Design of control system and fabrication of special compartment in Static Refrigerators

Author

MUHAMMAD BILAL ARSHAD

Registration Number

329707

Supervisor

DR. JAWAD ASLAM

DEPARTMENT OF MECHANICAL ENGEERING

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY, ISLAMABAD

AUGUST 2022

Design of control system and Fabrication of special compartment in Static Refrigerators

Author

MUHAMMAD BILAL ARSHAD

Registration Number

329707

A thesis submitted in partial fulfillment of the requirements for the degree of

MS Mechanical Engineering

Thesis Supervisor:

Dr. JAWAD ASLAM

Thesis Supervisor's Signature:

____

DEPARTMENT MECHANICAL ENGINEERING,

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY,

ISLAMABAD

AUGUST 2022

Declaration

I certify that this research work titled "*Design of control system and fabrication of special compartment in Static Refrigerators"* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources has been properly acknowledged / referred.

MUHAMMAD BILAL ARSHAD

00000329707

Plagiarism Certificate

It is certified that MS Thesis Titled "**Design of control system and Fabrication of special compartment in Static Refrigerators"** by **Muhammad Bilal Arshad** has been examined by us. We undertake the follows:

a. Theses have significant new work/knowledge as compared to already published or are under consideration to be published elsewhere. No sentence, equation, diagram, table, paragraph or section has been copied verbatim from previous work unless it is placed under quotation marks and duly referenced.
b. The work presented is original and own work of the author (i.e. there is no plagiarism). No ideas, processes, results or words of others have been presented as Author own work.
c. There is no fabrication of data or results which have been compiled/analyzed.
d. There is no falsification by manipulating research materials, equipment or processes, or changing or omitting data or results such that the research is not accurately represented in the research record.
e. The thesis has been checked using TURNITIN (copy of originality report attached) and found within limits as per HEC plagiarism Policy and instructions issued from time to time.

Signature of Student
MUHAMMAD BILAL ARSHAD

Registration Number
00000329707

Signature of Supervisor

DR. JAWAD ASLAM

Copyright Statement

Acknowledgements

In the name of Allah, the most Magnificent, and the most Merciful.

Research work is a never-ending struggle, and I am happy to have support from family and friends. I have my fair share of mistakes along the way, but as Einstein once said, “Anyone who has never made a mistake has never tried anything new.” After each roadblock, Dr. Jawad Aslam has been a beacon of hope, enlightening the path; guiding. I am forever in gratitude to Dr. Jawad Aslam, my research supervisor. Also, the encouragement and guidance of my Examination Committee is estimable.

I am profusely thankful to my parents and siblings who have continuous support for me throughout every department of my life.

To everyone who was a part of this journey with me, thank you and wish you all the best in the future.

Dedicated to my exceptional parents and adored siblings whose tremendous support and cooperation led me to this wonderful accomplishment.

Abstract

Refrigerators being used for domestic purposes are of three types, namely static, brewed, and no-frost. The aim of this project was to introduce a new compartment in static refrigerators to enhance the quality and freshness of food present in this compartment. It was achieved by having control over temperature depending on the needs of the user and needs for the type of food inside the compartment. There can be two methods to fabricate this special compartment. One is by using parallel evaporators and other is by using fan and airduct. The parallel evaporator method is expensive but highly efficient, while air duct is less expensive and does not compromise enough efficiency, in term of energy consumption and cooling. The airduct was implanted in the refrigerator and results were taken. The result shows the total time to reach the target temperature, and time to drop per half degree of temperature. The target was to set the temperature at any value between 5 to -5 ^{o}C. In this project, the minimum temperature achieved was -1 ^{o}C, as the average temperature of evaporator goes to -12 ^{o}C, rather than the -18 ^{o}C for most of the domestic refrigerators.

Key Words: *Control system, Static refrigerators, No-frost refrigeration*

Table of Contents

List of Figures

List of Tables

CHAPTER 1: INTRODUCTION

Domestic refrigerators are widely used in all over the world industry. Today households have more than 4 billion refrigerators in their use. Epidemiological data from all the continents suggest that food poisoning is among the major reasons for most diseases. [1] The data suggests that the most problems arise due to inadequate temperatures for food in the refrigerator. The product's temperature determines its quality and freshness.

1.1 Background, Scope, and Motivation

In our world industry there are three types of domestic refrigerators, namely brewed, static and no-frost. [2] Static refrigerators are most common due to their low cost and generally less overall maintenance [3]. The basic principle involving static refrigerators is natural convection due to which heat is transferred and air flow occurs due to change in air density [4]. The brewed type is an advanced form of static refrigerator. In addition to simple static refrigerator the brewed type has a fan for circulation of air [5]. Due to this forced convection, the cooling of refrigerator is improved, now all the parts in the refrigerator will receive equal amount of refrigerator cooling. So, the overall density of cold air has been improved in brewed type. The final type is no-frost which includes a defrost system in the refrigerator [6]. It improves the overall efficiency of a refrigerator and the quality of food, but the energy consumption is higher.

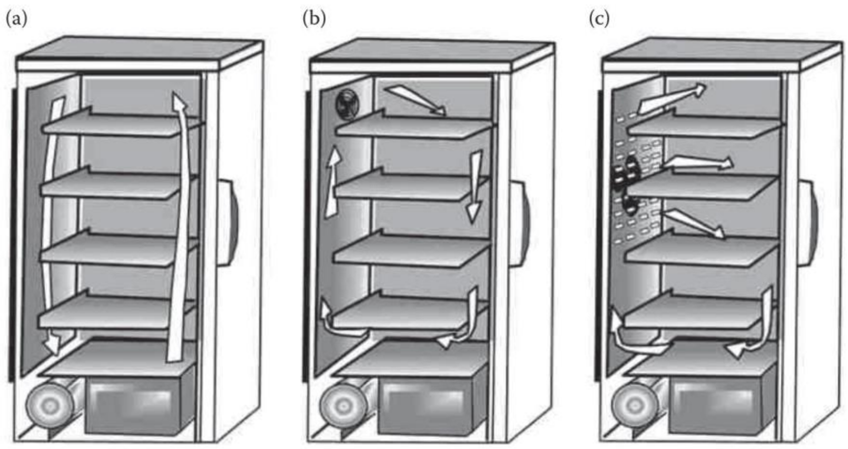

Figure 1.1: Three types of domestic refrigerators, (a) Static, (b) Brewed, (c) No-frost.

1.1.1 Static Refrigerators

A static refrigerator, also known as a passive refrigerator, is a cooling system that operates without any moving parts. It works by utilizing the temperature difference between a warm source and a cold sink to transfer heat and reduce the temperature of the cold sink.

A static refrigerator operates on the principle of thermodynamics and typically relies on the Peltier effect, which states that when a current is passed through a circuit of two dissimilar materials, heat will be transferred from one material to the other. In a static refrigerator, the Peltier effect is used to transfer heat from a warm source, such as a room, to a cold sink, such as a refrigerated compartment [4].

Static refrigerators have several advantages, including low noise, low maintenance, and low energy consumption. They are also well-suited for use in remote or harsh environments where access to power or refrigerants is limited. However, their cooling capacity is typically limited, and they may not be as efficient as dynamic refrigerators, which use compressors and refrigerants to transfer heat.

1.1.2 Brewed Type Refrigerators

Brewed is a static refrigerator with a fan, is a type of cooling system that combines the principles of static refrigeration with forced convection. The static refrigerator uses the Peltier effect to transfer heat from a warm source to a cold sink, while the fan is used to increase the heat transfer rate by forcing air over the cold sink.

In a static refrigerator with a fan, the Peltier device is used to transfer heat from a warm source to the cold sink, causing the temperature of the sink to decrease. The fan is used to increase the rate of heat transfer by increasing the flow of air over the sink and increasing the surface area for heat transfer [8].

This combination of static refrigeration and forced convection can improve the cooling efficiency of the system, making it more suitable for use in applications where higher cooling capacities are required. The use of a fan also allows for more precise control over the heat transfer rate, making it easier to achieve a desired temperature in the cold sink. However, the addition of a fan also increases the noise and power consumption of the system.

1.1.3 No-Frost Refrigerators

A no-frost refrigerator, also known as a frost-free refrigerator, is a type of household refrigerator that prevents the buildup of frost on the interior walls. This is achieved by using a defrosting mechanism that periodically melts the frost, allowing it to drain away.

In a traditional refrigerator, frost can build up on the walls due to the accumulation of moisture from the air inside the fridge. This can affect the cooling efficiency of the refrigerator and also make it difficult to clean the interior. In a no-frost refrigerator, a heating element is used to periodically melt the frost, preventing it from accumulating on the walls [10].

No-frost refrigerators are more convenient to use than traditional refrigerators, as they do not require manual defrosting and the interior is easier to clean. They also tend to be more energy-efficient, as the accumulation of frost can increase the energy consumption of the refrigerator. However, no-frost refrigerators are generally more expensive than traditional refrigerators and may also have a slightly higher power consumption due to the use of the defrosting mechanism.

1.1.4 Comparison

Static refrigerators and no-frost refrigerators are both types of household refrigerators that are used to keep food and other perishable items fresh. However, they differ in how they operate and the features they offer.

Static refrigerators rely on the Peltier effect to transfer heat from a warm source to a cold sink, while no-frost refrigerators use a defrosting mechanism to prevent the buildup of frost on the interior walls. This makes no-frost refrigerators more convenient to use, as they do not require manual defrosting and the interior is easier to clean.

Static refrigerators are typically more energy-efficient and have a lower noise level than no-frost refrigerators. They are also well-suited for use in remote or harsh environments where access to power or refrigerants is limited. However, their cooling capacity is typically limited, and they may not be as efficient as no-frost refrigerators in terms of cooling performance.

No-frost refrigerators, on the other hand, are generally more expensive than static refrigerators and have a slightly higher power consumption due to the use of the defrosting mechanism. However, they offer improved cooling efficiency and convenience, making them a popular choice for household use.

Unfortunately, all these refrigerators are not providing the feature to separately adjust for different types of food products according to the specific temperature, a particular food item needs to remain fresh [7]. Different food items, for example cereals, meat, fruits, etc., all need their own specific type of temperature to remain fresh [9].

1.1.5 Aim and Objectives

The aim of the study is to introduce a new compartment in static refrigerators to enhance the quality and freshness of the food present. Hence implementing the no frost technology in static refrigerators at low cost. The objective is to build the compartment in static refrigerator, that will function as a frost-free compartment, that allows the user with variable temperature range of -5 to 5^{o}C, which would be independent of the other sections of refrigerator.

There are two methods to introduce the independent compartment in refrigerator, they are parallel evaporators and by using air duct.

A refrigerator using parallel evaporators is a type of refrigeration system that utilizes multiple evaporator coils to cool different sections of the refrigerator. This design allows for separate temperature control of the freezer and fresh food compartments, allowing each compartment to maintain its own optimal temperature.

