ANALYSIS OF ENERGY PERFORMANCE OF DOMESTIC REFRIGERATORS

G. S. Roshani Costa

158278R

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Department of Mechanical Engineering

University of Moratuwa
Sri Lanka

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G.S.R. Costa

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Declaration

This report contains no material which has been accepted for the award of any other degree or diploma in any University or equivalent institution in Sri Lanka or abroad, and that to the best of my knowledge and belief, contains no material previously published or written by any other person, except where due reference is made in the text of this report

The work described in this report is carried out under the supervision of Dr. M. M. I. D. Manthilake and Prof. R. A. Attalage

Name of Student: G. S. Roshani Costa

Registration No: 158278R

Signature: Date:

Name of Supervisors

1. Dr. M.M.I.D Manthilake

   Signature: Date:

2. Prof. R.A. Attalage

   Signature: Date

Abstract

One of the most common appliances in today's households is the refrigerator, for cooling and preserving food. Continuous maintenance of correct compartment temperature is the key factor which contributes to food quality at preservation, though it results in high energy utilization. It is estimated that refrigerator consumes one third of total electricity demand from a typical household. If energy efficient refrigerators could be identified from different models in the market, it would contribute towards individual and national level benefits. SLS 1230:2003 is the refrigerator testing standard in Sri Lanka for energy labeling of domestic refrigerators which has the key responsibility to illustrate energy efficient refrigerator models in the market. Further inverter-based refrigerators are the new tendency today, and there is limited number of studies comparing performance of inverter and non-inverter refrigerators and SLS 1230:2003 does not consider loading and temperature stabilization connected with energy performance of refrigerators are the limitations that motivated for carrying out this research. The aim of this research is to study the temperature stabilization rate along with energy consumption of inverter and non-inverter types of domestic refrigerators, after loading a given mass, and to apply the results to make necessary amendments to present refrigerators testing methodology in SLS 1230:2003. Experiments were accompanied with pairs of inverter and non-inverter refrigerators with unique capacity, manufacturer and brand, incorporated with door-opening, loading and cooling. Tests were carried out at Refrigerators Testing Laboratory at, National Engineering Research and Development Centre. As per results, inverter refrigerators consumed 22% less energy than non-inverter refrigerators but the models with inverters had low cooling rate and consumed 3 more hours to cool down 3kg of test load than non-inverter refrigerators. This result is beneficial to refrigerator consumers, manufacturers, dealers as well as policy makers when making decisions on energy efficient refrigerators.

Key Words: Domestic refrigerator, Energy performance, Inverter based refrigerators

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1 INTRODUCTION

This chapter explains the research background of Domestic refrigerators. Then identified issues and the Problem Statement of the research are described. Proposed solution to the issue with Justification is conversed next. The overview to the structure of the project is also presented.

1.1 Research Background

Refrigerator is an essential and most popular appliance in almost all houses for preserving food. Freezing is predominant for maintaining freshness, texture, appearance, and taste of food when compared with other food preserving methods. Continuously maintaining correct freezing temperature is the fundamental requirement of food preservation [1]. In order to achieve this, refrigerator should operate whole day throughout the year which results in substantial amount of energy consumption. Controlling of energy consumption of this appliance is critical as it severely affects the quality of food and may cause serious food poisoning which might result in serious illness.

1.2 Problem Statement

The typical domestic refrigerator used today is an electrically powered vapor compression system. Over the generations the refrigerators widely evolved in vertical as well as horizontal technical improvements. Therefore, many consumers confuse when selecting an energy efficient model out of these different models. In order to cater this issue, it is important to identify the basic technical differences between refrigerators available today. Domestic refrigerators available today are of two basic types based on the frost removal mechanism. They are manual defrosting which was the old method and the automatic defrosting the latest technology. Mainly automatic defrosters further categorized by compressor characteristics. Those are refrigerators with inverter technology and without inverter technology.

As terms implies it is easy to understand the difference between automatic defrosting and manual defrosting of a refrigerator. There are many studies explaining the difference of defrosting mechanisms. Automatic Defrosting refrigerators are safer to cater the temperature fluctuation than manual defrosting refrigerators since; the refrigeration is continued while heating for defrosting [2]. Based on recent survey at a public workshop at National Engineering Research and Development Centre (NERDC) it was understood that users get confused when encountered with inverter and non-inverter refrigerators. Many people think that inverters are better as inverter technology came later, but they don’t know the exact benefits. Further there are limited studies in this area and few studies based on real data. Even in these studies the refrigerant used does not match with the regulations in Sri Lanka today, since the use of R134a is not recommended.

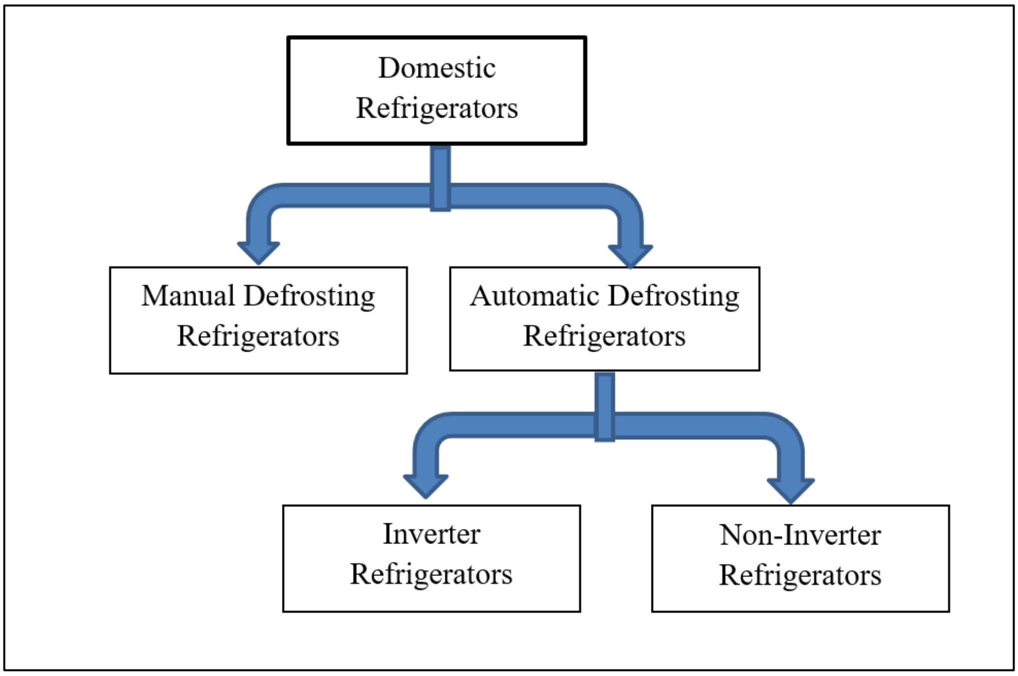


Figure 1: Key types of Domestic Refrigerators

There are energy labeling programs available in globally, and energy efficiency rating is labeled on the refrigerator which is mandatory under many cases. In Sri Lanka refrigerator testing standard was developed in 2003 and it was named Sri Lanka Standard 1230 (SLS 1230:2003), where Energy Labeling is included and to be implemented in future. So, it will be more beneficial to the refrigerator manufacturers as well as consumers to understand the energy efficient models out of many models available right now in the market as those will be demanded for near future.

The aim of this research is to test the impact of cooling load to energy performance of the refrigerator. At present, the testing standard SLS 1230:2003 is carried out for testing the empty refrigerators, as that is the worst-case scenario for energy consumption of a refrigerator. However, in general refrigerators rarely run empty during their actual operation. Therefore, this study addresses the real situation of domestic refrigerators where loading is common.

1.3 Scope of the Research

The research is focused on testing and analysis of main two key types of refrigerators. They are Inverter and Non-Inverter type domestic refrigerators. Two units of each type, i.e. four refrigerator units were tested. As there is a testing methodology in the refrigerator Testing Standard SLS 1230:2003, this research can be considered as supplementary to the existing testing protocol of domestic refrigerators. The testing methodology in this research consists with door opening, loading and cooling of the refrigerator freezer compartment, which is not included in SLS 1230:2003.

Refrigerators were tested in the Testing Chamber where the ambient condition can be controlled. The temperature and humidity settings of the chamber were set to simulate the average environment condition of the country, and set values of refrigerators compartment temperatures were accordance with SLS 1230:2003.

1.4 Aim

To study the stabilization rate with energy consumption of domestic refrigerators, after loading a given mass in order to make necessary amendments of present refrigerators testing standard.

1.5 Objectives

1. To explore the state of the art of Inverter and Non-Inverter type Domestic Refrigerators (DR)
2. To understand the relationship between key parameters affecting energy consumption of DR

3. To analysis the performance of inverter and non-inverter two type domestic refrigerators.
4. To make recommendations for present testing methodology.

1.6 Methodology

Phase 1: Literature Review

1. History of refrigeration
2. Basic Working principal of the refrigerator
3. Refrigerant
4. Performance evaluation of the refrigerator

