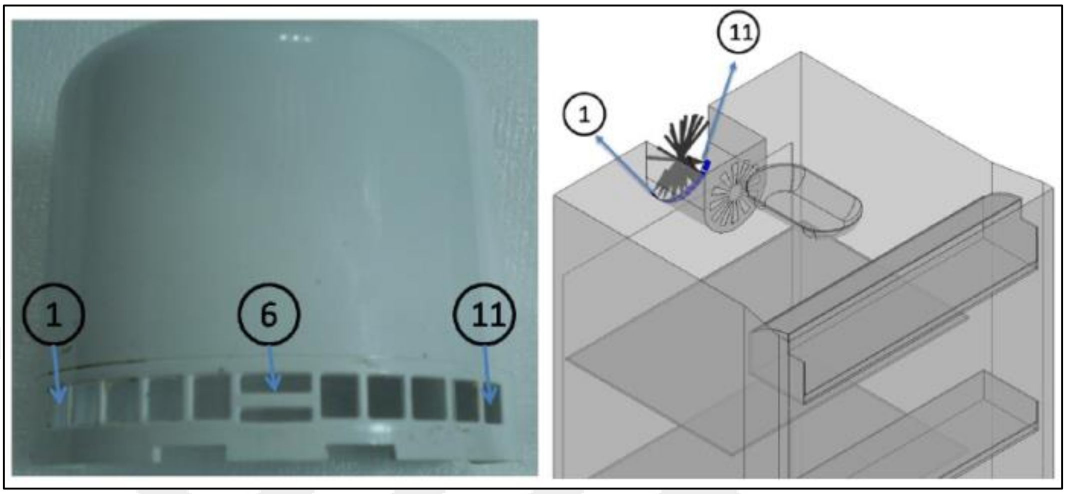

Figure 4.4 Output zones of the fan housing and the position on the refrigerator (Avcı et al., 2013)

Table 4.2 Outlet velocity values of fan zones

Fan Output Zones	Velocity (m/s)
1	4.35
2	4.60
3	4.68
4	4.35
5	4.00
6	3.00
7	3.47
8	3.58
9	3.20
10	2.84
11	2.80

The thermophysical properties of internal air in compliance with $\boldsymbol{T_f}$ (temperature of film) 3.75˚C are shown in the Table 4.3. These properties are density (ρ), specific heat (Cp), thermal conductivity (k), thermal diffusivity (α), kinematic viscosity (ν).

Table 4.3 The properties of interior air

T_f [K]	ρ [kg/m^3]	Cp [J/kgK]	k [W/mK]	α [m^2/s]	ν [m^2/s]
276.9	1.269	1006.538	0.024	1.94508 x 10^{-5}	1.38341 x 10^{-5}

Finally, the conditions of internal air volume are determined as steady state, laminar flow, effects of natural, forced convection and radiation.

4.4 Parametric Study

The effect of different blowing agents on the thermal performance of a refrigerator and indoor air temperature distribution was investigated parametrically with the numerical analysis method. In the previous study, polyurethane, which has pentane for blowing agent, was used as an insulation material of the model. The thermal conductivity coefficient was 0.026 W/mK. In this study, LBA, which is an alternative blowing agent and its' thermal conductivity coefficient is measured by the experimental method, is defined as a parameter. The thermal conductivity coefficient of polyurethane which uses LBA as a blowing agent is measured 0.017 W/mK.

In the study, the effect of the fan on the insulation design was also investigated. For this reason, besides the polyurethane blowing agent change, the effect of the fan is examined as a parameter in the analysis.

In parametric study, the output data were determined according to the temperature of three temperature measurement points shown in Figure 4.5 which are located interior volume of the refrigerator according to ISO 15502 and the amount of heat capacity (QEvap) from the evaporator surface (ISO, 2005). According to the standard, each point (T1, T2, T3) must be in the range $0 < T < 10$ °C and the average temperature (TAvg) of these three points must not exceed maximum 5 °C. Five output parameters of T1, T2, T3, TAvg and QEvap are obtained under these boundary conditions.

The insulation thickness around the refrigerator is defined as input parameters. These can be listed as; Side Surfaces, Front (Door) Surface, Bottom Surface, Back Surface, Compressor Top Surface, Compressor Side Surface, Top Surface.