In a parallel evaporator system, each evaporator is connected to its own thermostat and fan, which helps to ensure that the temperature in each compartment is accurately regulated. This design also allows for improved energy efficiency, as the fan and compressor only need to run when a specific compartment requires cooling.

Parallel evaporator systems are commonly found in side-by-side or French door style refrigerators, where it is desirable to have separate temperature control of the freezer and fresh food compartments. By using separate evaporators, this design allows for more efficient cooling and better temperature control, improving the overall performance and longevity of the refrigerator.

An air duct in a refrigerator is a component that allows for the flow of air from one part of the refrigerator to another. It is typically connected to the evaporator and the condenser coils, and it helps to distribute cold air evenly throughout the interior of the fridge, ensuring that all food items are stored at the desired temperature. The air duct is typically made of metal or plastic and may be part of the fridge's sealed system or may be connected to the fan, which helps circulate air within the unit.

The air duct is typically connected to the evaporator and the condenser coils and allows cold air to circulate from the evaporator to the interior of the refrigerator. This cold air is produced by the refrigerant passing over the evaporator coils, which absorb heat from the air inside the unit.

The air duct is often made of metal or plastic and may be part of the sealed refrigeration system or may be connected to a fan that helps circulate air within the unit. The fan helps to remove moisture and prevent frost buildup on the evaporator coils and also helps to distribute the cooled air evenly throughout the interior of the fridge.

In addition to helping maintain consistent temperatures, the air duct also helps to improve the efficiency of the refrigerator. By directing air flow and reducing the formation of warm spots, the air duct helps to prevent temperature fluctuations that can affect the freshness and quality of food stored in the fridge.

Overall, the air duct is an important component in any refrigeration system, playing a critical role in ensuring that the interior of the refrigerator stays cool and well-ventilated, and that the food stored within remains fresh and properly preserved.

In a refrigerator, a fan is used in conjunction with an air duct to circulate and distribute cold air throughout the interior of the unit. The fan is typically located near the evaporator and pulls air in from the freezer and refrigerator compartments, passing it over the evaporator coils to cool it. The cooled air is then redirected back into the fridge via the air ducts. This continuous circulation of air helps to ensure even temperature distribution and helps prevent warm spots or temperature fluctuations within the fridge. The fan also helps to remove moisture and prevent frost buildup on the evaporator coils.

1.2 Literature Review

For development of this compartment, various strategies were used in past, including the parallel evaporator [11], where two evaporators were installed side by side, by using valves and refrigeration lines. While other technology implemented was using air duct with synchronous control scheme [12]. Same technique is used in making novel air distributor, which supply air from system, situated outside the refrigerator [13]. Further the duct system which supplying the airflow was made, and analyzed by using CFD techniques [8]. Also the duct system improved by using multi duct technology [14]. Similarly investigation were carried out to analyze the rapid increase in temperature during fan shutdown [15], hence providing the necessity of insulation. Vibroacoustic analysis was also performed on air duct flow to increase its efficiency [16]. Similarly, to check the wall conditions for variable compartment (VC), the flow and heat transfer analysis was performed, where efficiency of different materials have been discussed [17]. In addition to the air dampers, the thermal vacuum panels were also tested along the air duct [18]. Another method by introducing the outside fresh air for third compartment was also used, and results were depended on the outside environment [19]. Then air duct performance was investigated and provided the most optimized version of airduct in the refrigerator [20]. For defrosting, the air duct is also used to provide air using fan situated at evaporator [21]. Also, the numerical simulation of air flow in the duct was conducted and optimized using CFD techniques [10]. Forced convection was also discussed, which is helpful in the simulation of fan, which is also using forced convection for cooling purpose [22]. Same airduct system was utilized with addition to cold phase change material as well [23]. To fabricate the special compartment, performance analysis was taken out having evenly distributed cold air [24]. The effect of door opening and closing was discussed, and energy saving technique was implemented according to the data [25]. Apart from the air duct method, the parallel evaporator method was also discussed and optimized [26]. In addition to fan performance, its effect on refrigerator was also discuss and optimized [27].

For parallel evaporators [11], the results are generally more accurate other than air duct technology [28], but it is more expensive as the components required here are generally expensive than air duct. The parallel evaporator technology is implemented in figure 1.2.

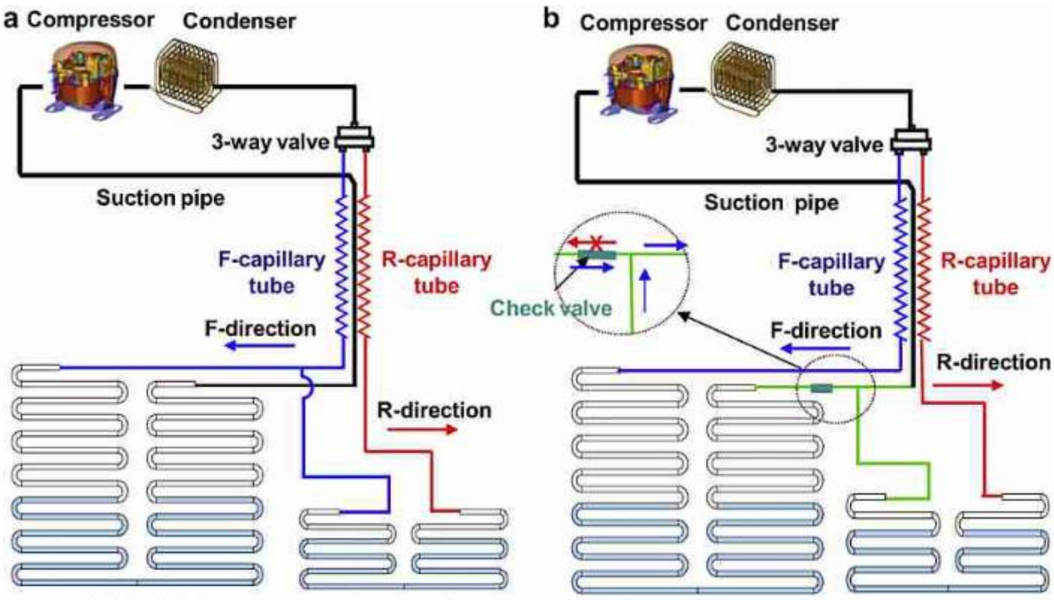

Figure 1.2: Parallel Evaporator with (a) by-pass and (b) with check valve. [2]

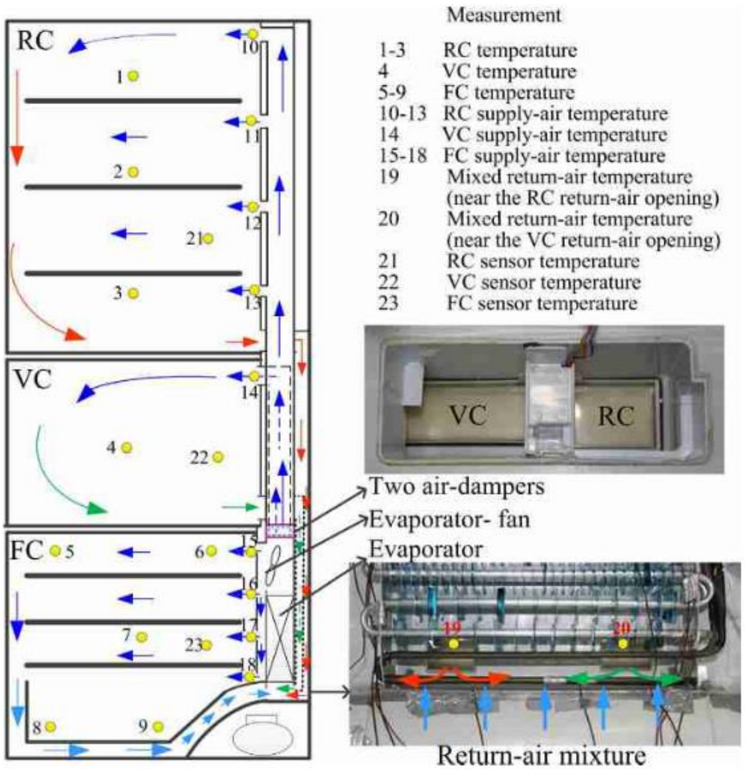

Figure 1.3: Air circulation for three compartments. [1]

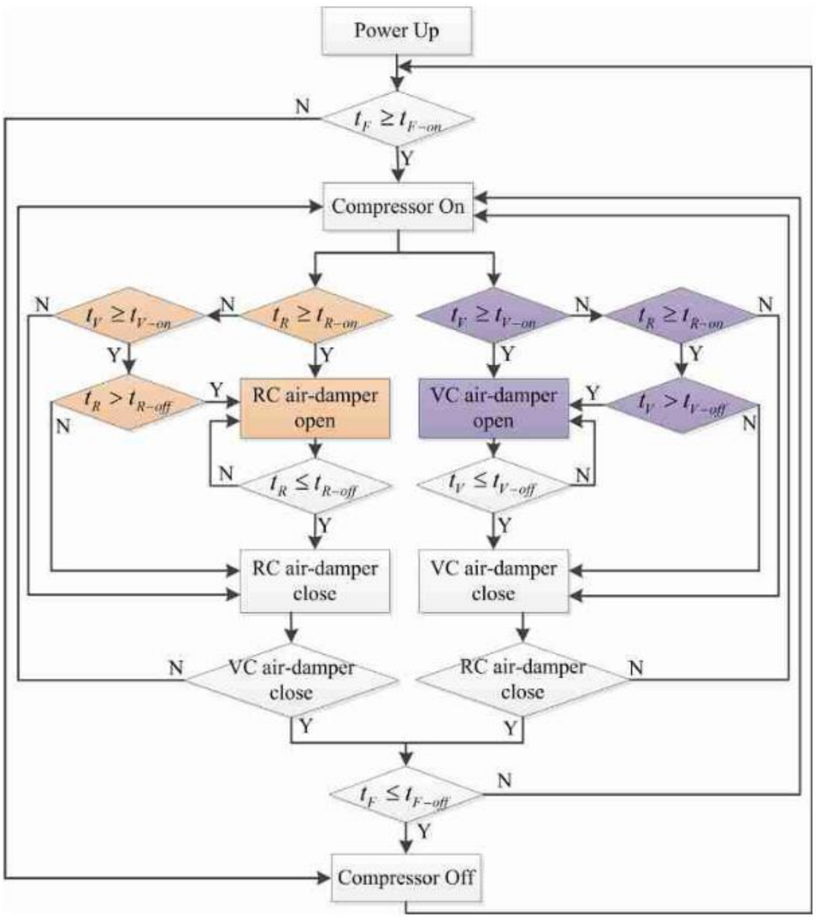

Figure 1.4: Schematic for Synchronous Control strategy. [1]

For the air duct method [12], the synchronous control system was developed which is shown in figure 1.3. But here, the air dampers are only installed at VC & RC. The freezer compartment (FC) where the evaporator is installed, can be overcooled [29].

The synchronous control mechanism is presented in figure 1.4, which describes the most energy efficient method for operating the air dampers in the air duct [30]. It is one of the most profound methods, if air duct method is implemented here.