Phase 2: Data Collection

1. Experiment Design
2. Carrying out experiment and obtain data
3. Analysis of data

Phase 3: Analysis of results and key findings

1. Key findings and discussion
2. Recommendations
3. Future work

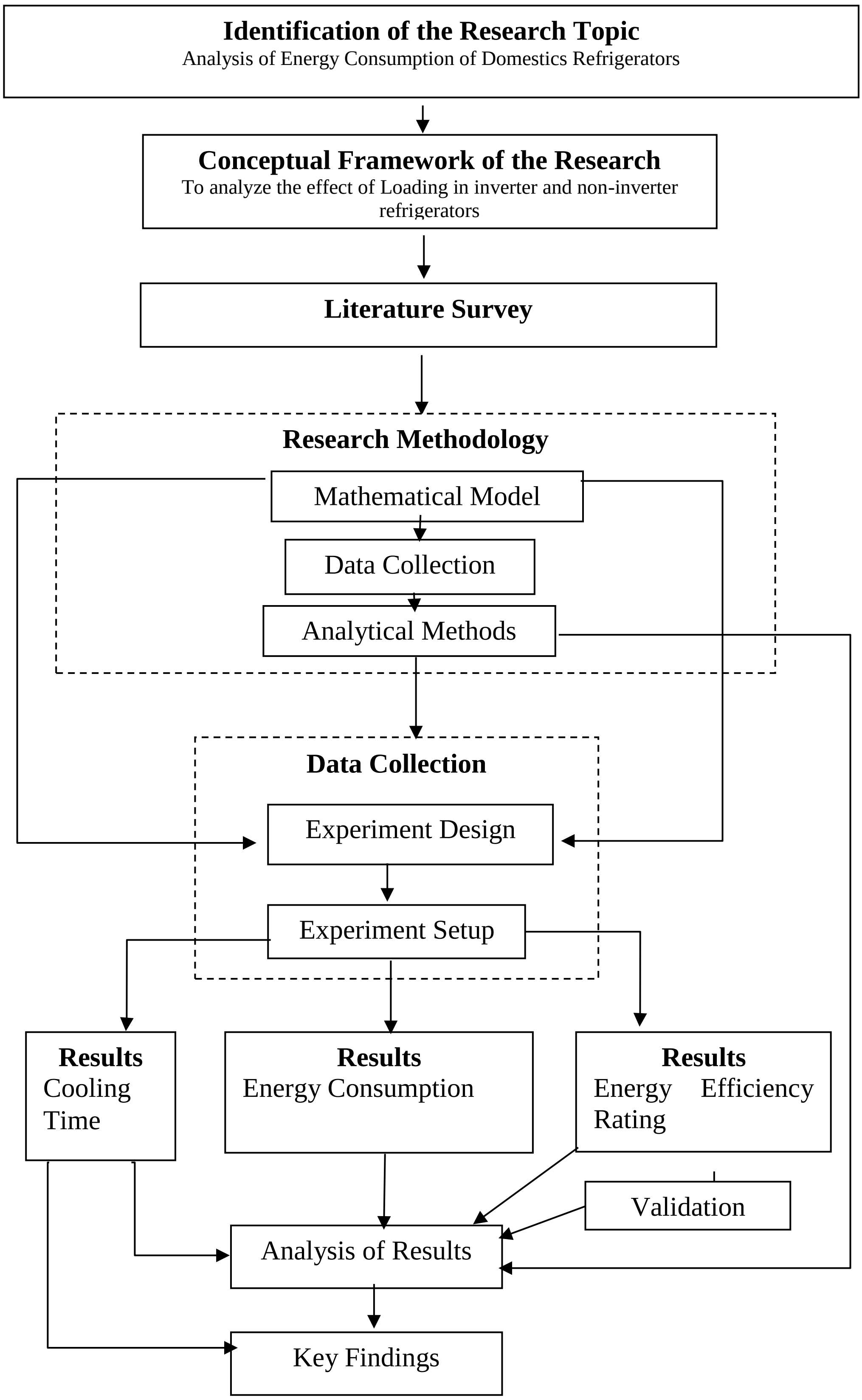


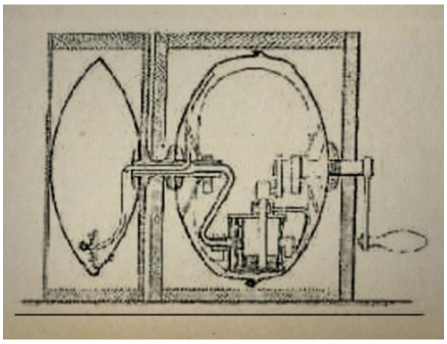
Figure 2: Work Flow Diagram

2 EVOLUTION OF REFRIGERATORS

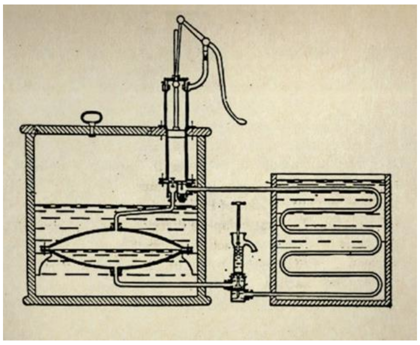
This chapter explains evolution of refrigerator, vapor compression refrigeration system, progress of refrigerant and food preservation by refrigeration. Next this chapter explains how the significant factors such as; temperature setting of compartments, door opening, ambient settings, defrosting operation and compressor efficiency affects the energy consumption of domestic refrigerators.

2.1 History of the refrigerator

Preserved food after freezing on ice and snow was found by ancient hunters accidentally. Animals when covered by snow, was found preserved for some times. Refrigeration in caves or under water was a well-known ancient technique of food preservation [3]. About one and half centuries ago in China, foods were kept under the streams or in ice houses which were built near streams. Further in many places in the world Ice/Snow was harvested and used for ice houses to keep food safe and fresh, until snow will melt. Hebrews, Greeks, and Romans used to place huge amounts of snow into storage pits and covered it by insulator [4].



(a)



(b)

Figure 3; Evolution of the Refrigerator

(a) William Cullen's first artificial refrigerator, (b) Jacob Perkins first vapor Compression Refrigeration [5]

Later on, ice boxes were introduced. Ice box were used in houses and saw-dust or seaweeds were used to keep ice longer. Also, there was a tray beneath the ice blocks to collect melted water. First artificial refrigerator was developed in 1740s by William Coulan [6]. William Coulan's cooling machine was popular in 1775 and it uses diethyl ether with a pump; this was the first development of absorption refrigeration. The first vapor compression refrigerator was developed by Jacob Perkins in 1834which was the first commercial ice maker [6]. In 1913 domestic refrigerators were developed. In 1923 first self-contained refrigerator unit was developed [6]. First electric refrigerator was developed by Nathanial Wales a Michigan inventor in 20th century and the company called "Kelvinator" manufactured the commercial refrigerators based on Nathanial Wales's concept [6]. Until 1930 s many accidents were reported due to toxicity of the refrigerator gasses. Then Freon was invented in 1930. In 1970s energy labeling programs were recognized and people were focused on energy efficiency of refrigerators, which encouraged engineers to bring new energy efficient refrigerator models to the market [6].

2.2 Vapor Compression Refrigeration

Typically, all domestic refrigerators today are, vapor compression refrigerators. Vapor compression system could be configured to a closed looped refrigerant flow arrangement which resulted in compact refrigerator designs. This advantage is utilized in many architectural designs of household refrigerators. The vapor-compression has a circulating refrigerant medium and it takes in the heat from the refrigerator compartment to be cooled and then rejects that heat to the surrounding.

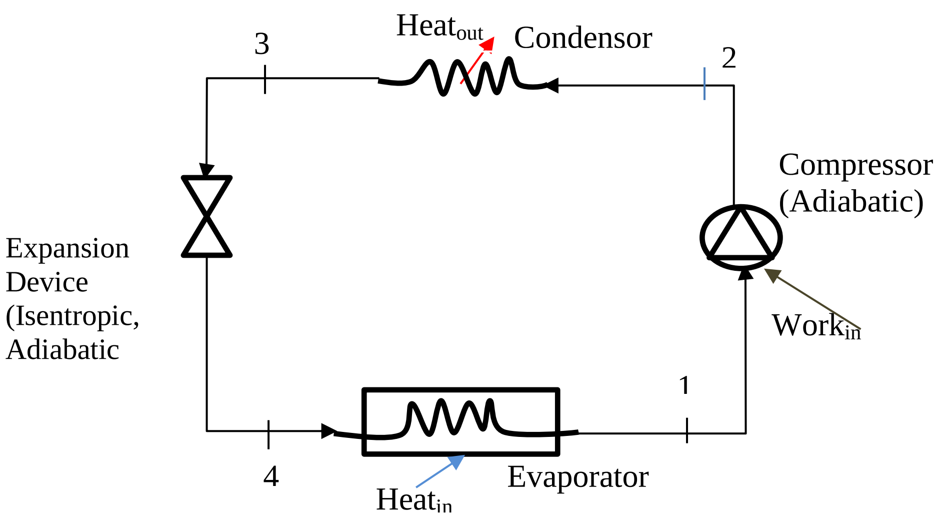


Figure 4; Basic Components of Domestic Refrigerator

This system basically has four key components. They are compressor, condenser, thermal expansion valve and evaporator as shown in Figure 4.

The cooling technique is such that refrigerant at saturated vapor state enters the compressor and it is compressed to high pressure and temperature. This hot compressed vapor is at superheated state. It will be condensed in the condenser by air cooling.

This saturated liquid is passed through the expansion valve where it undergoes sudden pressure reduction resulting adiabatic partial evaporation. This partial evaporation reduces the temperature of the refrigerant. This refrigerant mixture which is colder than the space to be cooled enters the evaporator.

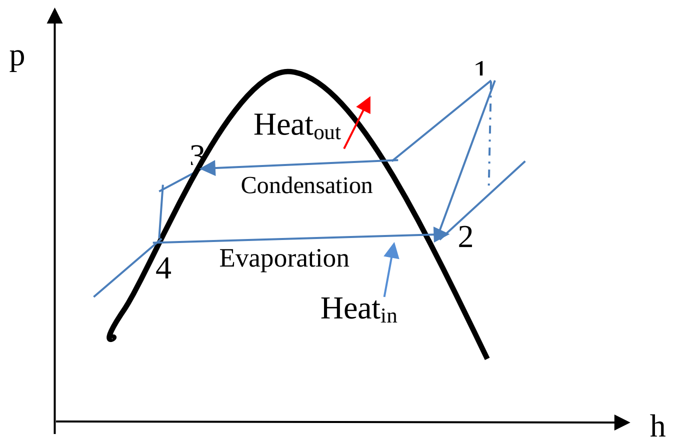


Figure 5: A pressure-enthalpy diagram for a typical refrigeration cycle

A fan circulates the warm air inside the space and when warm air touches the evaporator coil it will cool. Refrigerant in evaporator vaporizes due to the heat from the warm air. This is a saturated vapor which again flows to the compressor to complete the cycle. The cooling effect is propagating via conduction and convection inside the refrigerator. The heart of the vapor compression system is the compressor which accounts for nearly 80% of total energy consumed by the refrigerator [7].