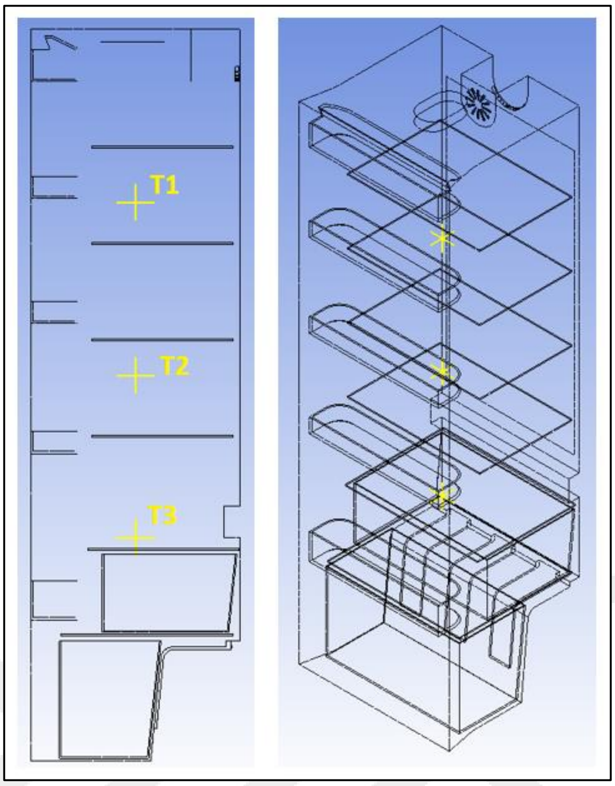

Figure 4.5. Temperature measurement points according to ISO 15502 Standard (ISO 2005)

CHAPTER FIVE

RESULTS AND DISCUSSIONS

The effect of the fan on the insulation design was also investigated in this study. Therefore, both the polyurethane blowing agent change and the effect of the fan is examined as a parameter in the analysis.

The output data was established according to five parameters; T1, T2, T3, TAvg and QEvap. The average temperature of three temperature measurement points which are located interior volume of the refrigerator according to ISO 15502 standard shown in Figure 5.1 (ISO, 2005). The average temperature (TAvg) of these three points must not exceed maximum 5 °C and each point (T1, T2, T3) must be in the range 0 <T <10 °C according to standard. Qevap is the amount of the heat capacity from the evaporator surface.

Obtained thermal conductivity coefficient for pentane and LBA was defined as the boundary condition in the model and analyzes were carried out with the pentane agent and the alternative LBA agent.

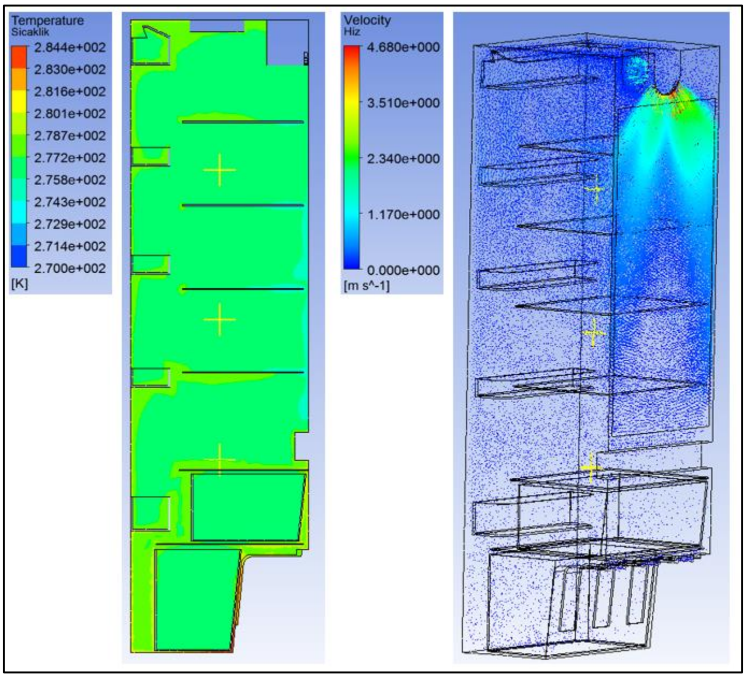

Figure 5.1 Temperature and velocity distribution of air volume with fan model

Table 5.1 demonstrates a comparison of the obtained output values for pentane and LBA blowing agents at a refrigerator with fan. It is seen that, when LBA is used instead of Pentane as a blowing agent the TAvg temperature is decreased approximately 0.03 ^{0}C and the amount of heat capacity from the evaporator surface (QEvap) is decreased by approximately 1.17 W. Approximately 5.50% improvement can be achieved at QEvap when polyurethane with LBA blowing agent is used as a thermal insulating material in the refrigerator model. Also, there is no significant difference in temperature distribution in the air volume of the model.