Similarly, for novel air distributor [13], the only drawback here is the variable compartment (VC) is not independent of other compartments. The rubric for the top five most relevant literature is presented in table 1.1, which indicates the research objective and its approach.

Table 1.1: Literature Rubric

Journal	Title	Approach/Method
Applied Thermal Engineering (2018)	Comparison of independent and synchronous opening control strategies of two air-dampers in three-temperature frost-free refrigerator. [12]	Effect of air dampers control strategy on the refrigerator performance. Two types of Control Strategies. The independent control strategy causes longer compressor on period.
International Journal of Refrigeration (2020)	Development of novel air distributor for precise control of cooling capacity delivery in multi-compartment indirect cooling household refrigerators (MIR). [13]	A method to deliver cooling capacities by installing a novel air distributor in a MIR and changing the position of air supply dampers in this air distributor. Hence addressing the freezer compartment (FC) overcooling.
Journal of Supercomputing (2020)	Air volume improvement in the duct system in frost-free refrigerators based on the CFD method. [8]	This paper is focused on the air volume improvement based on the optimization of the duct structure. The new air duct system has a better air supply capability and has a better cooling effect.
Applied Thermal Engineering (2021)	Temperature uniformity analysis of a domestic refrigerator with different multi-duct shapes. [14]	The effect of four different shapes of the multi-duct system on the temperature uniformity in the top-freezer refrigerator system was considered.
International Journal of	Analysis of temperature rapid rise phenomenon during damper-	Based on natural convection, the results show that the violent natural

Refrigeration (2022)	off cycle in side-by-side frost-free refrigerator.[15]	convection airflow driven by the non-uniform temperature distribution will lead to the significant variation of RC temperature.

1.2.1 Research gap

The objective of this research is to make a special compartment in static refrigerator, having low budget and high efficiency, in term of energy consumption and cooling. As described earlier there can be two major methods to implement this, one is by using parallel evaporator and other is by using air duct.

Parallel evaporator technology is expensive; hence air duct method was chosen, but for air duct, two most important literature have research gaps, i.e., for multi-compartments, the air duct have dampers only at VC and RC region [12], where FC compartment is fully receiving the air, hence can be overcooled. Similarly, to implement the novel air distributor [13], the variable compartment (VC) is not fully independent.

So, after complete study of previous literature, it was decided to implement the independent working of Variable Compartment (VC) with synchronous control strategy to minimize the energy consumption [31].

CHAPTER 2: METHODOLOGY & SETUP

As described in previous literature, there can be various methods to introduce a new compartment with required functionality. Two methods are prominent, one is by inserting parallel flow evaporators by using valves and refrigeration lines, while other is introducing a fan which will provide cold air from evaporator to the variable compartment (VC) by using duct flow.

For this project, an air duct method is used where the fan will provide cold air to the variable compartment (VC) and the purpose of selecting this method is primarily because, first it is a low-cost method with respect to introducing valves and evaporators. Second, it is more efficient in energy consumption as well.

2.1 Designing and Fabrication

The process of designing and fabricating a special compartment in refrigerator involves several techniques and components. They are explained thoroughly in this section, starting with the selection of refrigerator.

2.1.1 Refrigerator

A refrigerator is a household appliance that is used to keep food and beverages cool. A domestic refrigerator is a type of refrigerator that is designed for use in a household or residential setting. These refrigerators come in a variety of sizes, styles, and configurations, including top-freezer, bottom-freezer, side-by-side, French door, compact, counter-depth, built-in, and smart refrigerators, to meet the needs of different households. Domestic refrigerators are typically smaller in size than commercial refrigerators and are used to store food and beverages for personal consumption. They are an essential appliance in most modern kitchens and are available in a range of prices to suit different budgets.

There are several types of domestic refrigerators, including:

i. Top-Freezer Refrigerator: the most common type, with the freezer compartment on top of the fridge.
ii. Bottom-Freezer Refrigerator: the freezer is located below the refrigerator compartment.
iii. Side-by-Side Refrigerator: two separate compartments, with the fridge and freezer side by side.

iv. French Door Refrigerator: a combination of a side-by-side refrigerator and a bottom-freezer refrigerator.
v. Compact Refrigerator: smaller version of a standard refrigerator, often used in apartments, RVs, and dorm rooms.
vi. Counter-Depth Refrigerator: designed to blend in with kitchen cabinetry, with the depth of the refrigerator being the same as the surrounding cabinets.
vii. Built-in Refrigerator: designed to be installed into a cabinet or wall, giving the kitchen a seamless look.
viii. Smart Refrigerator: equipped with advanced features, such as Wi-Fi connectivity and a touch screen display.

A refrigerator with a combined fridge and freezer compartment is known as a "top-mount refrigerator" or "top-freezer refrigerator". This type of refrigerator has the freezer compartment located above the fridge compartment, and often features a simple design with basic shelves and storage options. This type of refrigerator is a popular choice for those who are looking for a basic, cost-effective refrigeration solution for their home.

Some of the advantages of top-mount refrigerators are:

i. Affordability: They are generally less expensive compared to other types of refrigerators.
ii. Energy Efficiency: Top-mount refrigerators typically have a simpler design, which can make them more energy-efficient.
iii. Convenient Access: The freezer compartment is located on top, making it easily accessible and convenient for storing frozen foods.
iv. Space-saving Design: With the freezer on top, this type of refrigerator takes up less floor space in your kitchen.
v. Easy to Clean: The freezer compartment is elevated, making it easier to clean and maintain.
vi. Good for Small Kitchens: Top-mount refrigerators are a good option for those who have small kitchens and limited space for a refrigerator.
vii. Simple Design: They have a simple design that makes them easy to use and maintain.

The refrigerator selected for this project was top-mount and is shown in figure 2.2 and properties are given in table 2.1. It has 90 Watts of compressor. The reason for selecting this refrigerator is because it can be amended to our needs easily by applying the fan near the evaporator and fabricating the duct and compartment at the lower end of refrigerator.

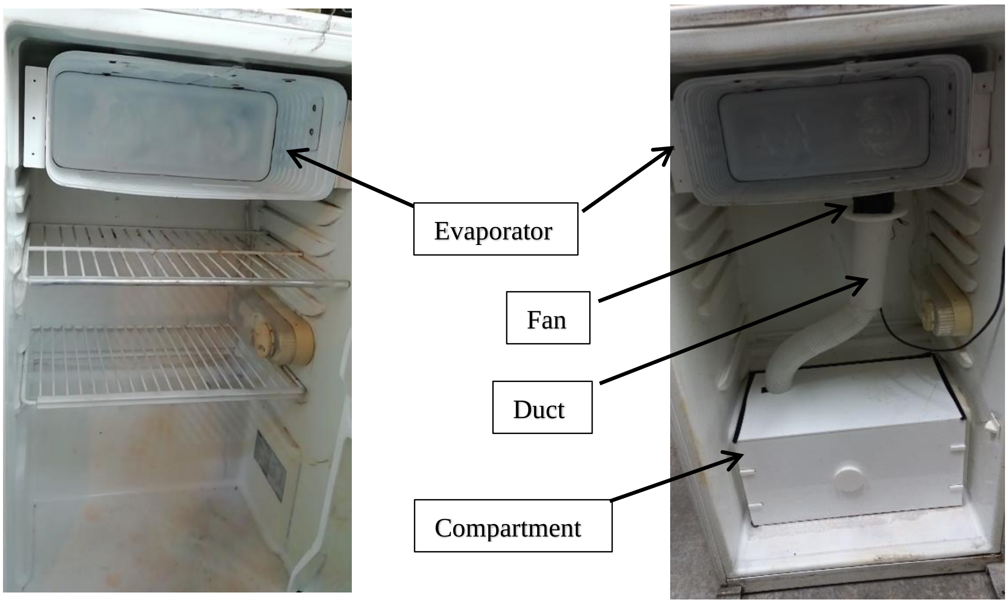

Figure 2.1: Refrigerator and components

Table 2.1: Properties of selected refrigerator

Model	Haier HR-135A
Input Power	100 W
Voltage	200-240V ~ 50Hz
Energy Consumption	0.80 kWh/24h
Refrigerant	R 134a 69g
Climate Class	T

The list of components used in the project is given in table 2.2 and explained in the following section.

Table 2.2: List of Components

Variable Compartment (VC)	16000cc Volume
Duct	Diameter of two inches
Fan	12V DC Fan
Arduino with 12V Adapter and Relay	-
Temperature Sensor	Three (DS 18B20 Temp Sensor)

2.1.2 Variable Compartment (VC) and Air Duct

The variable compartment (VC) has a volume of 0.016 m^3 or 16000 cc and dimensions are 40 cm in length, 20 cm in width and 20 cm in height. The diameter of the duct was 2 inches, or 5.08 cm.

2.1.2.1 Material Selection

The variable compartment (VC) is made up of Acrylic Plastic. Acrylic plastic, also known as polymethyl methacrylate (PMMA), is a transparent thermoplastic that is widely used in a variety of applications, including construction, engineering, and consumer goods.

It is a popular choice for these applications due to its combination of desirable properties, including:

i. Transparency: Acrylic plastic is highly transparent, making it ideal for applications where visibility is important.
ii. Light weight: Acrylic plastic is lighter than glass, making it a suitable alternative for applications where weight is a concern.
iii. Impact resistance: Acrylic plastic is highly resistant to impact, making it ideal for applications where durability is important.
iv. Weather resistance: Acrylic plastic is resistant to UV radiation, weathering, and environmental degradation, making it ideal for outdoor applications.
v. Chemical resistance: Acrylic plastic is resistant to many chemicals, including acids and alkalis, making it ideal for use in chemical environments.
vi. Ease of fabrication: Acrylic plastic is easily fabricated and molded into various shapes, making it a versatile material for many applications.

In addition to these properties, acrylic plastic is also a good electrical insulator and has good optical properties, making it suitable for use in a wide range of applications, including LED lighting fixtures, optical devices, and windowpanes. Overall, acrylic plastic is a versatile and useful material that is widely used in many applications due to its combination of desirable properties.

Acrylic plastic is commonly used in refrigerators for various purposes, including:

i. Shelves: Acrylic plastic shelves are lightweight, strong, and durable, making them ideal for use in refrigerators. They are also easy to clean and provide good visibility of the contents of the refrigerator.
ii. Light diffusers: Acrylic plastic is often used as a light diffuser in refrigerator lighting systems. Its transparency and ability to scatter light evenly make it a suitable choice for this application.
iii. Door liners: Acrylic plastic is often used to line the doors of refrigerators. Its resistance to impact and weathering makes it ideal for use in this location, where it is exposed to repeated impacts and changes in temperature and humidity.
iv. Food trays: Acrylic plastic is sometimes used to make food trays in refrigerators, due to its resistance to impact, chemicals, and staining.

In general, acrylic plastic is a versatile material that is well-suited to many applications in refrigerators, due to its combination of desirable properties, including transparency, impact resistance, and weather resistance. These properties make it a suitable choice for a wide range of applications within refrigerators, where durability, cleanability, and visibility are important considerations.