2.3 Developments of Refrigerants

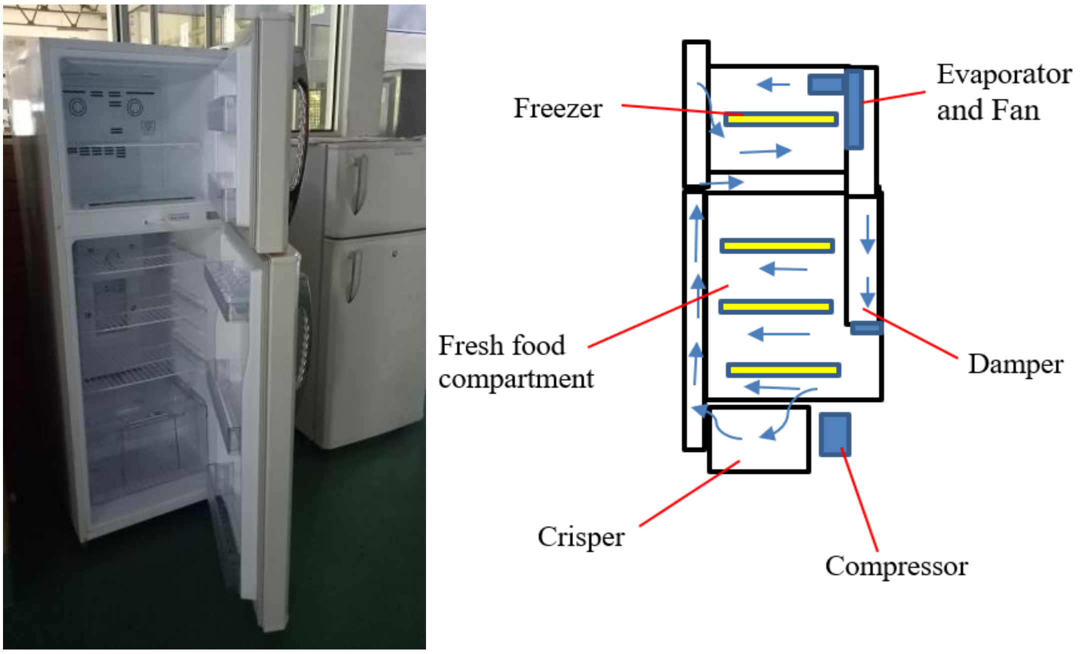
In early days water and air were used as refrigerant. Later, SO_2 and NH_3 were used because these refrigerants had qualifying physical and chemical properties which can improve the heat transfer efficiency. But later on, it was discovered that these refrigerants were toxic. As an improvement in refrigerant researches, Chlorofluorocarbon (CFC) was introduced. In the 20th century almost all refrigerators manufactured had CFC or its combinations as refrigerant. R-12 and R-22 are CFC and HCFC refrigerants. Experiments showed that chlorine in CFC catalysts the reaction of ozone in the atmosphere and due to leakages of CFC to the atmosphere began Ozone layer depletion. Due to this reason CFC was banned at an agreement of Montreal Protocol in 1987 [8]. Then Hydro fluorocarbon (HFC) was introduced and it was also eliminated due to high Global Warming Potential (GWP). R-134a, R-410 and R-404a are very common HFCs. Most HFCs has GWP of 2000 - 40000.

Next generation of refrigerant was hydro carbons. Propane, isobutene, and propylene are commonly used hydro carbons. Isobutene with notation R600 has the chemical formula C_4H_{10} was accepted due to zero Ozone layer Depletion Potential (ODP) and with very small GWP of less than 3. One of the studies highlighted energy saving of R600a is 12% higher than R134a [9].

2.4 Features of Domestics Refrigerators

Domestic refrigerator is featured for house hold requirements. Normally it consists with small freezer with ice making ability, normally at the top and large fresh food compartment for fresh fruits and vegetables. Domestic refrigerators are free standing or built in type, vapor compression system.

In some country's domestic refrigerators had many intentions. As an example, Soviet domestic refrigerators were grouped in to four. One to store unfrozen products: these refrigerators miss a freezer compartment, second for the short-run storage for few days of frozen foods, third type deliberate for the medium-term storage up to few weeks of frozen products, and fourth type was to the long-term storage up to about three months of frozen products [10]. It was understood refrigerator used in house hold has first intention of preserve food and to maintain freshness high as possible [11].



(a) (b)

Figure 6: (a) A front view and (b) Air flow arrangement of a Domestic Refrigerator

In order to protect freshness and quality at preservation cooling has to be maintained. Cooling is maintained all over the refrigerator compartments by circulating the cool air by a natural draft of by a use of a fan. Figure 6 shows how cool air circulates inside the refrigerator compartments. The damper controls the amount of air flow in between compartments.

2.5 Refrigeration and Food Preservation

It was understood that microorganism's growth depends on the chemical structure of food like pH value and Temperature and humidity of the environment. Due to the variation of them deterioration time is varying. Foods like raw meat, fish and milk which are highly perishable deteriorate faster than vegetables and fruits. To treat different categories of food accordingly domestic refrigerator has generally two main compartments. Freezer is for highly perishable food like fish and meat. Fresh food compartment is for food like vegetable fruits and pre-cooked food. Further fresh food compartment consists of vegetable crisper in order to maintain humidity for vegetables.

Refrigerating means cooling above zero degrees of centigrade (freezing temperature of water) which is required for perishable foods like fruits and vegetables. Further freezing (cooling below freezing point of water, 0 degrees of centigrade) is desirable for foods like meat. The basic idea behind preserving by cooling is to slow down the activity of Microorganisms which is present in all types of food. Bacteria like microorganisms are enzyme catalyzed and their reaction rate is depending on temperature [12].

There are two types of bacteria that cause food spoilage. One is spoilage bacteria, this type of bacteria effect foods to deteriorate and give unpleasant smells, flavors, and appearance of food. Therefore, there is limited possibility of consuming this type of spoiled food if human senses work well. Even if consumed the consequences are not deadly and harmful. Second type is pathogenic bacteria. Pathogenic bacteria which are very dangerous, may result sever foodborne illnesses. As an example, common deadly Diarrhea is due to the pathogens named Salmonella [13]. It was estimated there are about 5000 deaths in each year in United State due to food poisoning [14]. In contrast to spoilage bacteria, the presence of Pathogenic bacteria action on food cannot be detected by human senses [15].

Some studies had shown that pathogens can survive even in the refrigerator cool environment. *Staphylococcus aureus* and *Salmonella* are kinds of pathogen can grow even inside refrigerators basically those operates above recommended temperature of 5℃ [16]. A study by Rssvol has shown; even below recommend temperature of 5℃ pathogens can survive only but restricted in grow [17].

2.6 Effect of Temperature for food preservation

Microorganisms grow well in the temperature danger zone, 60°C – 5°C [18]. Therefore, food should not be kept in this temperature band. Pathogenic bacteria can grow at cold temperatures, even inside the refrigerator. Pathogenic bacteria will grow fast in the temperature range between 4.4 °C and 60 °C. Figure 7 highlights how bacteria growth rate is increasing with temperature and with time [19]. At 5℃ growth rates is very low compared to above temperatures. Food can be kept long time at low temperature as microbe’s growth is low.

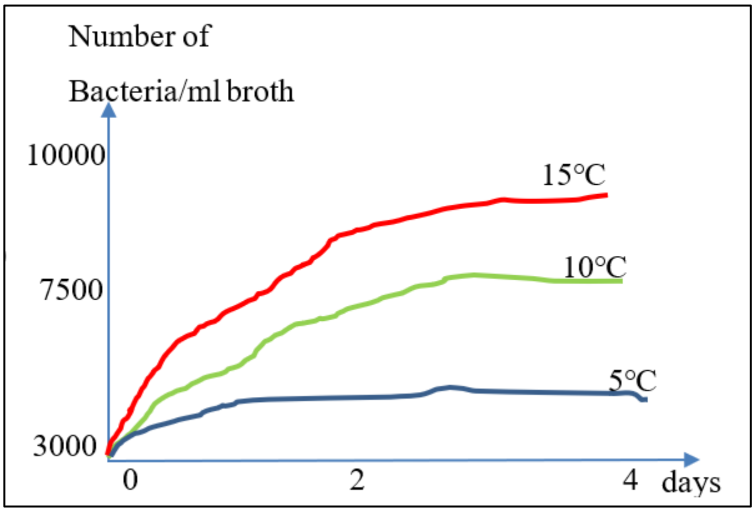


Figure 7: Bacteria Growth Rate

According to the World Health Organization (WHO) cooked food should not be kept in room temperature for more than 2 h, and cooked and perishable food should be quickly refrigerated below 5 °C (World Health Organization 2001). This was due to microorganisms grow faster and faster at room temperature. Due to this reason refrigeration above 5°C is necessary to protect food from spoiling. However, such studies in the Sri Lankan context are almost unavailable in literature. One of the worldwide studies in 2006 had shown, there were 61% of refrigerators that operate at average temperature above the recommended temperature of 5°C [20]. This is basically due to unawareness of the temperature inside the refrigerator and it may lead to health issues.

2.7 Indication of compartment temperatures

A survey-based study in North Ireland, United Kingdom, France, Netherland and New Zealand shows at least more than 50% of domestic refrigerators were operated at above 6°C of average temperature [21]. One of the studies in Sweden showed that only 25% of households were aware and concerned on refrigerator temperature settings [22]. In U.S it was estimated by a survey that, only 9% of refrigerators had a temperature measuring device [23]. Almost all the refrigerators in Sri Lanka do not have temperature indicators. Limited brands imported to Sri Lanka are having a temperature indicator of the refrigerator compartments (see Figure 8(a)) while many refrigerators have a dial only with a reference point that is difficult to identify at a first glance as shown in the photograph in Figure 8 (b).

(a) (b)

Figure 8 : Refrigerator Regulators (a) Indicates Temperature (b) Not Indicates Temperature

It is very important to have an indicator in the refrigerator to show the average temperature of the refrigerator compartments. Average temperature is because point to point inside the refrigerator compartment, temperature is varying specially based on the volume and air flow pattern of the refrigerator. Many temperature sensor points are important in measuring the temperature inside the refrigerator compartment than a single point [24]. Although it is still not emphasized in the SLSI standard, in order to raise public awareness to avoid food born complexities due to refrigeration, temperature indicator must be made compulsory. This requirement is practicing in many countries. In France temperature indicator was compulsory for refrigerators since year 2002 [25]. Maintaining proper temperature level can, weaken the microorganisms' action on food as mentioned before.