Table 5.1 Effect of changing blowing agent on performance of with fan model

BLOWING AGENT	**PENTANE**	**LBA**
T_1 (^{0}C)	3.39	3.35
T_2 (^{0}C)	3.91	3.91
T_3 (^{0}C)	3.97	3.93
TAvg (^{0}C)	3.76	3.73
TAvg (%)	REF	0.71
QEvap (W)	**21.21**	**20.04**
QEvap (%)	REF	5.50

Effect of the fan is examined in the next study. Thereby, the importance of the thermal design on natural convection in a cooling system can be established. Figure 5.2 and Figure 5.3 shows the effect of pentane and LBA as blowing agent on temperature and velocity distribution of air volume without fan model.

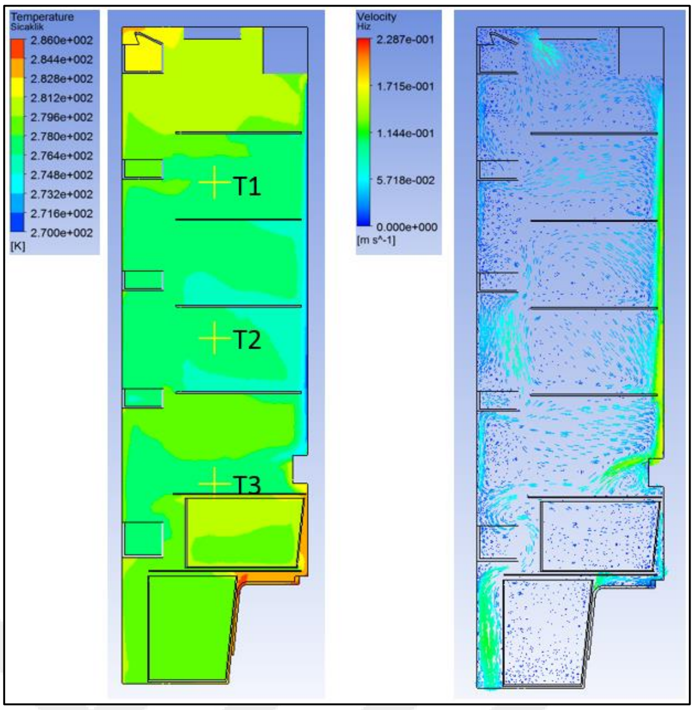

Figure 5.2 Effects of pentane as blowing agent on temperature and velocity distribution of air volume without fan model

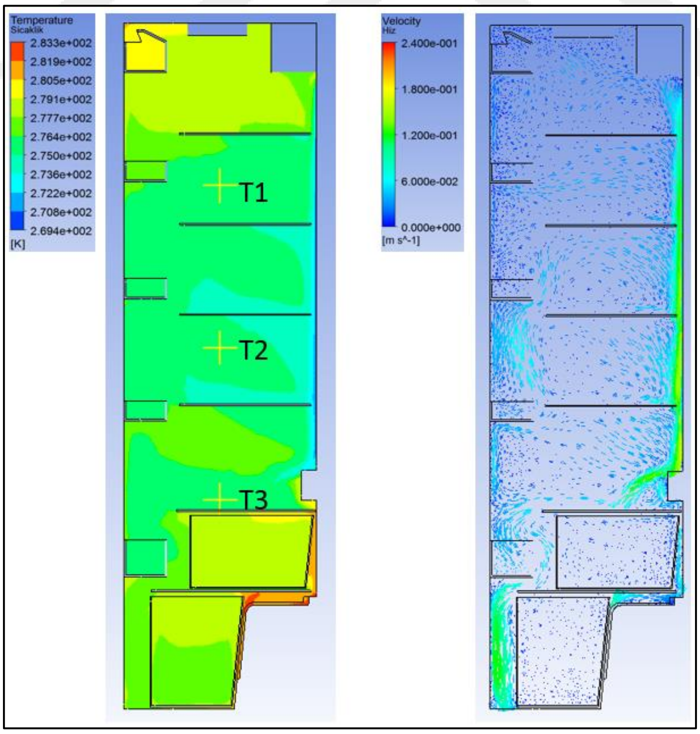

Figure 5.3 Effects of LBA as blowing agent on temperature and velocity distribution of air volume without fan model

Table 5.2 demonstrates a comparison of the obtained output values for pentane and LBA blowing agents at a refrigerator without fan.