Acrylic sheets, can be welded using a variety of techniques, including:

i. Solvent welding: This is the most common method of welding acrylic sheets. The process involves using a solvent, such as methylene chloride, to dissolve the edges of the acrylic sheets and then bonding them together. The solvent is applied to the edges of the sheets and then held together until the solvent evaporates, leaving a strong bond.
ii. Hot air welding: This method involves using hot air to melt the edges of the acrylic sheets and then fusing them together. Hot air welding is a quick and efficient method of welding acrylic sheets, but it requires specialized equipment and is best suited for large-scale production.

iii. Hot gas welding: This method is like hot air welding, but it uses a hot gas, such as propane or butane, to melt the edges of the acrylic sheets. The melted edges are then fused together to form a strong bond.
iv. Ultrasonic welding: This method uses high-frequency sound waves to generate heat and melt the edges of the acrylic sheets, which are then bonded together. Ultrasonic welding is a fast and efficient method of welding acrylic sheets, but it also requires specialized equipment.

It is also important to ensure that the edges of the acrylic sheets are clean and free of dirt, oil, or other contaminants before welding, as these can weaken the bond between the sheets. Additionally, it is important to follow the manufacturer's instructions and recommended procedures when welding acrylic sheets to ensure a strong and durable bond. For this purpose, cement solvent was used to bind the acrylic sheets for the variable compartment (VC).

The following are some of the advantages of using cement solvent for welding acrylic sheets:

i. Easy to use: Cement solvent is easy to use, as it only requires the application of the solvent to the edges of the acrylic sheets and then holding them together until the solvent dries.
ii. Strong bond: Cement solvent creates a strong bond between the acrylic sheets, making it suitable for a wide range of applications.
iii. Cost-effective: Compared to other welding methods, such as hot air welding or ultrasonic welding, cement solvent is a relatively inexpensive option.
iv. Versatile: Cement solvent can be used to bond acrylic sheets to a variety of other materials, including wood, metal, and plastic.
v. Low heat emission: Unlike hot air or hot gas welding, which can generate significant heat during the welding process, cement solvent does not generate heat and therefore does not pose a risk of damage to the acrylic sheets or the surrounding materials.

Overall, cement solvent is a versatile and cost-effective option for welding acrylic sheets. However, it is important to follow the manufacturer's instructions and recommended procedures to ensure a strong and durable bond.

The air ducts in refrigerators can be made from a variety of materials, including:

i. Aluminum: Aluminum is a common material for air ducts in refrigerators because it is lightweight, durable, and has good heat transfer properties.
ii. Steel: Steel is also used for air ducts in refrigerators because it is strong, durable, and has good heat transfer properties. However, it is heavier and more expensive than aluminum.
iii. Plastic: Plastic air ducts are becoming increasingly popular in refrigerators due to their light weight and low cost. Some common types of plastic used for air ducts in refrigerators include polypropylene and PVC.
iv. Foam: Foam air ducts are sometimes used in refrigerators to reduce noise and improve insulation.

The choice of air duct material in a refrigerator will depend on various factors, including the size and type of refrigerator, the intended use, and the budget. In general, aluminum and steel are more commonly used for larger refrigerators, while plastic and foam are more common in smaller refrigerators.

The air duct in this project was made from plastic. Plastic air ducts have several advantages in the field of refrigeration:

i. Lightweight: Plastic air ducts are lighter than metal ducts, making them easier to handle and install.
ii. Corrosion-resistant: Plastic air ducts are resistant to corrosion, making them suitable for use in damp or humid environments.
iii. Low thermal conductivity: Plastic air ducts have low thermal conductivity, reducing heat loss and improving energy efficiency in refrigeration systems.
iv. Low cost: Plastic air ducts are generally less expensive than metal ducts, making them a cost-effective option for many refrigeration applications.
v. Durable: Plastic air ducts are durable and resistant to damage, making them ideal for use in harsh environments.
vi. Easy to install: Plastic air ducts can be easily installed using common tools and techniques, reducing installation time and costs.
vii. Good insulation properties: Plastic air ducts have good insulation properties, reducing the amount of refrigerant needed to maintain the desired temperature.

viii. Non-toxic: Plastic air ducts are non-toxic and do not pose any health hazards, making them safe to use in food storage and preparation areas.

Overall, plastic air ducts offer a combination of low cost, durability, and good thermal performance, making them a popular choice for many refrigeration applications.

Regardless of the material used, the air ducts in refrigerators are designed to channel cold air from the evaporator to the interior of the refrigerator, while also dissipating heat generated by the refrigeration system. The air ducts are a critical component of the refrigeration system, as they play a key role in maintaining optimal temperature and humidity conditions inside the refrigerator.

2.1.2.2 Insulation

Refrigerators typically use insulation materials to reduce heat transfer between the interior of the fridge and the surrounding environment. The type of insulation material used can affect the cooling efficiency of the fridge, as well as its cost, durability, and environmental impact.

Some common materials used for insulation in refrigerators include:

i. Polyurethane (PU) foam: This is a common type of insulation material that is widely used in refrigerators due to its high thermal insulation properties, low cost, and ease of production.

ii. Polystyrene (PS) foam: This is another common type of insulation material used in refrigerators, especially in older models. Polystyrene foam is lightweight, durable, and has good insulation properties, but it is not as environmentally friendly as some other materials.

iii. Expanded Polyethylene (EPE): This is a material made from polyethylene that is expanded to create a foam-like material. EPE is lightweight, environmentally friendly, and has good insulation properties, making it a popular choice for high-end refrigerators.

iv. Cyclopentane: This is a type of blowing agent used in PU foam insulation that is more environmentally friendly than traditional blowing agents like chlorofluorocarbons (CFCs).

v. Polyisocyanurate (PIR) foam: This is a type of insulation material that is made by combining polyols and isocyanates. PIR foam has good insulation properties, low flammability, and low environmental impact, making it a popular choice for high-end refrigerators.

In summary, the choice of insulation material for a refrigerator will depend on factors such as cost, insulation performance, durability, and environmental impact. The most common materials used for insulation in refrigerators are PU foam, PS foam, EPE, and PIR foam.

Here for insulation, polyethylene (PE) sheets were used around the duct and variable compartment (VC), hence the temperature will remain constant for a longer period. Polyethylene is a type of plastic that is commonly used as an insulator in refrigeration systems.

Some of its key properties that make it a suitable material for this application include:

i. Low thermal conductivity: Polyethylene has a low thermal conductivity, which means that it is a good insulator and helps to keep cold air inside the refrigeration system.
ii. Durability: Polyethylene is a tough and durable material that can withstand the harsh environment of a refrigeration system.
iii. Chemical resistance: Polyethylene is resistant to many chemicals, making it suitable for use in refrigeration systems where it may encounter refrigerants or other chemicals.
iv. Moisture resistance: Polyethylene is moisture-resistant, which helps to keep the refrigeration system dry and prevent the growth of mold and bacteria.
v. Lightweight: Polyethylene is a lightweight material, which makes it easy to handle and install in a refrigeration system.

Overall, polyethylene is a versatile and cost-effective material that is widely used as an insulator in refrigeration systems. Its low thermal conductivity, durability, and chemical resistance make it a good choice for this application.

The model was generated in Solidworks and fabricated using cement solvent. The Solidworks model of the compartment and its duct is shown in figure 2.2.

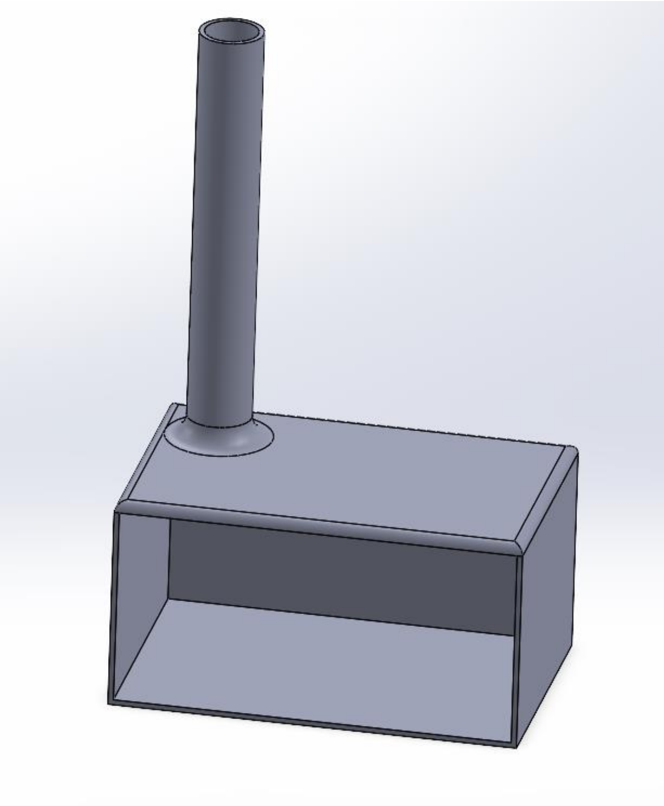

Figure 2.2: Variable Compartment (VC) with duct

2.1.3 Fan

Fans are commonly used in refrigerators to circulate air and distribute cold air evenly throughout the interior. The fan is typically located in the back of the refrigerator and is used to blow air over the evaporator coils, which are used to cool the interior of the refrigerator.

There are several types of fans that can be used in refrigerators, including axial fans, centrifugal fans, and blower fans. Axial fans are the most commonly used type of fan in refrigerators, as they are simple, reliable, and cost-effective.

The fan used in a refrigerator is typically driven by an electric motor, which is controlled by the refrigerator's thermostat. The fan is designed to run continuously while the refrigerator is in operation, in order to circulate cold air evenly throughout the interior.

In addition to circulating air, the fan in a refrigerator also helps to dissipate heat generated by the compressor and other components of the refrigeration system. By removing heat from the interior of the refrigerator, the fan helps to maintain optimal cooling conditions, which are essential for keeping food fresh and safe.

Overall, the fan is an important component in the refrigeration system, as it plays a key role in maintaining the proper temperature and humidity conditions inside the refrigerator

Here, a fan was used at the evaporator to supply chilled air into the variable compartment (VC) by using duct. DC fan having 12V power is used with diameter of 2 inches, equal to the diameter of duct. The maximum flow rate of this fan captured using an anemometer was 49.50 CFM.

Figure 2.3: 12V DC Fan

2.1.4 Temperature Sensor

The temperature sensor used was DS18B20. The DS18B20 is a digital thermometer that is commonly used to measure temperature in various applications, including refrigeration systems. Some of its key properties and advantages include:

i. High accuracy: The DS18B20 is capable of measuring temperature with a high degree of accuracy, typically to within ±0.5°C.
ii. Digital interface: Unlike analog thermometers, the DS18B20 uses a digital interface, which provides more stable and accurate readings over time.
iii. One-wire interface: The DS18B20 uses a one-wire interface, which reduces the number of wires required to connect the thermometer to a control system.
iv. Small size: The DS18B20 is small and compact, making it easy to integrate into a wide range of applications.

v. Wide temperature range: The DS18B20 is capable of measuring temperatures ranging from -55°C to +125°C, making it suitable for use in a wide range of environments.