2.8 Energy Consumption of Domestic Refrigerators

Domestic refrigerator consumes considerable portion of electricity out of total electricity bill. It was recorded as 7% of the total country bill in United State in 2015 [26]. South Asian countries refrigerator electricity consumption is 10% to 70% [27]

of total countries electricity bill. Average energy consumption of a domestic refrigerator of 240L is nearly 30kWh/ month (Annex: D); with monthly utility bill of an average household of 200kWh (electricity units), energy consumption for a refrigerator counts 15%. This is a considerable amount. So, it is beneficial to pay attention to analysis of refrigerator energy consumption in order to control the energy consumption by optimizing the refrigerator performance.

There are many factors affects the energy consumption of the refrigerators. Regulating the temperature setting of the compartments, door opening time and frequency and temperature and humidity of the surrounding, defrosting mechanism, compressor efficiency, loading arrangement, [28] are among them. Energy consumption is further increase if optional features like automatic ice maker, water dispenser, side by side door cabinet and many more features available right now in modern refrigerators.

2.8.1 Temperature Setting

It should be noted that thermostat or regulator setting of the refrigerator is critical, since thermostat position regulates the temperature of the refrigerator compartment. As it was discussed in chapter two it should be careful to set the temperature of the compartments below 5°C. This is the optimum position of the refrigerator regulator. But further reduction of refrigerator compartment temperature beyond optimum point results higher energy consumption. But due to unawareness of this and due no indication in the refrigerator to read the temperature there is a potential of incorrect temperature setting.

Figure 9 shows percentage number of households from the total population of 143 refrigerators' in France, position the refrigerator thermostat at different settings to ratio to maximum cooling setting. Beyond optimum setting of the refrigerator regulator, may account for energy wastage [21].

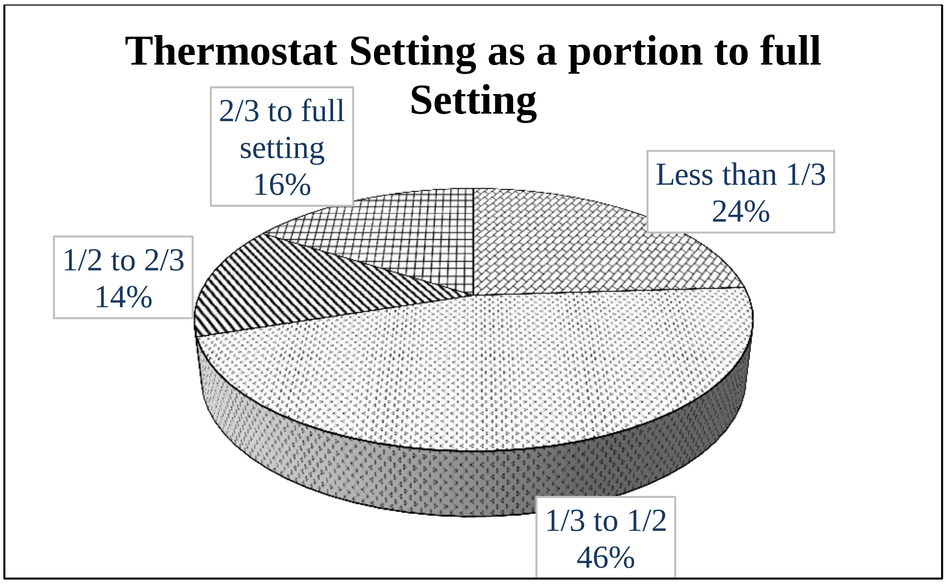


Figure 9 : Thermostat Settings

However, without a temperature indicator one cannot identify the correct regulator position.

2.8.2 Effect of door opening on energy use

One of the parameters increases the energy consumption of domestic refrigerators is the door openings. At door openings, the cold air replaced by warm air from the environment, which is a risk for freshness of food preserved. Same time compressor has to do additional work to cool down newly entered worm air at each door opening.

Table 1: Door Opening Frequency a Survey Statistics [21]

	% of total survey
Less than 10 times/day	19
10 to 20 times/day	43
More than 20 tomes/day	38

One of the studies in Bangladesh at 32^{o}C ambient temperature showed that the energy consumption increases 7%-30% as per the behavior of door openings [29].

Percentage contribution to door openings for container replacement, accounted 16.8% to 23.2% out of the overall load refrigerator consumed [30].

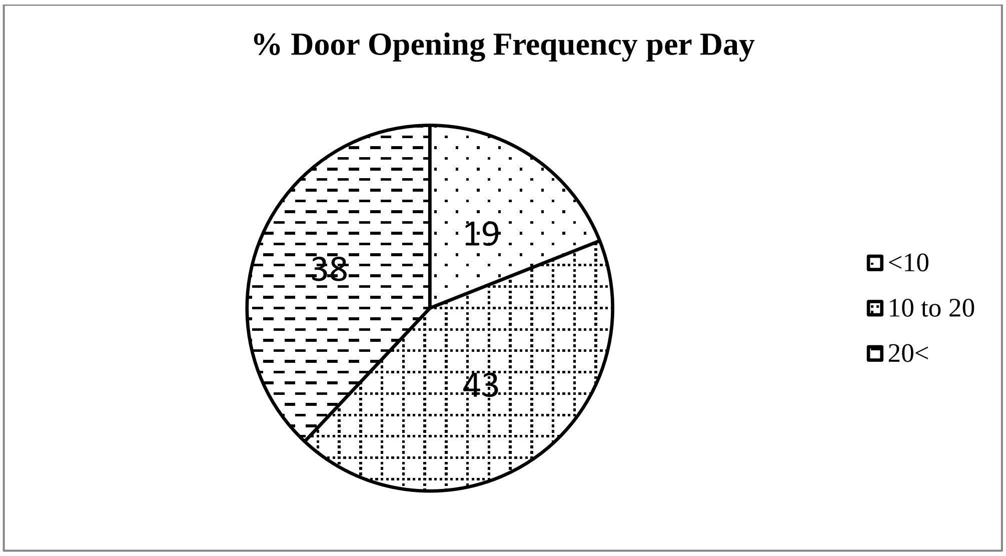


Figure 10: Door Opening frequency of a typical domestic refrigerator

In order to control the cooling loss at door openings, some refrigerators had a design so that refrigerator comprises of many small compartments with many doors to retain cold air in other compartments at the door opening [24]. Each door open increases the temperature within 5% and to recover back it was taken 1to123 seconds and each door opening generally lasts for 33 seconds [31]. One of survey study in France with 143 domestic refrigerators conducted in year 1999 showed door opening frequency was accordance to the Figure 10 [21].

As per the statistics available, it appears door opening has an effect on energy consumption which cannot be neglected when estimating energy performance of the appliance. If any refrigerator model has solutions to this it should be able to gather positive outcome during performance testing.

2.8.3 Ambient Temperature Setting

Ambient environment condition had some effect to the refrigerator energy consumption. As refrigerator heat removed to the surrounding, process efficiency is depending on the surrounding temperature. It was identified that refrigerator energy consumption increases by 2.25% to 2.5% due to the variation of 1℃ in the surrounding air temperature. This can be concluded as Refrigerator energy consumption increases when the surrounding temperature increases [32].

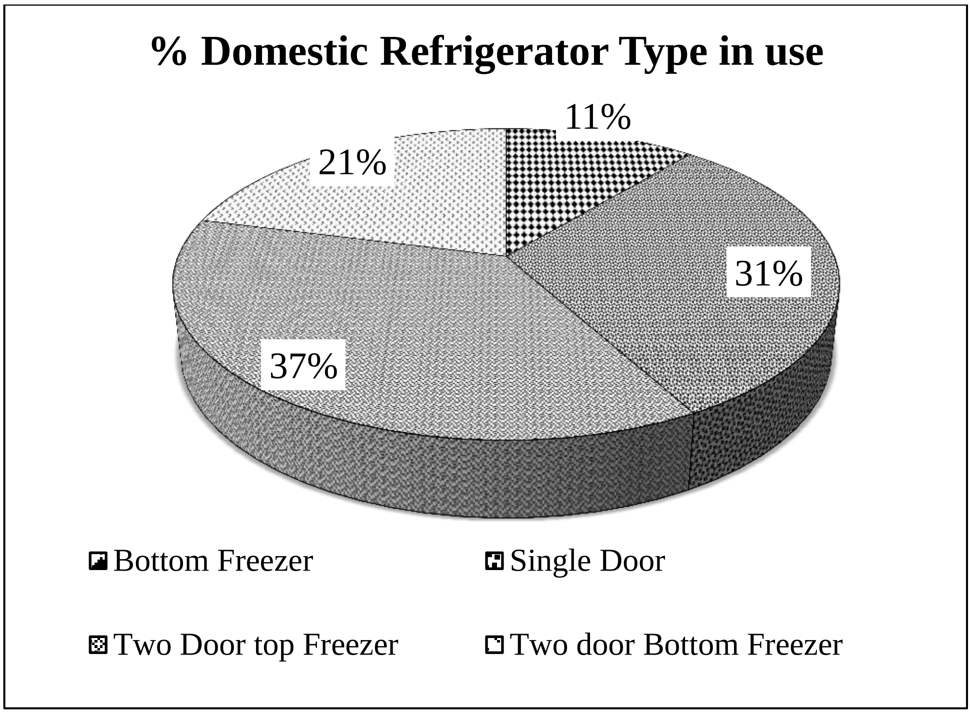


Figure 11: Single door and top freezer double door models are more common [21]

According to the Figure 11 most available refrigerators were single door refrigerators and top freezer two door refrigerators. Generally single door refrigerators were direct coolers where cool air from freezer flows to the fresh food compartment which was at the bottom by natural draft. Heavy cold air, due to high density tends to flow down-wards. These refrigerators were early generation type and can be easily recognized since they have a tray beneath the freezer to collect water drain from the freezer. This type of refrigerators has manual defrosting mechanism.

2.8.4 Automatic Ice maker: Optional Device

Automatic ice maker is a unit which produces ice automatically as automatic ice maker has a heater which consumes energy. A research done by Alan Meier has stated that automatic ice maker consumes 7% to 26% more energy due to ice making. One of the studies in California where more than eighty refrigerators were tested and found, automatic ice making refrigerators consumed 8% more energy than labeled and manual ice makers had consumed 5% less amount of energy than labeled [33] .

2.8.5 Defrosting Process of Refrigerator

The cold temperatures inside the refrigerator results frost formation especially inside the freezer where average temperature is always bellow 0°C. The water vapor in the air will condense and deposited on the walls of the freezer as frost. These frost retardates the heat transfer through the evaporator to the freezer space. So, frost removal is very important to maintain the efficiency of the refrigerator. Meaning of defrosting is frost removal. Defrosting in domestic refrigerators is basically of two types. They are Manually Defrosting and Automatic Defrosting.