Table 5.2 Effect of changing blowing agent on performance of without fan model

BLOWING AGENT	**PENTANE**	**LBA**
T_1 (^{0}C)	4.56	3.11
T_2 (^{0}C)	3.41	2.24
T_3 (^{0}C)	3.69	2.58
TAvg (^{0}C)	3.89	2.64
TAvg (%)	REF	31.99
QEvap (W)	**23.42**	**18.89**
QEvap (%)	REF	19.39

When LBA is used instead of Pentane as a blowing agent the TAvg temperature is decreased approximately 1.25 ^{0}C and the amount of heat capacity from the evaporator surface (QEvap) is decreased by approximately 4.54 W and approximately 19.4% improvement can be achieved at Qevap. When the fan effect is neglected and the model is transformed to a natural convective static cooler, the importance of the thermal design has become apparent.

Experimental and numerical results in this section show that LBA has better thermal resistance than the pentane blowing agent. However, this advantage can also be used to decrease the insulation thickness to increase the refrigerator's internal volume.

In the following comparisons, the insulation thickness of different areas evaluated regarding internal volume gain. The value with the lowest QEvap has the same insulation thickness as the initial design and, as the insulation thickness decreased QEvap increases. However, an internal volume is gained by reducing insulation thickness. This relation showed for the side surfaces in Figure 5.4, for the front surface in Figure 5.5, for the bottom surface in Figure 5.6, for the back surface in Figure 5.7, for the compressor top surface in Figure 5.8, for the compressor side surface Figure 5.9 and the top surface in Figure 5.10.

It must be noted that the QEvap value of the initial design with the Pentane blowing agent is 23.42 W. So, any smaller QEvap value means it is better insulation than the initial design.

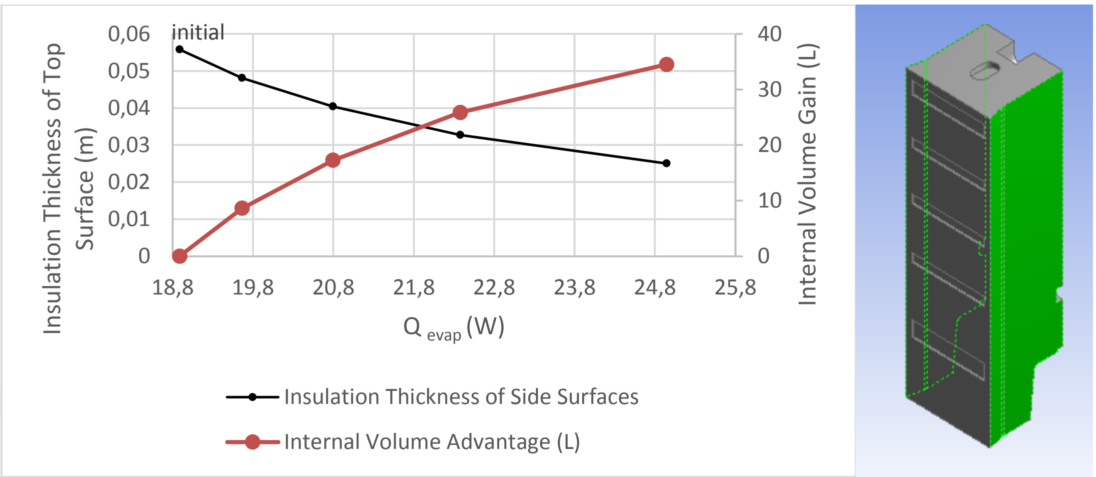

Figure 5.4 Effects of insulation thickness at the side surfaces on Q_{Evap} and internal volume

Figure 5.4 shows the insulation thickness's effects at the refrigerator's side surfaces on Q_{evap} and internal volume. Since this is the largest surface of the system, the volumetric gain and Q_{evap} are most affected. Results suggest that using LBA as the blowing agent and just changing the sidewall thickness, the refrigerator's internal volume can be expanded by 29.48 L.