Some of the disadvantages of the DS18B20 include:

i. Limited resolution: The DS18B20 has a limited resolution, typically 9 to 12 bits, which means that it may not be suitable for applications that require very precise temperature measurements.
ii. Requires external power: The DS18B20 requires an external power source to operate, which may increase the complexity of the system.
iii. Limited communication range: The one-wire interface of the DS18B20 has a limited communication range, typically around 1 meter, which may limit its use in larger systems.

Overall, the DS18B20 is a useful and versatile digital thermometer that is widely used in a variety of applications, including refrigeration systems. Its high accuracy, digital interface, and small size make it a popular choice for temperature measurement in these systems.

The DS18B20 temperature sensor can be easily interfaced with an Arduino microcontroller. This allows for easy and accurate temperature measurements in refrigeration systems.

Here are the steps for using the DS18B20 with an Arduino:

1. Connect the DS18B20 to the Arduino: Connect the DS18B20 data pin to the Arduino digital pin 2 and connect the DS18B20 VDD pin to the Arduino 3.3V pin.
2. Install the OneWire library: Download the OneWire library and install it in the Arduino software. This library provides functions for reading data from the DS18B20.
3. Write the code: Write an Arduino sketch that uses the OneWire library to read the temperature data from the DS18B20 and display it on the serial monitor.
4. Upload the code: Upload the code to the Arduino and check the serial monitor for the temperature readings.

With these steps, we interfaced the DS18B20 temperature sensor with an Arduino and used it to measure the temperature in a refrigerator. In this project three DS18B20 temperature sensors were used, one placed in freezer compartment (FC), one in the refrigerator while other at Variable Compartment (VC).

Figure 2.4: DS18B20 Temperature Sensor

2.2 Control System Design

The feedback control system was designed and implemented using the Arduino as the controller and actuating device while process is conducted by using the fan. A feedback control system is a type of control system that uses feedback to regulate the behavior of a system. In a feedback control system, the output of a process or system is compared to a desired or reference value, and the difference between the two is used to adjust the input or control variables to achieve the desired behavior.

Feedback control systems are widely used in a variety of applications, including process control, motor control, temperature control, and others. They are characterized by their ability to respond quickly to changes in the system and to maintain stability even in the presence of disturbances.

There are two main types of feedback control systems: open-loop control systems and closed-loop control systems. Open-loop control systems do not use feedback to adjust the control inputs, whereas closed-loop control systems use feedback to regulate the behavior of the system.

Feedback control systems can be implemented using various control algorithms, such as proportional-integral-derivative (PID) control, state-space control, linear quadratic regulator (LQR) control, and others. The choice of control algorithm depends on the specific requirements of the application, such as the desired response time, stability, and accuracy.

A closed-loop system is a type of control system in which the output of a system is used as feedback to adjust the inputs to the system. The purpose of a closed-loop system is to control the behavior of the system so that it behaves in a desired manner.

A closed-loop system consists of the following components:

1. Sensors: These measure the output of the system, such as temperature, pressure, position, or velocity. The sensors generate a signal that represents the current state of the system.
2. Control Algorithm: This uses the sensor signals to calculate the control inputs to the system. The control algorithm is based on a mathematical model of the system and uses a feedback mechanism to compare the actual output of the system to a desired or reference value.
3. Actuators: These are the devices that implement the control inputs and cause changes to the system. For example, actuators might include valves, motors, or heaters.
4. System Dynamics: This represents the physical or electrical processes that govern the behavior of the system. The system dynamics determine how the inputs to the system affect the outputs.

In a closed-loop system, the control algorithm receives the sensor signals and calculates the control inputs, which are then applied to the system by the actuators. The output of the system is then measured again by the sensors, and the process is repeated continuously. The feedback from the sensors allows the control algorithm to adjust the control inputs so that the output of the system converges to the desired value.

Closed-loop systems are widely used in a variety of applications, including process control, temperature control, motor control, and others. They are characterized by their ability to respond quickly to changes in the system, to maintain stability even in the presence of disturbances, and to achieve high accuracy and precision in the control of the system.

Overall, closed-loop systems are a critical component in many control applications, and their design and implementation require a strong understanding of control theory and system dynamics. Here for feedback, the sensing element which is temperature sensor is used.

The input receives the set value of temperature, while Arduino controls it by turning the process on and off, which is the fan in this case. The temperature sensor placed in variable compartment (VC) will give the current value of temperature. Whether it is above or below the required or set temperature, the Arduino, which is controller in this case, will judge and correspond signal to the fan to turn on or off, respectively. Once the desired temperate is achieved, we will receive it in an output, which is the required temperature in variable compartment (VC).

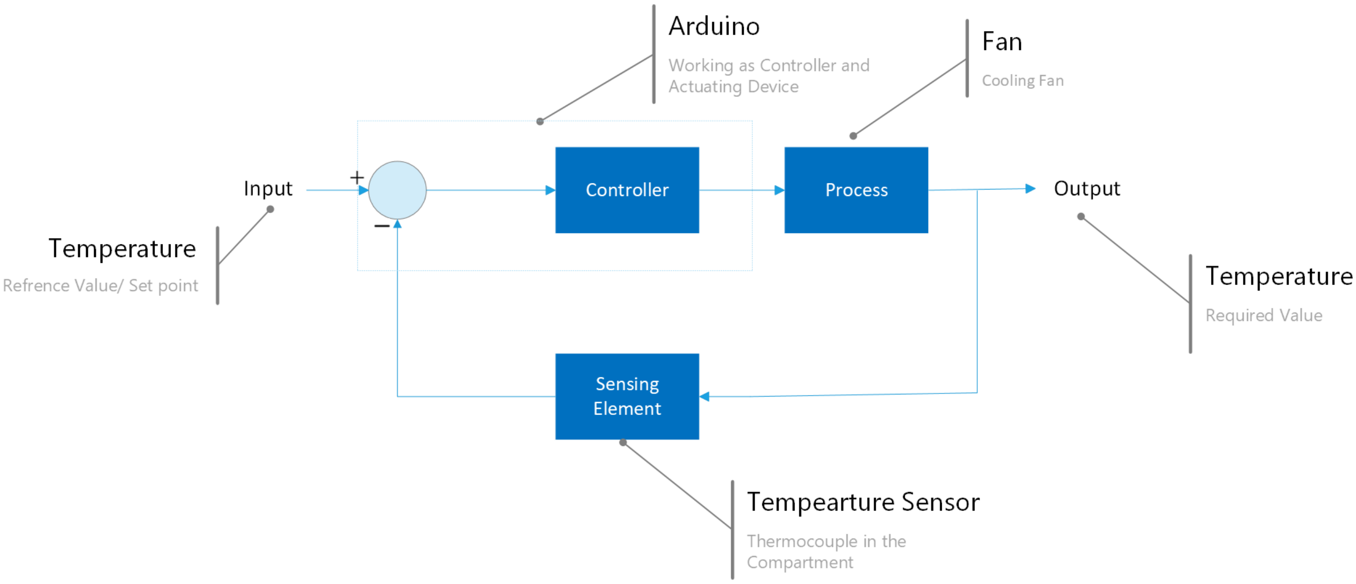

Figure 2.5: Control Diagram

The control program implemented has the following conditions and variables.

i. The target is to maintain the temperature of Variable Compartment (VC) between 5 to -5 ^{o}C.
ii. Depending on the needs, it can be set at any point between 5 to -5 ^{o}C.
iii. Once at input, the temperature X is set (X is any degree between 5 to -5 ^{o}C), the fan will turn on if the temperature is greater than set temperature X.
iv. The fan will keep running at constant speed unless the temperature reaches the set value X. Once it reaches X, the fan will stop.
v. As the fan is stopped, slowly the temperature will rise. Once it rises one degree above X, the fan will start running and the temperature will again fall to X.
vi. Hence the temperature will be maintained at set temperature X.

CHAPTER 3: EXPERIMENTAL RESULTS

The experiments were conducted by implementing the procedure discussed in previous chapter, Methodology and Setup. The experimental results were averaged on thirty days readings. All the results are presented in the form of time verses temperature. A time versus temperature graph is a graph that plots the change in temperature over time. The x-axis of the graph represents temperature, and the y-axis represents time. By plotting temperature data over time, a time versus temperature graph provides a visual representation of the temperature changes that occur in a particular system or process.

Such a graph is commonly used in many scientific and engineering fields, including refrigeration, where it is used to track the temperature changes in a refrigeration system. For example, a time versus temperature graph could be used to track the temperature changes in a refrigerated container as it is transported, or to monitor the performance of a refrigeration system in a laboratory setting.

By visualizing the temperature changes over time, a time versus temperature graph provides valuable information about the performance of a system or process, helping engineers and scientists to identify trends, patterns, and any deviations from expected temperature changes. This information can then be used to optimize the performance of the system, improve energy efficiency, and ensure the desired temperature conditions are maintained.

3.1 Total Time Taken

The graph given in figure 3.1 shows the total time taken to drop the variable compartment (VC) temperature from 10 to -1 ^{o}C. In these experiments the minimum temperature achieved was -1 ^{o}C, the reason being the high temperature of freezer compartment (FC) or the evaporator. The evaporator averaged about -12.5 ^{o}C temperature during this whole process, which is greater than the average freezers in the market which averaged about -18 ^{o}C, hence the minimum temperature achieved here is -1 ^{o}C rather than -5 ^{o}C.

The results were divided into two parts, first the time taken to reach from 10 to 5 ^{o}C while second was the time taken to reach from 5 to -1 ^{o}C. The results were taken for four scenarios, i.e., for no load condition, for 1.5 liters of volume occupied out of 16 liters (16000cc), for 3 liters and for 3 liters in addition to the freezer load as well.