Figure 12: Frost formation inside the freezer

2.8.6 Manual Defrosting Refrigerators

Manual Defrosters or early generation of refrigerators used cold wall technology to sustain cabinets inside temperature. In this technology refrigerant is circulating through tubing in the walls. Temperature difference inside the compartment was promoted the cool air to circulate throughout the unit. In this case fog was buildup on interior walls of the refrigerator and when it became denser it caused barrier to the heat transfer through the wall. In order to prevent this, periodic frost removal process was to be carried out. This manual frost removal was in early generation of refrigerators which are still available in the market due to low cost. Manual defrosting refrigerators are sometimes called direct coolers, because direct cooling technology used natural draft to propagate the cold inside the refrigerator. This kind of design is simple and at low cost. A study shown there was 16% more energy consumption for automatic defrosters than manual defrosters [34]. Though it felt that there is a saving it is not at all because energy loss due to manual defrosts operation is not pictured in this study. At manual defrost operation food to be transfer to the secondary refrigerator. To remove frost the refrigerator has to heat up to the surrounding temperature. After removing frost refrigerator again cool to the required temperatures. All these stages consume energy. If this was included, the result may change drastically. Consumers select manual defrosters only by looking at initial cost but not the operational cost and energy efficiency.

2.8.7 Automatic Defrosting Refrigerators

In Automatic Defrosting refrigerators evaporator coli is inside the enclosed housing ceiling and walls. By using the forced air technology cool air is circulated throughout the compartment by a fan. In this method formation of frost will eliminates because cold air which has lower humidity level absorbs any ice formed. Further if freezer door is opened fan will off to prevent warm air circulation inside the cabinet. There is a heating element inside the housing with evaporator coil. Periodically it heats up the frost on the evaporator coil and drains out from the freezer and evaporates. These refrigerators consume extra energy of around 17.7%

more, basically for periodic heating, to remove frost whereas the surface temperature of the heater goes up to around 520℃ [35].

2.8.8 Compressor Efficiency

Compressor used for refrigerator is generally reciprocating type single or multi cylinder, where the arrangement of cylinder and piston is used and centrifugal, scroll and screw types also were used in limited occasions [36]. In general refrigerator compressor operates at around 3000 rpm and its duty cycle is 60% [37] .

Compressor is the heart of the refrigerator which powers the refrigeration cycle. Refrigerator Energy requirement to maintain temperature inside the compartments is highly depends on the compressor efficiency. The compressor consumes approximately 80% of a refrigerator’s power consumption and it is operating at 80%-90% of its total time [7]. Also, it has higher tendency of contribute to the losses out of total of the refrigerator and it is 69% [37]. As compressor consumes lager portion of energy out of total energy consumption of the refrigerator, losses also higher in compressor compared to the other losses as shown in Figure 13 [37].

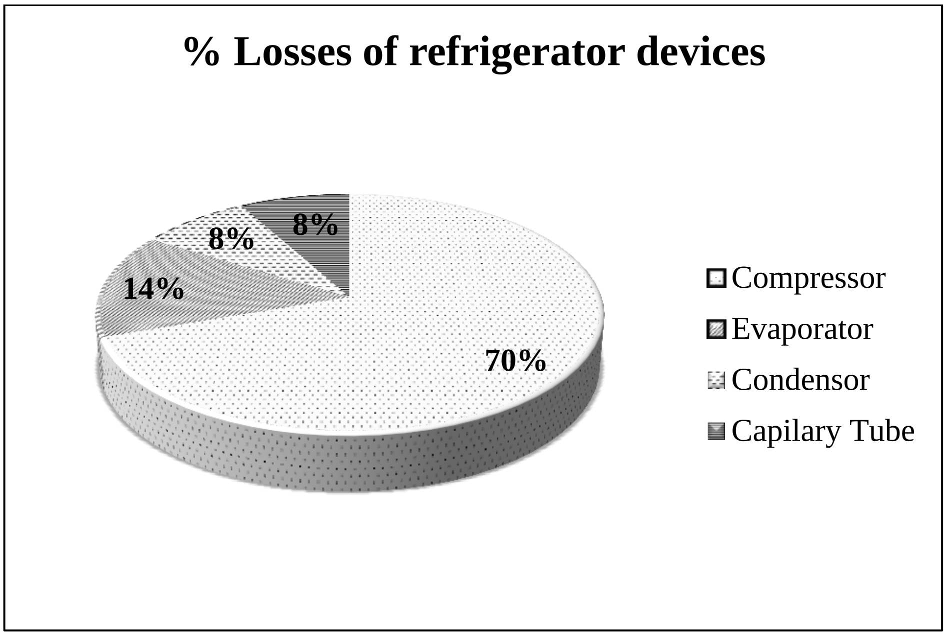


Figure 13: % Losses of Refrigerator Devices

So, it is more essential to improve the performance of the compressor. Compressors in domestic refrigerators are of two types. They are single speed compressors and inverter support variable speed compressors.

Figure 14: Compressor is the heart of the refrigerator

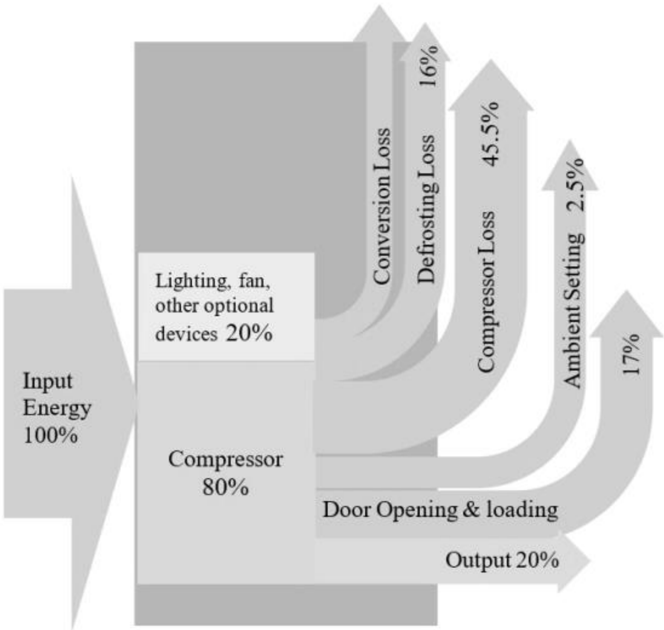


Figure 15: Percentage Energy flow of a typical refrigerator at equilibrium

2.9 Draw backs of Refrigerator with Single Speed Compressor

Many eras refrigerator had single speed compressor normally it is around 3600rpm. This ordinary refrigerator compressor operates under on/off mode to maintain compartment temperature. When refrigerator reaches few degrees above the set temperature compressor will switch off. This cyclic ON/OFF behavior generates cycle loss which causes the reduction in efficiency of the process. Further when compressor is at off state the high-pressure refrigerant tends to be equilibrium with that of evaporator which is at low pressure and low temperature phase. This causes the increase in energy consumption to recover this when compressor is switch ON again.

These traditional compressors, the freezing capacity is equal to the maximum static cooling load of the refrigerator plus some allowance for door openings and other losses. Though the freezing capacity is maximizing at the design it has become excessive when the actual load in the refrigerator is not that heavy at many situations. Variation of storing amount of food in the compartments, temperature and humidity variations in surrounding specially during night time are some of such situations. Based on this allowance encounters a loss at its operation, further loss increases if compressor has higher rpm [37].

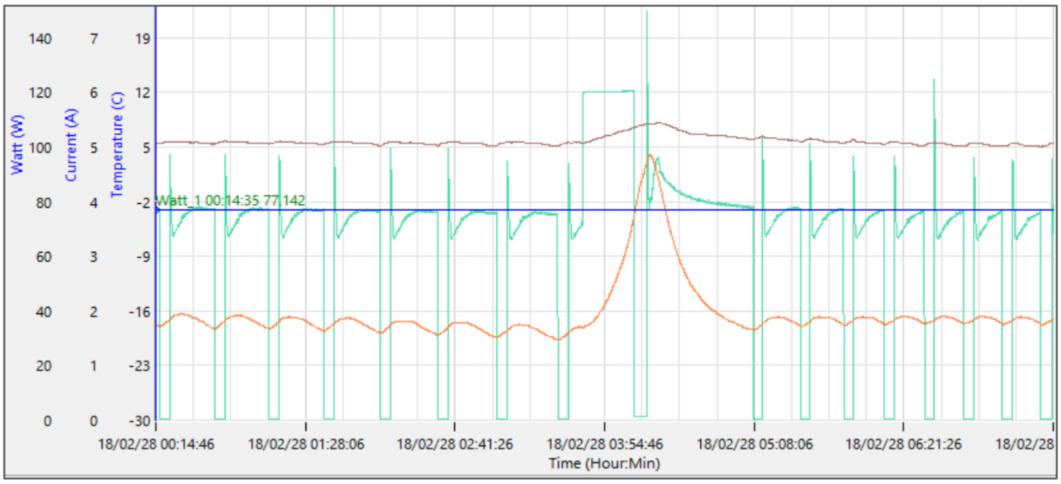


Figure 16: Display of power consumption of a Non-Inverter refrigerator

These compressors perform according to the load requirement by changing compressor on-time interval and by altering compressor off time interval. If we pictured the power by a power meter it always operates at a certain maximum and minimum power level as per the Figure 16: Display of power consumption of a Non-Inverter refrigerator.

Green color line in Figure 16 shows the power meter readings and red colour line and pupal colour lines were the temperature sensor reading of freezer and fresh food compartment temperatures respectively. Compressor ON and OFF can be identify by the graph of Power line. Compressor of Figure 16 has power of around 75W at its operation. It can be observed from the graph temperature drastically increases at a certain point where defrosting operation initiate. At this point defrosting heater start to operate and temperature is increasing few degrees above. Power consumption given by Wattmeter reading includes the both compressors and heaters power consumption.