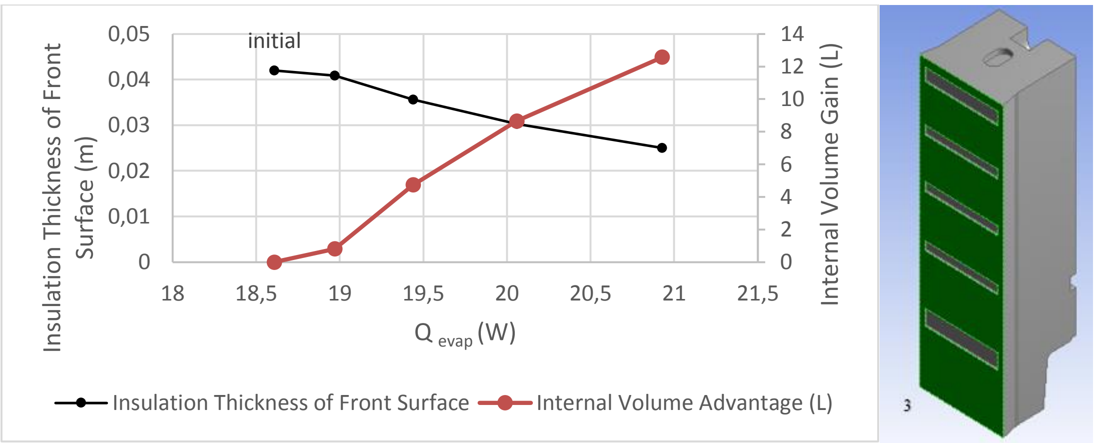

Figure 5.5 Effects of insulation thickness at the front surface on Q_{Evap} and internal volume

The front door insulated with LBA can reduce the insulation thickness of 45 mm to 25 mm (Figure 5.5). This modification increases the internal volume 12.58 L while still decreasing the Qevap by 11%. This thickness was not reduced furthermore due to mechanical requirements.

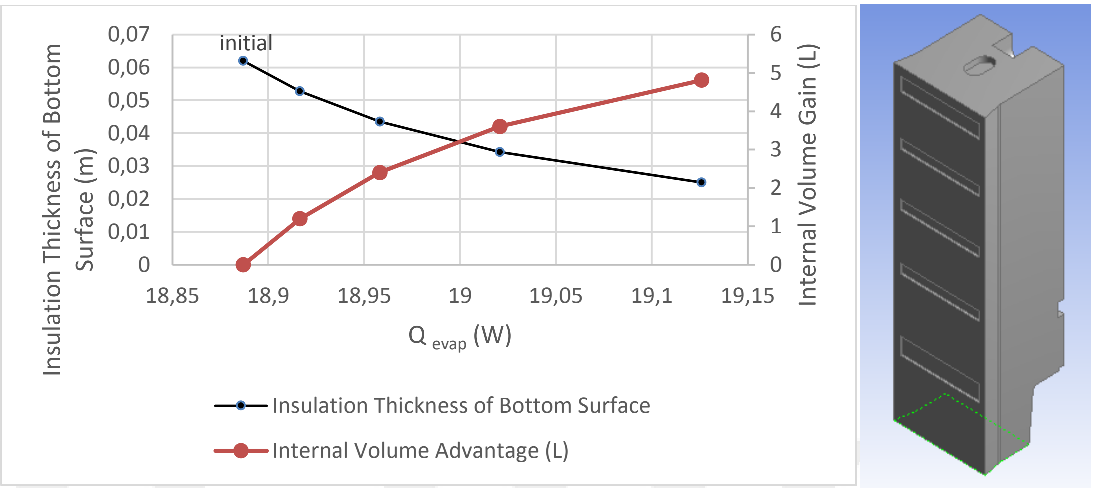

Figure 5.6 Effects of insulation thickness at the bottom surface on Q_{Evap} and internal volume

The least critical position is the bottom surface due to the low convection. The crisper blocks the refrigerator's circulating air (Figure 4.5), and the air velocity in the small horizontal space between the ground is not high. Because of these effects, changing insulation thickness 62 mm to 25 mm only affects Q_{evap} 1.3%. The volume gain is 4.81 L from this alteration. This can also be seen in Figure 5.6.

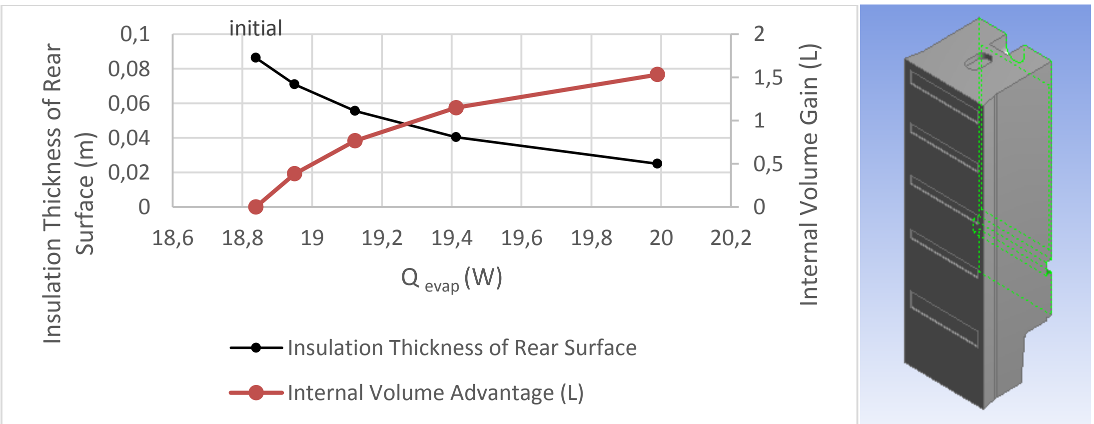

Figure 5.7 Effects of insulation thickness at the back surface on Q_{Evap} and internal volume