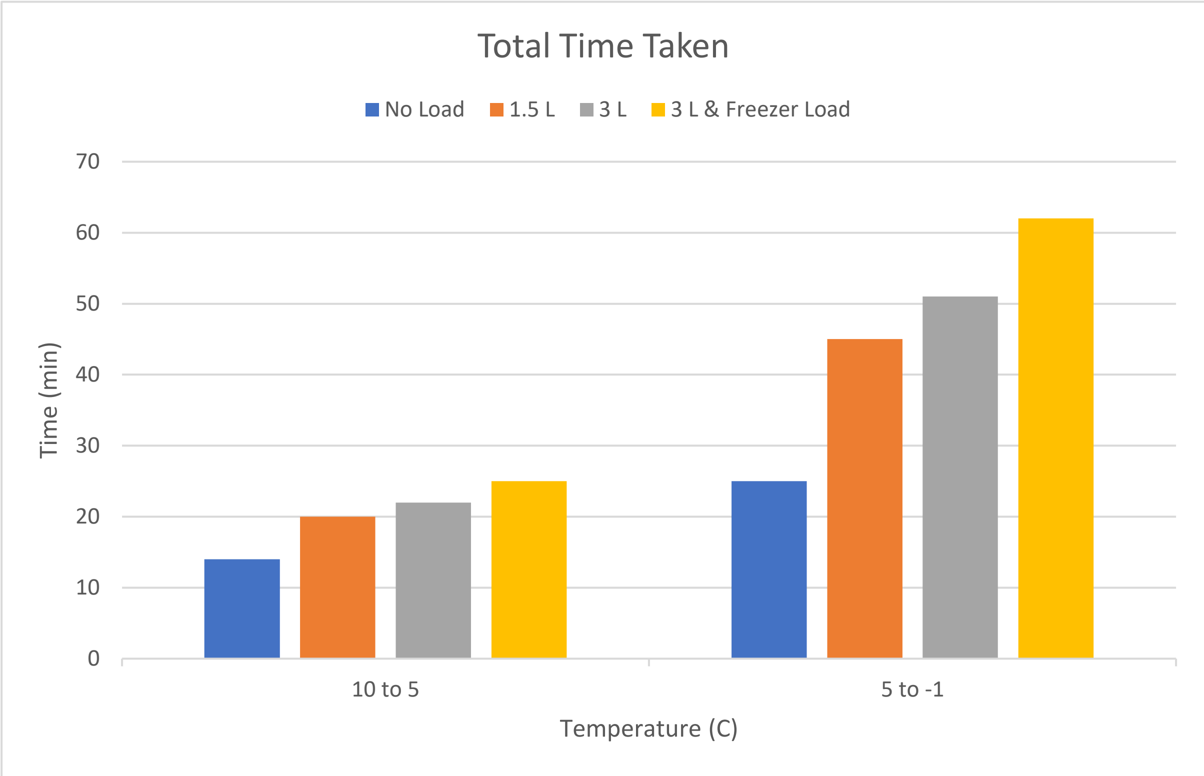

Figure 3.1: Graph of Total Time Taken to reach from 10 to -1 °C

For No load condition, when there is no load in variable compartment (VC) the total time taken to reach from 10 °C to 5 °C is less than any other scenario, because when there is no load on the compartment, the cooling will occur more rapidly. Similarly, it happens when temperature goes from 5 °C to -1 °C. The total time taken for these cases is 14 and 25 minutes, respectively. The average temperature during this process was 8.1 °C in the refrigerator section while -12.5 °C in the freezer compartment (FC).

For 1.5-liter load in the variable compartment (VC), the total time taken to reach from 10 °C to 5 °C is greater than the no load condition, because when there is some load on the compartment, the cooling will occur gradually. Similarly, it happens when temperature goes from 5 °C to -1 °C. The total time taken for these cases is 20 and 45 minutes, respectively. The average temperature during this process was 8.0 °C in the refrigerator section while -12.5 °C in the freezer compartment (FC).

For 3 liters of load in the variable compartment (VC), the total time taken to reach from 10 °C to 5 °C is greater than the previous two conditions, because if we keep increasing the load, the cooling will occur slowly. Similarly, it happens when temperature goes from 5 °C to -1 °C. The total time taken for these cases is 22 and 51 minutes, respectively. The average temperature during this process was 8.1 ^{o}C in the refrigerator section while -12.5 ^{o}C in the freezer compartment (FC).

For 3 liters of load in the variable compartment (VC) with addition to load of freezer compartment (FC), the total time taken to reach from 10 ^{o}C to 5 ^{o}C is greatest than any other condition, because in addition to the load on variable compartment, the freezer is also bearing load, hence the freezer average temperature drops which results in the increase of time taken to reach the set temperature for variable compartment (VC). Similarly, it happens when temperature goes from 5 ^{o}C to -1 ^{o}C. The total time taken for these cases is 25 and 62 minutes, respectively. The average temperature during this process was 9.6 ^{o}C in the refrigerator section while -10 ^{o}C in the freezer compartment (FC).

From this graph (figure 3.1), it can be noted that, the time taken to reach from 10 ^{o}C to 5 ^{o}C is much less than when it goes from 5 ^{o}C to -1 ^{o}C. The reason for this trend is because the fan is placed at evaporator having the average temperature of -12 ^{o}C. So as the temperature in the variable compartment (VC) reaches near to the average value of the source, the process slows down, hence the minimum temperature achieved was -1 ^{o}C rather than -5 ^{o}C, which could be achievable if the average evaporator temperature goes up to -18 ^{o}C, which most domestic refrigerators have.

3.2 Temperature Drop

The graph given in figure 3.2 shows the time taken to drop half a degree centigrade of temperature, for all the four scenarios discussed in previous section. The graph shows that as temperature drops to from 10 to -1 ^{o}C, the time taken for every half degree drop in temperature increases.

For No load condition, when there is no load in variable compartment (VC) the time taken for half degree drop in temperature, slightly increase as the temperature drops near to -1 ^{o}C, because as the temperature moves near to the source temperature, it will take more time, hence can be seen in the graph. The average for no load condition is 1.5 minutes for every half degree drop in temperature, as temperature drops from 10 to -1 ^{o}C, with maximum value of 3 minutes for temperature drop from -0.5 to -1 ^{o}C.

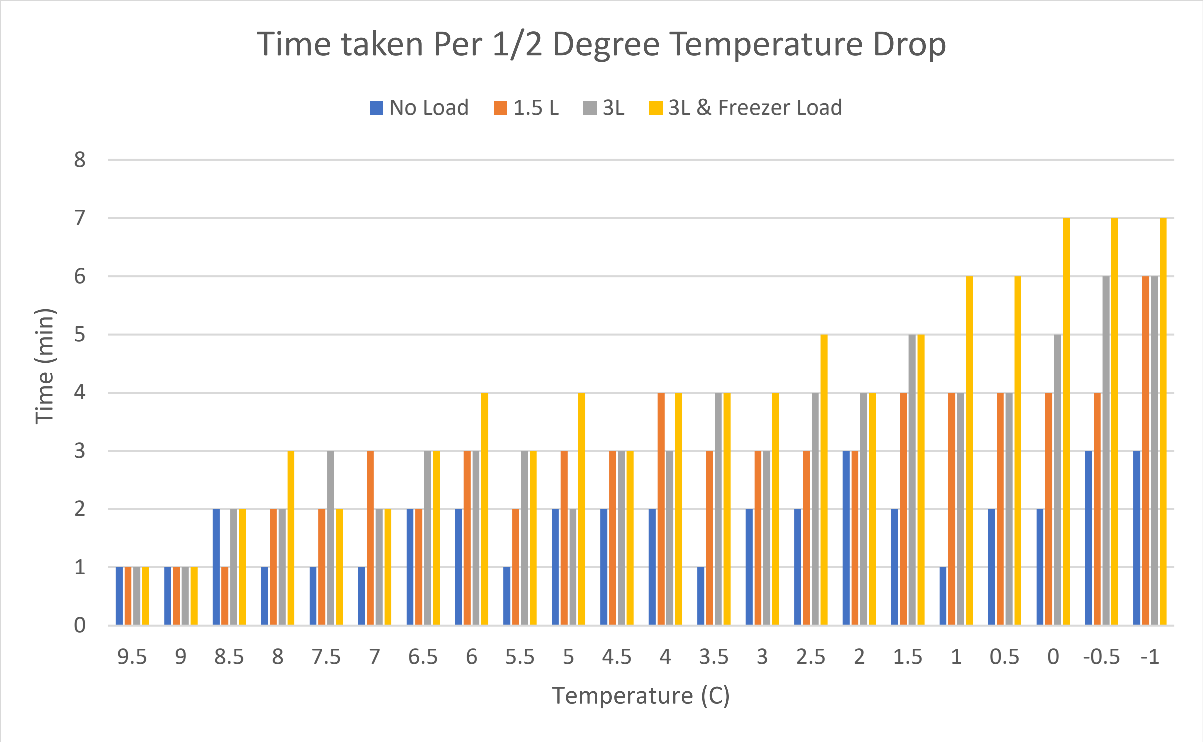

Figure 3.2: Graph of time taken per half degree temperature drop.

Similar trend is shown for other scenarios including 3 liters volume in variable compartment (VC) and 3 liters in VC in addition to freezer load. Having maximum value of time as 6 and 7 minutes, respectively as temperature drop from -0.5 to -1 ^{o}C. The reason for this trend is same as described earlier, that as the temperature reaches the source value, it will take more time to established rather than higher temperature (10 to 5 ^{o}C) which drops quickly due to larger difference between source and current temperature.

The phenomena that happened here is heat transfer. Heat transfer refers to the movement of thermal energy from a hotter region to a cooler region due to a temperature difference. There are three main mechanisms of heat transfer: conduction, convection, and radiation. Conduction is the transfer of heat through direct contact of particles, convection involves the transfer of heat through fluid motion, and radiation refers to the emission of heat as electromagnetic waves.

The heat transfer which is happening here is forced convection. Forced convection is a type of heat transfer that occurs when a fluid is forced to flow over a surface, transferring heat in the process. In forced convection, the fluid motion is externally induced, for example, by a pump or a fan. This type of heat transfer is different from natural convection, which occurs due to the buoyancy of fluid and does not require an external force.

Heat transfer rate is the amount of heat transferred per unit of time from a hotter to a cooler system. It is usually measured in units of watts (W) or joules per second (J/s). The heat transfer rate can be affected by several factors such as the temperature difference between the systems, the heat transfer coefficient, the surface area over which heat is being transferred, and the thermal conductivity of the material involved. The heat transfer rate can be calculated using the equation:

$$Q = h \times A \times \Delta T \tag{3.1}$$

Where:

Q = heat transfer rate (W or J/s)

h = heat transfer coefficient ($W/m^2 °C$)

A = heat transfer surface area (m^2)

ΔT = temperature difference between the systems (°C)

Heat transfer rate can be affected by several factors, including:

i. Temperature difference: The larger the temperature difference between the hot and cold systems, the greater the heat transfer rate.
ii. Heat transfer coefficient: The heat transfer coefficient represents the efficiency of heat transfer. A higher coefficient indicates a more efficient transfer of heat.
iii. Surface area: An increase in surface area results in an increase in heat transfer rate.
iv. Thermal conductivity: Materials with high thermal conductivity transfer heat more efficiently than materials with low thermal conductivity.
v. Flow rate of fluid: In convective heat transfer, the flow rate of the fluid plays a crucial role in the heat transfer rate. Faster fluid flow results in a higher heat transfer rate.
vi. Presence of insulation: Insulation reduces heat transfer by slowing down heat flow through conduction and convection.
vii. Pressure and altitude: The pressure and altitude of a system can affect the heat transfer rate. Higher altitudes or lower pressures result in lower heat transfer coefficients.
viii. Radiation: Radiant heat transfer can affect the overall heat transfer rate, especially in high temperature systems.

It is important to note that these factors can interact and influence the heat transfer rate. Hence the results shown in figures 3.1 and 3.2.