2.10 Inverter Refrigerator

Compressor is the heart of the refrigerator which supplies energy to the refrigeration operation. Inverter refrigerator has an inverter type compressor. This compressor varies its speeds as per the demand (generally 1100rpm to 4300rpm).When compressor operates at low speed its energy consumption is lower than when it operates at higher speed [37]. This phenomenon can control the energy consumption as well as temperature fluctuation inside the refrigerator better than single speed compressor. This compressor which operates at varying speeds can adapt to the day today loading variation; such as when the door is open long time, the inverter compressor operates in high speed to compensate for the cold air that has gone out and warm air coming in. Variable speed compressor can adjust its speed as per the demand. Even by fixing two optimal speeds of a compressor than single speed can save 20% of energy and if it is a variable speed the difference is further only 3% [37]. It is economical to go for a two-step speed compressor than totally variable speed compressor, which can be seen in modern refrigerators today. Speed variation in present refrigerators were obtained by use of an electronic means, frequency inverter, attached to temperature sensors reads temperature deviations at operation and regulates the speed accordingly. When the demand load/temperature is low (e.g.: during night) it operates at lower speed and when the demand is higher it operates at higher speed.

Traditional refrigerator compressor comprises with induction motor which is less efficient than permanent magnet motors in inverter compressors. The Permanent Magnet (PM) consumes less power as no need of current to magnetize the poles. But the problem on this is that PM motors need 3 phase connection. In order to provide 3 phase supply inverter circuit is used.

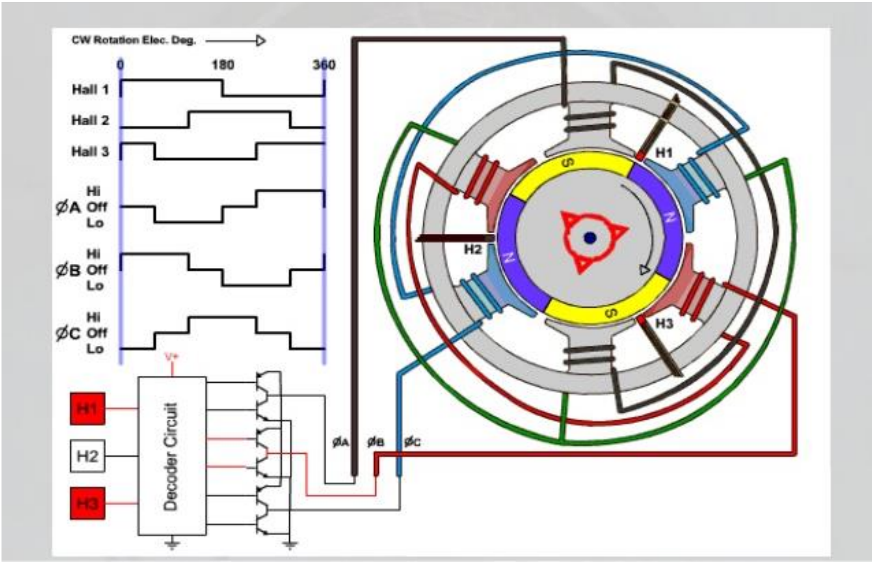


Figure 17: Brushless Direct Current Motor (BLDC) [38]

Digital inverter converts ac current to dc by forming a stepped wave-form and converts back to ac current. A modulation of electrical inverter produces the current of desired speed. For this Metal-Insulator-Semiconductor Field-Effect Transistor (MISFET) or Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) is used [39].

2.11 Performance Assessment of Refrigerators

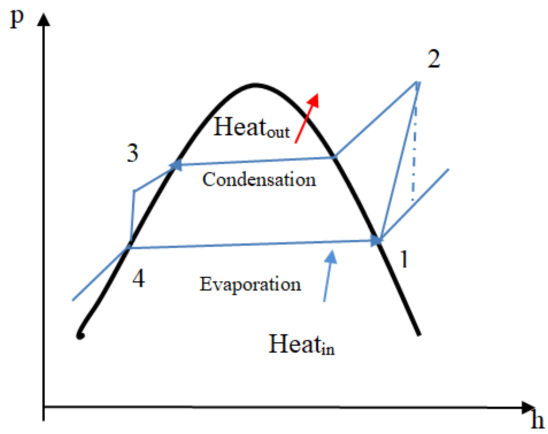


Figure 18: p-h diagram of typical refrigerator

Almost all domestic refrigerators are vapor compression type. Pressure-Enthalpy (p-h) diagram of vapor compression cycle is as in Figure 18. Refrigerator performance can be expressed in different ways.

2.12 Energy consumption per 24hours

Refrigerator energy consumption can be directly express by Energy consumption per 24 hours or day. Energy consumption can be obtained by attaching a power meter to the refrigerator. Readings were taken when the refrigerator compartments were at the equilibrium temperature conditions and at the laboratory-controlled environment. This methodology is widely used in International Electro technical Commission (IEC) testing standard of domestic refrigerators (IEC 62552-3, 2015 edition).

2.13 Energy Efficiency Ratio

Generally, efficiency of a system is defined as work out put to the energy input. Accordingly, Thermal Efficiency can be express as the equation (1).

$$\text{Thermal Efficiency} = \frac{\text{Work Output}}{\text{Heat Input}} \tag{1}$$

This is termed as Coefficient of Performance (COP).

$$\text{COP} = \frac{\text{Work Output}}{\text{Heat Input}} \tag{2}$$

In refrigeration heat at cold reservoir (Evaporator space or inside the refrigerator) is removed to hot reservoir (Condenser or surrounding) by applying an energy as shown in Figure 19.

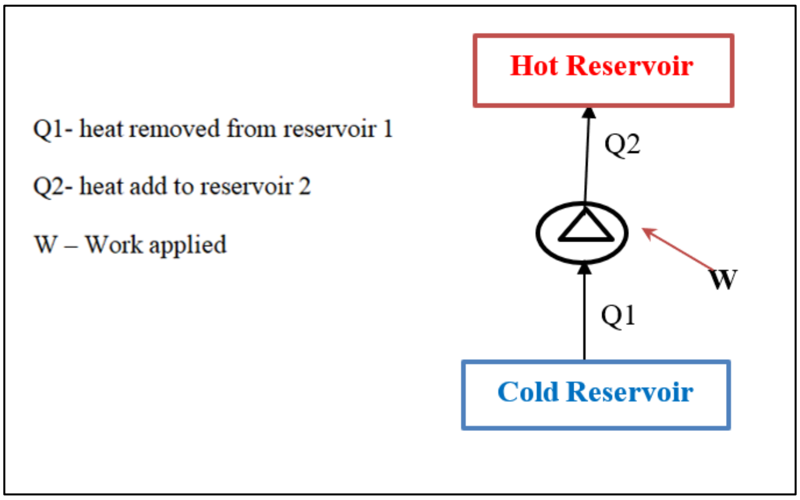


Figure 19: Refrigerator thermal system

$$\text{COP} = \frac{\text{Q1}}{\text{W}} \tag{3}$$

In refrigeration heat removal in Joules is the output and work applied in Watt-hour is the input to the system. This is described in inverse of Coefficient of Performance, defined in eq. 4. It was called Energy Efficiency Rating.

$$\text{Energy Efficiency Rating} = \frac{1}{\text{COP}} \tag{4}$$

2.14 Refrigerators Testing Standards

In order to recognized performance of refrigerators, Refrigerator Testing Standards are practicing in many regions of the world. SLS 1230:2003 is the available refrigerator testing standard in Sri Lanka for energy efficiency rating. Table 2 shows, key comparisons, between refrigerators testing standards commonly available in many regions in the world.

Table 2: Overview and Comparison of Main Characteristics of Test Standards [40]

Test Standard	**IEC (International Electro technical Commission) 62552-3**	**JISC (Japanese Industrial Standards Committee) 9801:1999**	**AS/ NAS (Australia and New Zealand Standards) 4474.2:2009**	**IS (Indian Standard) 15750:2006**	**SLS (Sri Lankan Standard) 1230:2003**
Countries used by	China /European Union	Japan	Australia/ New Zealand	India	Sri Lanka
Ambient Settings	16ºC and 32ºC	15º C, 73% & 30ºC, 27%, weighted average	32º C	32º C	32º C and RH 70%-80%
Freezer Temperature	-18º C	-18º C	-15º C	-15º C	-15º C
Fresh Food Compartment Temperature	5º C	4º C	3º C	3º C	5º C
Reporting Result	Energy Consumption (kWh)/day	Energy Consumption Efficiency (kWh/year)	Energy Rating (kWh/year)	Energy Consumption (kWh)/day	Efficiency Rating (kWh/year)

Table 2 shows some of globally available refrigerator testing standards. International Electro-technical Commission (IEC) is an international organization located in Switzerland, for prepare and publish International Standards for electrical and electronic appliances. European Standard, Japanese standard, Australian and New Zealand Standard, Indian Standard and Sri Lankan Standards were listed and some important testing parameters were shown.

2.15 Refrigerator Testing Methodology as per SLS 1230:2003

In Sri Lanka, Refrigerator energy rating is calculated according to SLS 1230:2003 after conducting tests inside the controlled laboratory environment as per the testing methodology stated in the standard. Accordingly, temperature sensors are attached to the refrigerator compartments and test is performing at ambient of 32^{o}C and at relative humidity between 70%-80%. Test is conducting for empty refrigerator, with doors closed and properly sealed. Testing period is 16 hours after reached the equilibrium temperature condition. Result during this period can be logged for later on calculations. Readings of temperature sensors of freezer and fresh food compartment, power and energy consumption readings, ambient settings with time were recorded.

Though SLS 1230:2003 testing procedure applied for empty refrigerators, at real situation in households' refrigerators are loaded and in order to load the refrigerators door-opening is incorporating which also may consumes energy. Time taken to cool a specific load will be one of important parameter which can be obtained if loading could be involved to the testing methodology. This extend of gap was covered by this research work by introducing a load to the refrigerator to be tested and by doing so, possible effect of performance of key types of refrigerators will be identified.

Summary

Refrigerator evolution has a great history and Vapor compression refrigeration system with R600a refrigerant and inverter technology is the current domestic refrigerator configuration. Energy consumption of the refrigerator is influence by many factors such as compartment temperature setting, door opening, ambient temperature and humidity settings, defrosting process and compressor efficiency. Refrigerator testing standards have the key responsibility for highlighting energy efficient refrigerator models accurately.

3 EXPERIMENT DESIGN AND DATA COLLECTION

This chapter focused on experiment design which included the derivation of mathematical model in order to compare the energy performance of refrigerators. Then experiment set up was explained.