The insulation area in Figure 5.7 covers around the evaporator. Therefore, the surface area is small, and also it is hard to gain meaningful volume. Using LBA in this area, the insulation thickness can be reduced to 25 mm from 86 mm while still decreasing Q_{evap} 14.6% and gaining 1.5 L internal volume. Q_{evap} can be further reduced by 19.5% if 86 mm insulation is used with LBA.

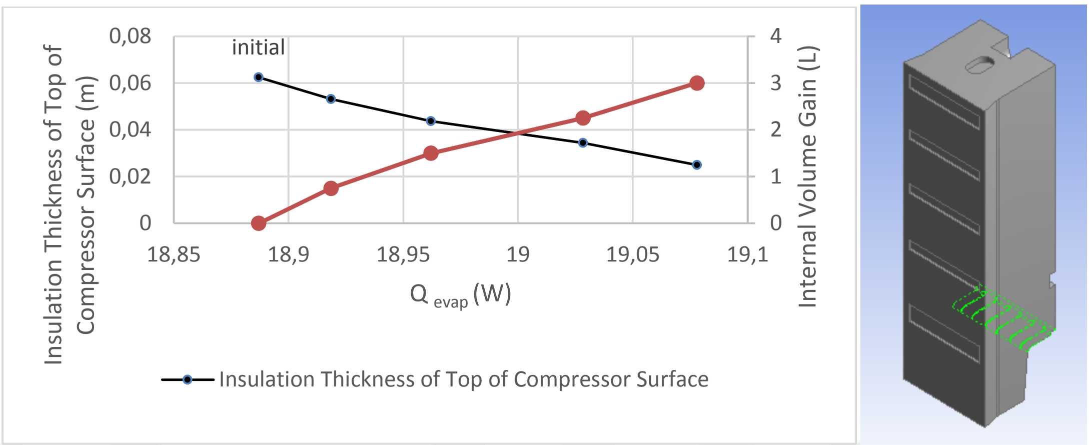

Figure 5.8 Effects of insulation thickness at the compressor top surface on Q_{Evap} and internal volume

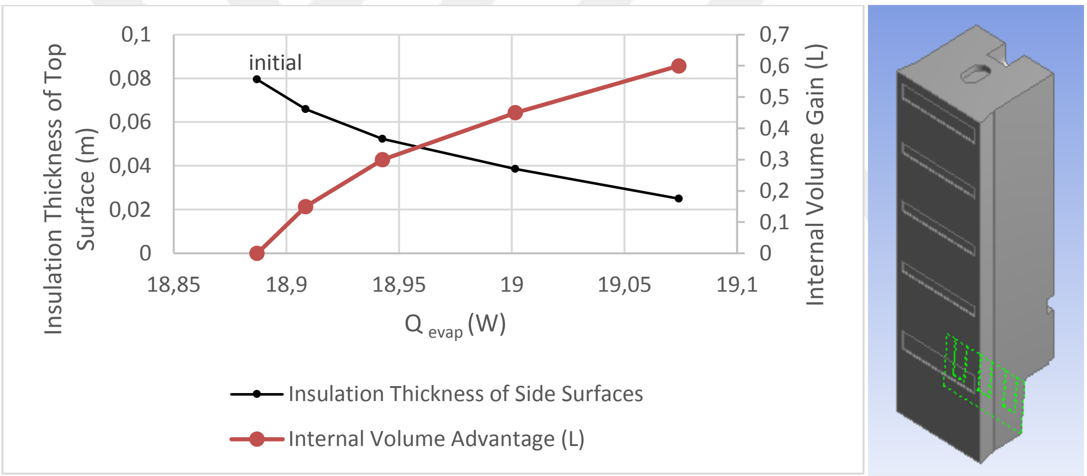

Figure 5.9 Effects of insulation thickness at the compressor side surface on Q_{Evap} and internal volume

Insulation areas between the compressor are also crucial because of the high-temperature difference. The insulation thicknesses can be reduced to 62.5 mm to 25 mm for the compressor top surface (Figure 5.8) and 69.5 mm to 25 mm for the compressor side surface (Figure 5.9). This results in 3 L volume gain from the top and 0.5 L volume gain from the sidewall while still reducing the Q_{evap} 18.5%.