3.3 Temperature Maintain

One objective of this project is to maintain the temperature as long as possible, after the fan turns off. It was achieved by applying the insulation around the variable compartment and duct, to insulate it from the rest of the refrigerator. The insulation used here was polyethylene (PE) sheet, which wraps around the VC and duct, making it separate compartment from refrigerator, where only fan can provide cooling, rather than the refrigerator own temperature. Similarly, it prevents the cooling of VC from leaking to refrigerator, and graph in the figure 3.3 shows that the insulation works perfectly in maintaining the required temperature for longer period of time.

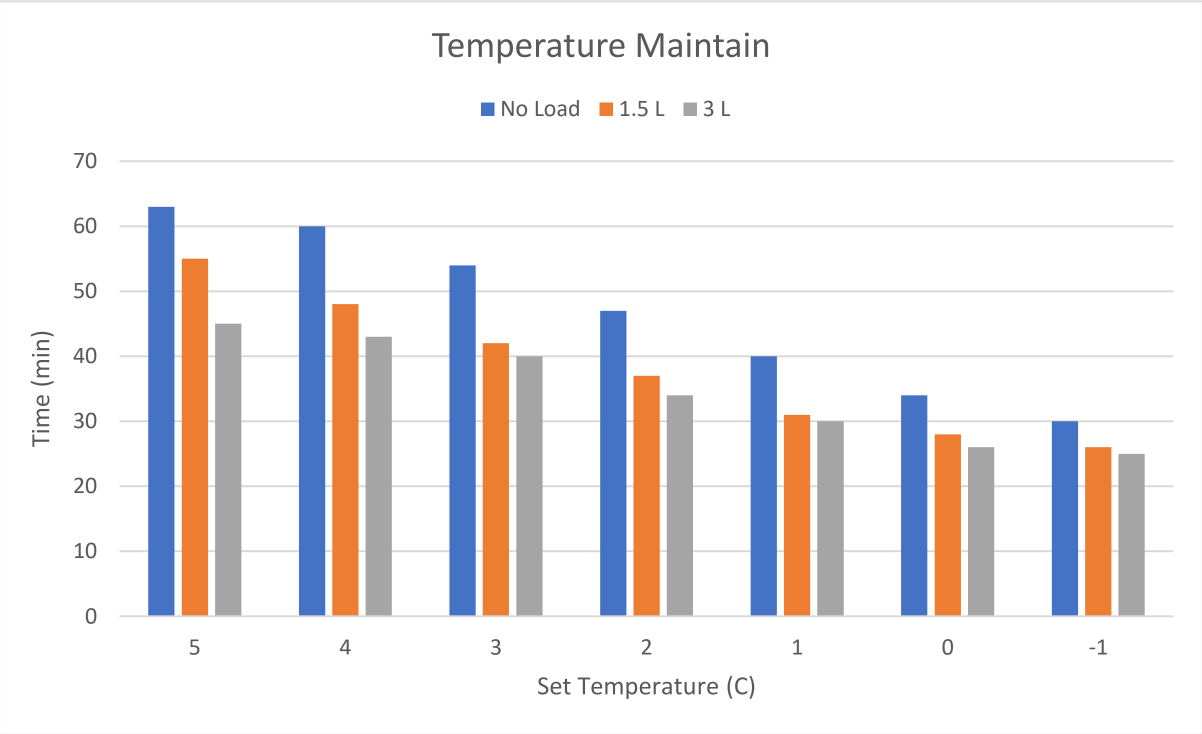

Figure 3.3: Graph of constant temperature with time, after turning off the fan.

For no load condition, the time period for temperature to remain constant is higher than other two cases which are load conditions having 1.5 and 3 liters of load. The reason is same as at no load condition there is nothing in the compartment which can contribute to rise in temperature, while other two cases when load increases the time period decreases because the load within the variable compartment (VC) will utilize the temperature and results in increase of temperature in quicker time than at no load condition. Hence for 5 ^{o}C to maintain in VC, the total time period to remain at 5 ^{o}C after turning of the fan for no load condition is 63 minutes, for 1.5 liters of load, it is 55 minutes and for 3 liters of load, it is 45 minutes.

Heat diffusivity and heat diffusion are two main phenomena happening here, Heat diffusivity is a property of a material that describes its ability to conduct heat. The units of heat diffusivity are typically m^2/s, and it represents the speed at which heat can diffuse through a material. It is defined as the ratio of thermal conductivity to heat capacity and is usually represented by the symbol "α". The equation for heat diffusivity is given by:

$$\alpha = k/(\rho \times Cp) \tag{3.2}$$

Where:
α = heat diffusivity (m^2/s)
k = thermal conductivity (W/mK)
ρ = density (kg/m^3)
Cp = specific heat capacity (J/kgK)

Heat diffusivity is an important parameter in many engineering applications, such as heat exchangers, insulation materials, and phase change materials. A material with a high heat diffusivity can conduct heat quickly and efficiently, while a material with low heat diffusivity will conduct heat slowly. The heat diffusivity of a material can be affected by factors such as temperature, pressure, and composition.

In general, materials with high thermal conductivity and low density and specific heat capacity will have high heat diffusivity, while materials with low thermal conductivity and high density and specific heat capacity will have low heat diffusivity.

Heat diffusivity is an important property in many applications, including refrigeration, where it is important to minimize heat transfer through the insulation material used in the refrigeration system. By selecting materials with low heat diffusivity for the insulation, the rate of heat transfer through the insulation can be reduced, improving the overall efficiency of the refrigeration system.

Heat diffusion is the spreading of heat through a material or a fluid due to a temperature gradient. It is a type of heat transfer that occurs through conduction and results in the mixing of thermal energy in a material or fluid. The properties of heat diffusion are described by the heat diffusion equation, which is given by:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \qquad 3.3$$

Where:

T = temperature (K)

t = time (s)

α = thermal diffusivity (m^2/s)

$\nabla^2 T$ = Laplacian of temperature, representing the spatial rate of change of temperature in the material

The heat diffusion equation can be used to determine the temperature distribution within a material or fluid over time, given the initial temperature distribution and the material's thermal diffusivity. The thermal diffusivity α is a measure of the rate at which heat diffuses through the material and is a function of the material's thermal conductivity, density, and specific heat capacity.

In practical applications, heat diffusion is used to model and understand a wide range of thermal phenomena, including heat transfer in solids and fluids, heat storage in phase change materials, and heat dissipation in electronic devices.

Another trend in figure 3.3 shows that the higher temperatures can be maintained for longer period of time as compared to the lower temperatures, because at lower temperature the difference between the temperatures of refrigerator compartment and variable compartment (VC) increases, so even if there is insulation, it will work less effective as compared to the higher temperatures, as explained by heat diffusivity and heat diffusion. A similar trend can be shown when there are hotter or colder conditions outside the refrigerator, where in winter, the refrigerator will achieve its target temperature more quickly than that of summer.

CONCLUSION

The objective was to develop the variable compartment (VC) where one can set temperature to their needs from 5 ^{o}C to -5 ^{o}C. In this project, we achieved the lowest temperature of -1 ^{o}C, rather than -5 ^{o}C, which is because, the average temperature for freezer compartment (FC) which is also act for evaporator source of fan, is around -12 ^{o}C, which is larger than most of the domestic refrigerators which is -18 ^{o}C. Hence as the source temperature is higher so the lowest temperature achieved was -1 ^{o}C. as this refrigerator was selected for experimental purposes, hence why it is not as efficient as other domestic refrigerators. All the results show that the variable compartment (VC) is fully functional and can be applied in domestic refrigerators.

For future recommendations, one can program the fan speed, to collect CFM as per requirement, rather than single CFM. Others can test this setup in any domestic refrigerator where the minimum freezer temperature goes up to -18 ^{o}C. Furthermore, the larger fan with greater CFM and diameter can be used to test the efficiency of this system. Similarly, one can test and examine the total energy consumption.

REFERENCES

[1] M. M. Farid, *Mathematical modeling of food processing*. Heat transfer and air flow in a domestic refrigerator. Boca Raton: CRC Press, 2010.

[2] J. Belman-Flores, S. Ledesma, A. Gallegos-Muñoz, and D. Hernandez, “Thermal Simulation of the Fresh Food Compartment in a Domestic Refrigerator,” *Energies*, vol. 10, no. 1, p. 128, 2017, doi: 10.3390/en10010128.

[3] L. Wang, L. Zhang, and G. Lian, “A CFD Simulation of 3D Air Flow and Temperature Variation in Refrigeration Cabinet,” *Procedia Engineering*, vol. 102, pp. 1599–1611, 2015, doi: 10.1016/j.proeng.2015.01.296.

[4] E. Söylemez, E. Alpman, A. Onat, Y. Yükselentürk, and S. Hartomacıoğlu, “Numerical (CFD) and experimental analysis of hybrid household refrigerator including thermoelectric and vapour compression cooling systems,” *International Journal of Refrigeration*, vol. 99, pp. 300–315, 2019, doi: 10.1016/j.ijrefrig.2019.01.007.

[5] N. O. Moraga and D. R. Rivera, “Advantages in predicting conjugate freezing of meat in a domestic freezer by CFD with turbulence k-ε 3D model and a local exergy destruction analysis,” *International Journal of Refrigeration*, vol. 126, pp. 76–87, 2021, doi: 10.1016/j.ijrefrig.2021.02.002.

[6] E. Söylemez, E. Alpman, A. Onat, and S. Hartomacıoğlu, “CFD analysis for predicting cooling time of a domestic refrigerator with thermoelectric cooling system,” *International Journal of Refrigeration*, vol. 123, pp. 138–149, 2021, doi: 10.1016/j.ijrefrig.2020.11.012.

[7] Hitesh Kumar, “CFD Simulation of Velocity and Temperature Distribution inside Refrigerator Compartment,” *ijeat*, vol. 8, no. 6, pp. 4199–4207, 2019, doi: 10.35940/ijeat.F9571.088619.

[8] Muhammad E. Haque, Rosli Abu Bakar, Gan Leong Ming, and M Shakaib, “PREDICTING AIRFLOW AND TEMPERATURE PATTERN INSIDE A REFRIGERATOR THROUGH CFD,” *ARPN Journal of Engineering and Applied Sciences*, vol. 11, no. 14, 2016.

[9] W. J. Yoon, H. W. Jung, H. J. Chung, and Y. Kim, “Performance optimization of a two-circuit cycle with parallel evaporators for a domestic refrigerator–freezer,” *International Journal of Refrigeration*, vol. 34, no. 1, pp. 216–224, 2011, doi: 10.1016/j.ijrefrig.2010.09.008.

[10] Z. Zhang, D. Huang, L. Shi, and L. Chi, “Comparison of independent and synchronous opening control strategies of two air-dampers in three-temperature frost-free refrigerator,” *Applied Thermal Engineering*, vol. 128, pp. 127–133, 2018, doi: 10.1016/j.applthermaleng.2017.09.005.