3.1 Approach to the experiment

As the compressor in inverter refrigerators had the ability to change its speed according to the load, by changing the load during the test period the behavior of inverter refrigerators can be monitored. A door opening, introducing loads into the freezer and allowing them to cool down will establish a new dimension to the testing methodology. Then analysis and comparison between the performance of inverter and non-inverter refrigerators can be carried out. The refrigerators with same model and capacity of inverter and non-inverter pairs can be compared easily. To compare the thermal efficiency between any refrigerators a common mathematical model was developed.

3.2 Experiment Design

Experiment was structured to compare the energy consumption characteristics between inverter and non-inverter refrigerators. For this, a mathematical model was developed by using basic energy balance equation. Energy Efficiency Rating was developed based on available Testing Standard, SLS 1230: 2003. A door opening and a loading was included in this research because, one of the factors that increases the energy consumption of domestic refrigerators is the door opening action. At door openings, cold air is replaced by the new load physically comprises with warm air from the environment, which is a risk for freshness of food being preserved. At the same time, compressor has to do additional work to cool down entered load at each door opening. It showed in previous studies that energy consumption increases 7%-30% as per the behavior of door openings. [41].

3.2.1 Mathematical Model for Energy Rating

In order to compare the performance under load condition a mathematical model was developed by using basic energy balance equation. Proposed model can be applied for any refrigerator at different ambient and loading situation.

Basic Energy balance equation for the refrigerator compartments at equilibrium

$$Total\ Energy = Energy\ in\ Freezer + Energy\ in\ Fresh\ Food\ compartment \qquad (5)$$

$$Total\ Energy\ in\ refrigerator = Energy\ of\ test\ pieces\ in\ the\ freezer + energy\ of\ air\ in\ freezer + Energyin\ fresh\ food\ compartment \qquad (6)$$

Energy in compromised with, heat energy, potential energy and kinetic energy, Then Total energy (E_1) can be written as;

$$E_1 = m_m (h_m + z_m + K.E_m) + m_a (h_a + z_a + K.E_a) + m_c (h_c + z_c + K.E_c) \qquad (7)$$

Where,

Mass of Test Pieces = m_m kg

Enthalpy of test pieces = h_m kJ/kgK

Kinetic Energy of test = $K.E_m$

Mass of air in the freezer = m_a kg

Enthalpy of air in the freezer = h_a kJ/kgK

Kinetic Energy of air in the freezer = $K.E_a$

Mass of air in the Fresh Food Compartment = m_c kg

Enthalpy of air in the Fresh Food Compartment = h_c kJ/kgK

Kinetic Energy of air in the Fresh Food Compartment = $K.E_c$

Here there is no kinetic work and there is no potential difference

z_m ,K.E_m ,z_a ,K.E_a ,z_c ,K.E_c =0

$$E_1 = m_m h_m + m_a h_a + m_c h_c \tag{8}$$

Where,

Total Volume of freezer compartment in m^3 =V_f

Volume of fresh food compartment in m^3= V_c

Volume of test pieces inside freezer in m^3 = V_o

Volume of test pieces inserted to the freezer in m^3 = V_n

Temperature of freezer in ⁰C = T_f

Temperature of fresh food compartment in ⁰C = Tc

Test Chamber dry bulb temperature in ⁰C = Tr

Total Work Provided (TWP) or power consumption of refrigerator (measured by power meter) to reach all test pieces to -15⁰C or nearest lesser = Ec (kW)

$$\mathrm{TWP} = \mathrm{Ec\ (kW)} \tag{9}$$

Where,

Specific heat of Freezer Test Pieces= C_m kJ/kgK

Specific heat of air inside Freezer and Fresh food compartment = C_a kJ/kgK

Dimensions of each 1kg pack =200mmx100mmx50mm

Assuming free space of freezer is replaced by outside air (worst case)

$$E_1= m_m C_m (T_r-T_f) +m_a C_a (T_r-T_f) + m_c C_a (T_r-T_c) \tag{10}$$

$$E_1= m_mC_m*(T_r-T_f) + C_ad_a* (V_f-(V_n+V_0))*(T_r-T_f) + C_ad_aV_c*(T_r-T_c) \tag{11}$$

For air, Ca ≃1 kJ/kgK

Air density, d_a ≃1 kg/m3

$$E_1 = m_mC_m + V_f - (V_n+V_0)*(T_r-T_f) + V_c(T_r -T_c) \tag{12}$$

$$Efficiency\ Rating\ (Er)\ = \frac{(\text{Work input})}{(\text{Energy output})} \tag{13}$$

$$Er = \frac{(\text{Ec (Wh)}}{\text{E1 (kJ)}} \tag{14}$$

$$\text{Er} = \frac{\text{EC}}{(\text{MmCm} + \text{Vf} - (\text{Vn} + \text{Vo}) * (\text{Tr} - \text{Tf}) + \text{Vc} * (\text{Tr} - \text{Tc}))} \tag{15}$$

Lower the $E_{r,}$ higher the performance of the refrigerator.

3.2.2 Estimation of Uncertainty of E_r and other key measurements

Error in measurement is the difference between result and the true value and is unknown. Error is theoretical and Uncertainty is the practical concept which assured the likely size of error (Figure 20).

Figure 20: Actual value lie inside Uncertainty range

Uncertainty of E_r and other key measurements were budgeted according to," Guide to the Expression of Uncertainty of Measurement, JCGM 100:2008" (GUM 1995) guidelines. Calculation detail is shown in Appendix D.

3.3 Experiment Setup

The key components and equipment required for this experiment are as explained below.

3.3.1 Two sets of Domestic refrigerators

This test is carried out for available refrigerators in the market. Two pairs of refrigerators of volume 220liter and 250 liters were tested. Each pair had the identical volume, model, brand, and manufacturer. Volume of fresh food compartment and frozen food compartment also were identical. In each pair one refrigerator unit is inverter type and the other unit is non-inverter type.

Figure 21: Domestic Refrigerators

3.3.2 Refrigerator Testing Chamber

Refrigerator testing chamber is located at National Engineering Research and Development center of Sri Lanka, and has the ability of testing three refrigerators at parallel. The vertical temperature gradient inside the chamber is less than $1^{o}C/m$ and air velocity inside the chamber up to 2m height from the floor is less than 0.1m/s. There is a facility of logging temperature sensor readings at required intervals. Temperature sensors can be connected to inside of each compartment of the refrigerator.

Table 3: Name Plate Data of Refrigerators

Refrigerator	220NON	220IN	250NON	250IN
Net weight(kg)	46	46	51.5	51.5
Capacity (l)	220	220	250	250
Refrigerant	R600a(54g)	R600a(54g)	R600a(55g)	R600a(55g)
No of Doors	2	2	2	2
Defrost Mechanism	Automatic	Automatic	Automatic	Automatic
Voltage (V)/Frequency(Hz)	230/50	230,240/50	220,240/50	220,240/50
Current (A)	0.5	0.32	0.5	0.5
Motor Input (W)	81	81	80	80
Technology	Non-inverter	Inverter	Non-inverter	Inverter

Figure 22: Refrigerator Testing Laboratory at National Engineering Research and Development Centre

Each refrigerator unit was located on a black colored wooden platform which was designed as per the SLS 1230:2003 in order to reduce the thermal radiation. It was facilitated to log power meter readings such as current in ampere, power in Watt, potential in volt and energy in Watthour during testing period. Temperature sensors used here is K-type thermocouples. Temperature sensors were prepared in two ways. One way is by attaching a standard copper cylinder (SLS 1230:2003) to the temperature sensing end to evenly sense the temperature at free space and the second way is by inserting to the standard test packages as explained in section 3.3.3.

3.3.3 Test Packages

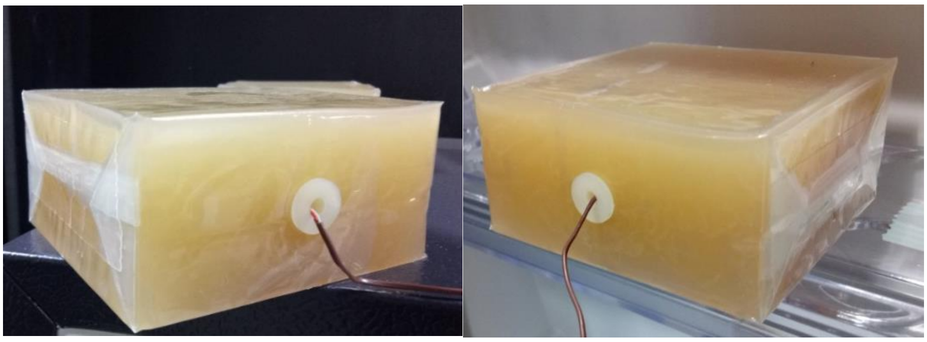


Figure 23: Test Packages

Test packages are used to load the freezer compartment. These are according to International Standard Organization (ISO) 15502, ISO 5155, ISO 7371, ISO 8187, ISO 8561, used for Cooling Appliances according to European Standards (EN) 441-4, 441-5, UNI EN ISO (Italian Edition of European and ISO Standard) 23953-2:2006 and relevant Amendments (Annex C).

Test packages were prepared for the test by inserting a thermocouple to the cap as shown in the Figure 23 to obtain internal temperature of each test package. When placing test packages to the freezer it was followed recommended air gaps as per (SLS 1230: 2003 page 50) Figure 24(a).

In this research refrigerator freezer was loaded with ISO standard test packages up to approximately half of its volume which is common in actual households. The selected weight of the load was 3kg. Therefore a ‘loading ratio’ can be introduced for systematic measure of the testing load to suit any freezer volume, as mathematically described below.

Loading ratio = Load Weight (kg)/ Freezer Volume (measured)(L)

In this research, Loading Ratio= 3/0.056 = 54

Loading Ratio for different ranges of volume of freezers can be introduced for freezer loading purposes.

3.3.4 Testing Methodology

Each refrigerator was equipped with temperature sensors in the freezer test pieces and few numbers of temperature sensors hang inside the freezer to read temperatures of free air in the compartment. Temperature sensors located in fresh food compartment was hung at the middle along the height at equal distance as per Figure 24 (a). Test was carried out under controlled environment condition of refrigerators testing chamber. Refrigerators were loaded by ISO standard test packages (Figure 23).