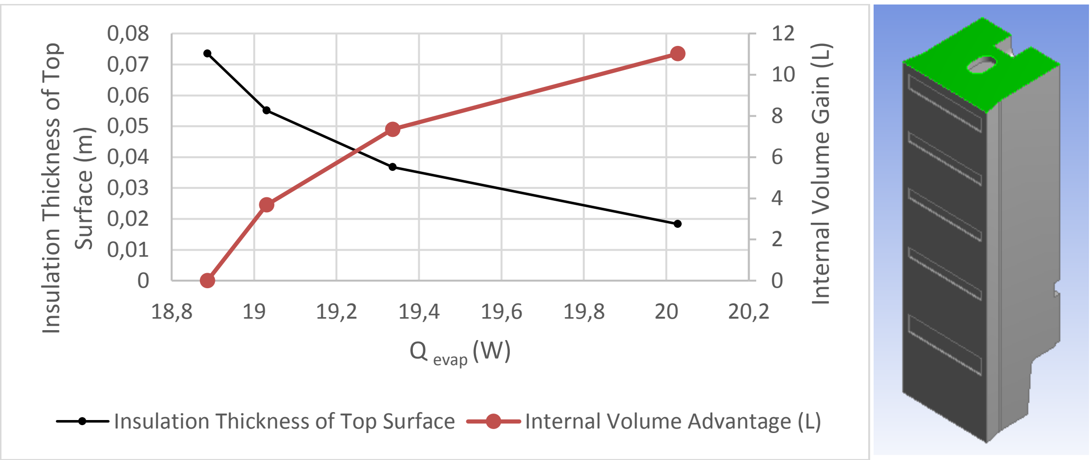

Figure 5.10 Effects of insulation thickness at the top surface on Q_{Evap} and internal volume

The top insulation area has the least temperature difference because the warmer air inside the refrigerator rises. The insulation thickness can be reduced to 18 mm from 73 mm with maintaining a 14.5% reduction in Q_{evap}. This can be seen in Figure 5.10.

All these results show that LBA blowing agent has a significant advantage in insulation, and it creates flexibility in design between the internal volume and the heat loss.

CHAPTER SIX

CONCLUSIONS

The goal of this study is to reduce the insulation thickness of a household refrigerator according to the heat transfer of the inner volume air by using alternative blowing agent materials.

At the beginning of this study, insulation foam materials of domestic refrigeration systems and their ingredients were investigated. Thermal performance of polyurethane foams correlate with blown material type. Liquid blowing agent (LBA) is the latest blowing agent material for polyurethane foams. Therefore, thermal conductivity coefficient measurements of polyurethane samples with LBA as blowing agent were obtained experimentally.

Numerical solution methodologies were examined and 3D model of internal air volume of a domestic refrigerator was designed and CFD analyses were performed.

In this study, it has been presented that the effect of Pentane and LBA agents on the air volume temperature distribution and thermal performance in a refrigerator can be valuable. The thermal conductivity coefficient of the material was measured as 0.01766 W/m^{o}C by the hot-wire method. It has a 32.08% lower thermal conductivity coefficient than the conventional polyurethane with the pentane blowing agent.

Seventy-two parametric CFD analysis of the whole refrigerator model was conducted. The numerical model validated with the experimental study. Parametric study results show that using polyurethane with LBA has 5.52% less Q_{evap} then conventional polyurethane, the pentane blowing agent.

This advantage increases to 19.34% when the interior fan is off since the conduction became the dominant heat transfer mechanism without the fan convection effects.

Insulation surfaces were also evaluated separately to investigate the heat transfer behavior of the system. Sidewalls provide the highest volume gain (29.48 L) due to its large surface area. Front door insulation thickness can be reduced to 25 mm from 45 mm with a 12.58 L volume gain and 11% Q_{evap} reduction. Bottom and top surfaces have the weakest effect due to low convection coefficients and temperature differences. Compressor side and top walls also crucial, and they can reduce the heat loss of the whole refrigerator by %18.5.

The numerical analysis also suggests that it can design a refrigerator with 62.87 L larger interior volume with the same heat transfer coefficient by utilizing LBA. It refers to a 17.7% expansion of internal volume, and it positively affects the refrigerator energy class since the refrigerator's volume is also a parameter for this classification.