[11] Z. Li, G. Ding, S. Miao, and X. Han, “Development of novel air distributor for precise control of cooling capacity delivery in multi-compartment indirect cooling household refrigerators,” *International Journal of Refrigeration*, vol. 119, pp. 175–183, 2020, doi: 10.1016/j.ijrefrig.2020.07.028.

[12] J. Ye, X. Huang, Y. Cheng, J. Shao, and Y. Zhang, “Air volume improvement in the duct system in frost-free refrigerators based on the CFD method,” *J Supercomput*, vol. 76, no. 5, pp. 3749–3764, 2020, doi: 10.1007/s11227-018-2586-0.

[13] J. Hyuk Wie, H. Woo Cho, Y. Gap Park, Y. Soo Kim, Y. Min Seo, and M. Yeong Ha, “Temperature uniformity analysis of a domestic refrigerator with different multi-duct shapes,” *Applied Thermal Engineering*, vol. 188, p. 116604, 2021, doi: 10.1016/j.applthermaleng.2021.116604.

[14] Y. Yang, D. Huang, R. Zhao, W. Guo, and X. Wei, “Analysis of temperature rapid rise phenomenon during damper-off cycle in side-by-side frost-free refrigerator,” *International Journal of Refrigeration*, vol. 133, pp. 201–213, 2022, doi: 10.1016/j.ijrefrig.2021.10.014.

[15] O. Çelikkan and H. Erol, “Vibroacoustic Analysis of a Refrigerator Freezer Cabinet Coupled with an Air Duct,” *Advances in Acoustics and Vibration*, vol. 2017, pp. 1–18, 2017, doi: 10.1155/2017/1960898.

[16] P. Cui, L. He, and X. Mo, “Flow and heat transfer analysis of a domestic refrigerator with complex wall conditions,” *Applied Thermal Engineering*, vol. 209, p. 118306, 2022, doi: 10.1016/j.applthermaleng.2022.118306.

[17] R. Zhao, L. Qiao, Z. Gao, and D. Huang, “Effect of Vacuum Insulation Panels on Energy Consumption and Thermal Load Transfer between Compartments in a Three-Temperature Frost-Free Refrigerator,” *Energies*, vol. 13, no. 7, p. 1559, 2020, doi: 10.3390/en13071559.

[18] Z. Liu, W. Gao, H. Lang, and Y. Chi, “Experimental study on new type of defrosting system using outdoor air for frost-free household refrigerators,” *Applied Thermal Engineering*, vol. 134, pp. 256–265, 2018, doi: 10.1016/j.applthermaleng.2018.02.007.

[19] M. Kılıç, T. Güler, and G. Sevilgen, “NOVEL AIR DUCT COOLING PERFORMANCE EVALUATION FOR THE REFRIGERATED PRODUCT

TRANSPORT IN A SEMI-TRAILER CABIN," *Heat Trans Res*, vol. 53, no. 5, pp. 17–30, 2022, doi: 10.1615/HeatTransRes.2022040717.
[20] Z. Li *et al.*, "Improving defrosting performance by controlling frost distribution to match defrosting heat distribution in frost-free household refrigerators," *International Journal of Refrigeration*, vol. 77, pp. 136–148, 2017, doi: 10.1016/j.ijrefrig.2017.03.003.
[21] X. Zhao, Y. Huang, J. Chen, P. Su, F. Sha, and Y. Yuan, "Numerical simulation of air flow and heat transfer in air refrigerated containers using clean energy technologies," *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 804, no. 4, p. 42068, 2021, doi: 10.1088/1755-1315/804/4/042068.
[22] G. B. Abdelaziz *et al.*, "Experimental investigation of heat transfer by forced convection from three dimensional suspended bodies subjected to free air stream," *Experimental Heat Transfer*, pp. 1–22, 2022, doi: 10.1080/08916152.2022.2074172.
[23] Z. Liu, D. Zhao, Q. Wang, Y. Chi, and L. Zhang, "Performance study on air-cooled household refrigerator with cold storage phase change materials," *International Journal of Refrigeration*, vol. 79, pp. 130–142, 2017, doi: 10.1016/j.ijrefrig.2017.04.009.
[24] T. Jiang *et al.*, "Analysis of an internal structure for refrigerated container: Improving distribution of cooling capacity," *International Journal of Refrigeration*, vol. 113, pp. 228–238, 2020, doi: 10.1016/j.ijrefrig.2020.01.023.
[25] B. N. Borges, C. Melo, and C. J. Hermes, "Transient simulation of a two-door frost-free refrigerator subjected to periodic door opening and evaporator frosting," *Applied Energy*, vol. 147, pp. 386–395, 2015, doi: 10.1016/j.apenergy.2015.01.089.
[26] G. Yan, G. Liu, M. Zhou, and J. Yu, "Experimental research on configuration optimization of a frost-free refrigerator-freezer with the parallel circuit cycle," *International Journal of Refrigeration*, vol. 118, pp. 415–426, 2020, doi: 10.1016/j.ijrefrig.2020.06.013.
[27] Y. Sun, R. Zhao, Y. Yang, and D. Huang, "Experimental and Numerical Study on Fan-Supplied Condenser Deterioration under Built-In Condition and Its Corresponding Refrigerator Performance," *Energies*, vol. 15, no. 22, p. 8666, 2022, doi: 10.3390/en15228666.
[28] S. Lee, S. Heo, and C. Cheong, "Prediction and reduction of internal blade-passing frequency noise of the centrifugal fan in a refrigerator," *International Journal of Refrigeration*, vol. 33, no. 6, pp. 1129–1141, 2010, doi: 10.1016/j.ijrefrig.2010.03.006.
[29] J. Fan, S. Lee, S. Kang, J. Cho, Y. Cho, and E. Yeom, "Design of drain hole for household refrigerator fan module based on experiments and CFD simulation," *Applied*

Thermal Engineering, vol. 219, p. 119567, 2023, doi: 10.1016/j.applthermaleng.2022.119567.
[30] Y. Fan, L. Luo, and B. Souyri, "Review of solar sorption refrigeration technologies: Development and applications," *Renewable and Sustainable Energy Reviews*, vol. 11, no. 8, pp. 1758–1775, 2007, doi: 10.1016/j.rser.2006.01.007.
[31] F. Afshari, M. Akif Ceviz, E. Mandev, and F. Yıldız, "Effect of heat exchanger base thickness and cooling fan on cooling performance of Air-To-Air thermoelectric refrigerator; experimental and numerical study," *Sustainable Energy Technologies and Assessments*, vol. 52, p. 102178, 2022, doi: 10.1016/j.seta.2022.102178.

Thesis

ORIGINALITY REPORT

9%	7%	4%	2%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	www.researchgate.net Internet Source	1%
2	archive.org Internet Source	1%
3	climbtheladder.com Internet Source	1%
4	Mascheroni, Rodolfo, and Viviana Salvadori. "Household Refrigerators andFreezers", Contemporary Food Engineering, 2011. Publication	<1%
5	Saurabh K Tiwary, Joel R Phillips. "WAVSTAN: Waveform based Variational Static Timing Analysis", 2007 Design, Automation & Test in Europe Conference & Exhibition, 2007 Publication	<1%
6	www.eaton.com Internet Source	<1%
7	Submitted to University of Idaho Student Paper	<1%

8	www.coursehero.com Internet Source	<1%
9	Submitted to Queensland Academy for Creative Industries Student Paper	<1%
10	stax.strath.ac.uk Internet Source	<1%
11	www.curtislumber.com Internet Source	<1%
12	Submitted to University of Bradford Student Paper	<1%
13	Submitted to Berlin School of Business and Innovation Student Paper	<1%
14	Zhiqiang Li, Guoliang Ding, Songtao Miao, Xiaolei Han. "Development of novel air distributor for precise control of cooling capacity delivery in multi-compartment indirect cooling household refrigerators", International Journal of Refrigeration, 2020 Publication	<1%
15	www.springerprofessional.de Internet Source	<1%
16	www.qats.com Internet Source	<1%

17	mdpi-res.com	Internet Source	<1 %
18	Tiancheng Ouyang, Zhiping Wang, Zhongkai Zhao, Jie Lu, Mingliang Zhang. "An advanced marine engine waste heat utilization scheme: Electricity-cooling cogeneration system integrated with heat storage device", Energy Conversion and Management, 2021	Publication	<1 %
19	Submitted to University of Northumbria at Newcastle	Student Paper	<1 %
20	Yue Cheng, Jianlin Yu, Gang Yan, Suxin Qian. "Improving Temperature Uniformity in a Large Frost-free Chest Freezer", International Journal of Refrigeration, 2022	Publication	<1 %
21	Submitted to Caledonian College of Engineering	Student Paper	<1 %
22	Submitted to Cranfield University	Student Paper	<1 %
23	Submitted to University of St Mark and St John	Student Paper	<1 %
24	bioone.org	Internet Source	<1 %

25	www.eng.fiu.edu Internet Source	<1 %
26	Jules Thibault. "COMPARISON OF NINE THREE-DIMENSIONAL NUMERICAL METHODS FOR THE SOLUTION OF THE HEAT DIFFUSION EQUATION", Numerical Heat Transfer, 2007 Publication	<1 %
27	ijedr.org Internet Source	<1 %
28	journals.sagepub.com Internet Source	<1 %
29	mdpi.com Internet Source	<1 %
30	Submitted to Iowa State University Student Paper	<1 %
31	docplayer.net Internet Source	<1 %
32	homes.es.aau.dk Internet Source	<1 %
33	Submitted to Sabanci Universitesi Student Paper	<1 %
34	dalspace.library.dal.ca Internet Source	<1 %
35	moam.info Internet Source	<1 %

36	pdfcoffee.com Internet Source	<1 %
37	B. T. KULAKOWSKI, F. W. SCHMIDT. "Explicit Design of Balanced Regenerators", Heat Transfer Engineering, 2007 Publication	<1 %
38	N. Kasayapanand, J. Tiansuwan, W. Asvapoositkul, N. Vorayos, T. Kiatsiriroat. "Effect of the Electrode Arrangements in a Tube Bank on the Characteristic of Electrohydrodynamic Heat Transfer Enhancement: Low Reynolds Number", Journal of Enhanced Heat Transfer, 2002 Publication	<1 %
39	blog.coldwellbanker.com Internet Source	<1 %
40	curve.coventry.ac.uk Internet Source	<1 %
41	etheses.whiterose.ac.uk Internet Source	<1 %
42	www.engproguides.com Internet Source	<1 %
43	Yikun Yang, Dong Huang, Rijing Zhao, Wenhua Guo, Xinghua Wei. "Analysis of temperature rapid rise phenomenon during damper-off	<1 %

cycle in side-by-side frost-free refrigerator", International Journal of Refrigeration, 2021
Publication

44	Zhenya Zhang, Dong Huang, Lihua Shi, Lihua Chi. "Comparison of independent and synchronous opening control strategies of two air-dampers in three-temperature frost-free refrigerator", Applied Thermal Engineering, 2017 Publication	<1 %

Exclude quotes	Off	Exclude matches	Off
Exclude bibliography	Off		