If this research had been carried out only by experimental method, achieving the results would be costly and would take too long. Considering all these results, it has been determined that the use of LBA as polyurethane blowing agent has advantages such as energy saving, reducing the applied insulation thickness and gaining space in the cooling air volume. Therefore, LBA will find more applications on cooling thermal designs and technologies in the future.

REFERENCES

Araki, K., Karnoto, D., & Matsuoka, S. (2009). Optimization about multilayer laminated film and getter device materials of vacuum insulation panel for using at high temperature. *Journal of Materials Processing Technology, 209* (1), 271-282

Çalış, T. (2007). *Poliüretan-kil nanokompozit sentezi ve karakterizasyonu*. MSc Thesis, Istanbul Teknik University, Istanbul.

Dutt, G. S. (1995). Energy efficient and environment-friendly refrigerators. *Energy for Sustainable Development, 1* (5), 57-68

Freirich, S.C (2015). Biopolymer foaming with supercritical CO2—thermodynamics, foaming behaviour and mechanical characteristics. *The Journal of Supercritical Fluids,1* (96), 349-358

Gönenlioğlu, E., Avcı, H. (2007). *Yalıtım panellerinin üretilmesi ve ısı iletim katsayılarının belirlenmesi.* Bachelor Thesis, Dokuz Eylül University, İzmir.

Griffith, B., & Arasteh, D. (1995). Advanced insulations for refrigerator/freezers: the potential for new shell designs incorporating polymer barrier construction. *Energy and Buildings, 22* (3), 219-231

ISO, (2005). ISO 15502:2005 household refrigerating appliances - characteristics and test methods. *Refrigeration and Air-conditioning, 1*, 35

Johnsom, R.W., (2004). The effect of blowing agent choice on energy use and global warming impact of a refrigerator. *International Journal of Refrigeration, 27* (2004), 794-799

Kumlutaş, D., Avcı, H., & Karadeniz, Z.H. (2013). Buzdolabı tasarımında vakum yalıtım paneli uygulamasının sayısal olarak incelenmesi. *XII. Ulusal Tesisat Mühendisliği Kongresi, 1* (137), 26-34

Kuranska, M., & Prociak, A. (2012). Porous polyurethane composites with natural fibres. *Composites Science and Technology,72* (2), 299-304

Kwon, J.S, Jang, C.H, Jung, H., & Song, T.H. (2009). Effective thermal conductivity of various filling materials for vacuum insulation panels. *International Journal of Heat and Mass Transfer,52* (23), 5525-5532

Little, A.D., Anderson, K., Biermann, Dr. W., Cole, R., Crawford, Prof. R., Ert, Dr. R., Glicksmann, Prof. L., Huffman, Dr. R., Kruse, Prof. H, McElroy, D., & Perez, A. (1993). *Energy efficient alternatives to chlorofluorocarbons (CFCs).* Retrieved February 5, 2019, from https://www.osti.gov/servlets/purl/766411

Metz, B., Kuijpers, L., Solomon, S., Andersen, S.O., Davidson, O., Pons, J., Jager, D., Kestin, T., Manning, M., & Meyer, L. (2005). *Safeguarding the ozone layer and the global climate system*, Cambridge: Cambridge University Press

Modesti, M., Baldoin, N., & Simioni, F. (1998). Formic acid as a co-blowing agent in rigid polyurethane foams. *European Polymer Journal, 34* (9), 1233-1241

Polyurethanes Blowing agent options for insulation foamafter HCFC phase out. (n.d.). Retrieved March 10, 2019, from http://www.huntsman.com/polyurethanes

Polyurethanes. (n.d.). Retrieved March 2, 2019, from http://www.essentialchemicalindustry.org/polymers/polyurethane.html

Trias, F.X., Oliet, C., Rigola, J., & Perez-Segarra, C.D. (2018). A Simple optimizateion approach for the insulation thickness distrubiton in household refrigerators. *International Journal of Refrigerator, 93* (2018), 169-175

Yang, C.G., Li, Y.J., Gao, X., & Xu, L. (2012). A review of vacuum degradation research and the experimental outgassing research of the core material- pu foam on vacuum insulation panels. *Physics Procedia*, *32* (1), 239-244

Yılmaz, U. (2008). *Ev tipi dondurucularda vakum izolasyon panel kullanımının enerji tüketimi üzerindeki etkisini bilgisayar destekli ve deneysel olarak incelenmesi.* MSc Thesis, Dokuz Eylül University, İzmir.

Zhang, H., Fang, W.Z., Li, Y.M., & Tao, W.Q. (2017). Experimental study of the thermal conductivity of polyurethane foams. *Applied Thermal Engineering, 115*, 528-538