Refrigerators were located inside the Testing Chamber, which was conditioned to temperature at 28ºC and 60-65 % of Relative Humidity level. Refrigerators were switched on and loaded with 9kg of test pieces into the freezer. When refrigerators reached the equilibrium temperature, results were started to record. Refrigerator compartment temperatures were decided according to SLS 1230:2003 of Domestic Refrigerators Testing Standard and allowed the temperatures to become stable.

(a) Test Sample (b) Testing Chamber

Figure 24: Testing Setup

As per the SLS 1230:2003 standard, each refrigerator was allowed to reach average temperature of -15ºC or less for Freezer, and less than 5ºC for Fresh food compartment. This was achieved by trial and error positioning of the regulator as absolute value-based temperature setting was not available in the refrigerators. Then Freezer door was kept open for 40S and placed 3kg of test pieces which were at ambient condition which is same as the condition of test chamber. Temperature sensors were already located inside the Test pieces. Temperature Sensors in the Fresh Food Compartment were located at equal vertical distances. Test was continued for at least16 h after door opening as per the test standard. Temperature sensor readings, Wattmeter readings, and Dry bulb temperature and relative humidity readings of the Test Chamber were logged at each 5s during the test period. Graphs of each recording were obtained. Recorded test graphs of tested four refrigerators were shown in Figure 26,Figure 27,Figure 28 and Figure 29 respectively. Each test graph has common features explained as in Figure 25 where the horizontal axis is the time axis and vertical axis is multi variable axis.

Stepped line represents the power measurement in Watt (W). The straight line with positive gradient which touches time axis at the beginning is the energy measurement in Watt hour (Wh) (Figure 25). All temperature sensing lines are in Celsius (^{0}C). The watt meter readings in Watt has sudden switch OFF and switch ON at each interval. Further there are two thin peaks where power goes maximum, these two peaks resulted the periodic defrosting.

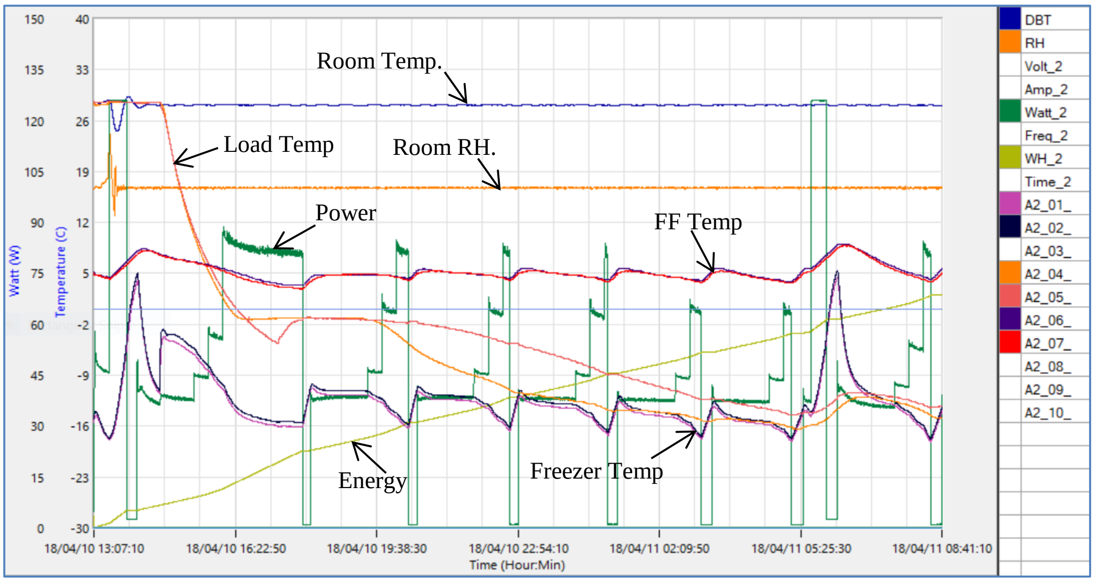


Figure 25: Test Result of inclusive of required out puts

At defrosting, heating coil operates and consumed more energy and freezer temperatures increases up to around 5°C as per the Figure 25. Further it shows how, two sets of temperature sensors were displayed in the graph. The sensors shown at bottom of the graph were sensors in the freezer and their average was -15ºC. The temperatures lines lie above were the sensors at fresh food compartment which have the average around +4. 5ºC. The temperature sensors which were inside the test piece which had room temperature at the beginning. These were displayed in graph in Figure 25 as Load Temp. Temperature readings of these sensors starts at room temperature and after placing them in freezer the temperature gradually goes down until equilibrium with freezer temperature.

Summary

Derivation of mathematical models for Energy Efficiency Rating and for its uncertainty estimation was explained in this chapter. Experiment setup including door opening to introduce 3kg of test load and the laboratory setup was explained next. Test result comprised of many output data was described finally.

4 ANALYSIS OF RESULTS

This chapter explains the test results, mainly cooling rates, energy consumption per unit volume and energy efficiency ratings of refrigerators. Next average temperature distributions of compartments, defrosting heating will be discussed.

4.1 Results of the Experiment

Test results of each refrigerator comprised with a graph of tested outputs as explained in chapter 3.

Table 4: Observations Calculations

	Description	**220NON**	**220IN**	**250NON**	**250IN**	***Expanded Uncertainty***
1	Refrigerator Type	Non - Inverter	Inverter	Non - Inverter	Inverter	
2	Total Rated Volume (L)	220	220	250	250	*NA*
3	Average Freezer equilibrium Temperature, T_f (ºC)	-17.70	-16.80	-16.08	-15.35	*±0.13*
4	Average Fresh Food compartment equilibrium temperature, Tc (ºC)	4.07	4.12	3.97	0.37	*±0.13*
5	Time taken, t (h:min) to achieve equilibrium temperature, T_f	11.24	17.36	13.15	16.51	*±1min*
6	Energy Consumption (Wh) during time duration, t	1040.91	674.81	953.50	927.47	*NA*
7	Energy Consumption (Wh) during 24h, Ec	1664.13	1062.16	1532.12	1177.63	*NA*
8	Energy Output (kJ), E1	1102.39	1080.74	1064.27	1047.49	*NA*
9	Number of defrosts during 24h	3	3	3	3	*NA*
10	**Energy Consumption per unit volume (Wh/*l*)**	**7.56**	**4.83**	**6.13**	**4.71**	***± 0.60***
11	**Energy Efficiency Rating, E_r=EC/E1 (Wh/kJ)**	**1.51**	**0.98**	**1.44**	**1.12**	***±0.012***

The graphs in Figure 26, Figure 27,Figure 28 and Figure 29 are these results. Rated Volumes were obtained from supplier data which were appeared in name plates. Freezer compartment and Fresh food compartment volumes were measured according to SLS 1230:2003, by deducting recommended accessories from total gross volume of compartments.

Average of temperature sensor readings of fresh food compartment and freezer compartment was recorded. Results of freezer temperature sensors and fresh food compartment temperature sensors and time taken to cool the 3kg of test pieces up to target temperature were tabulated.

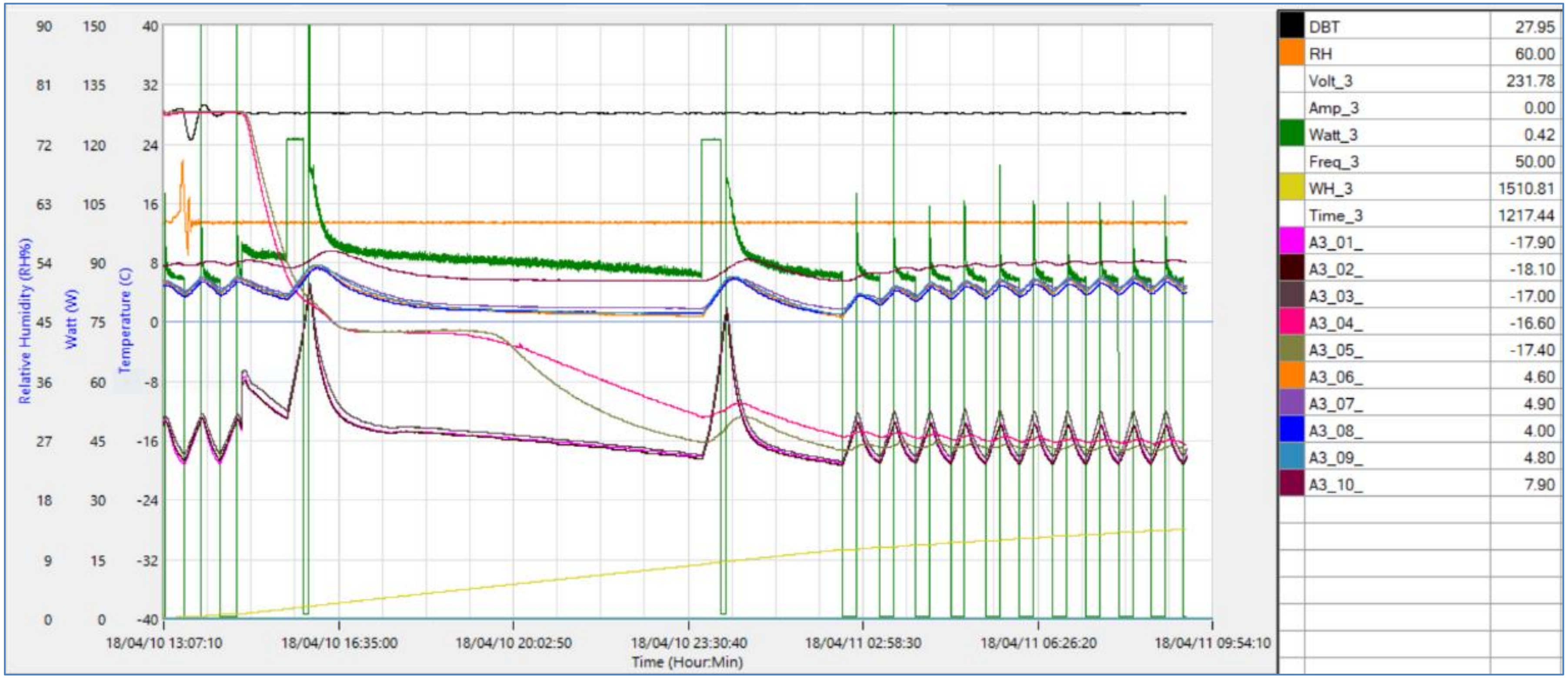


Figure 26: Test Results of 220NON refrigerator

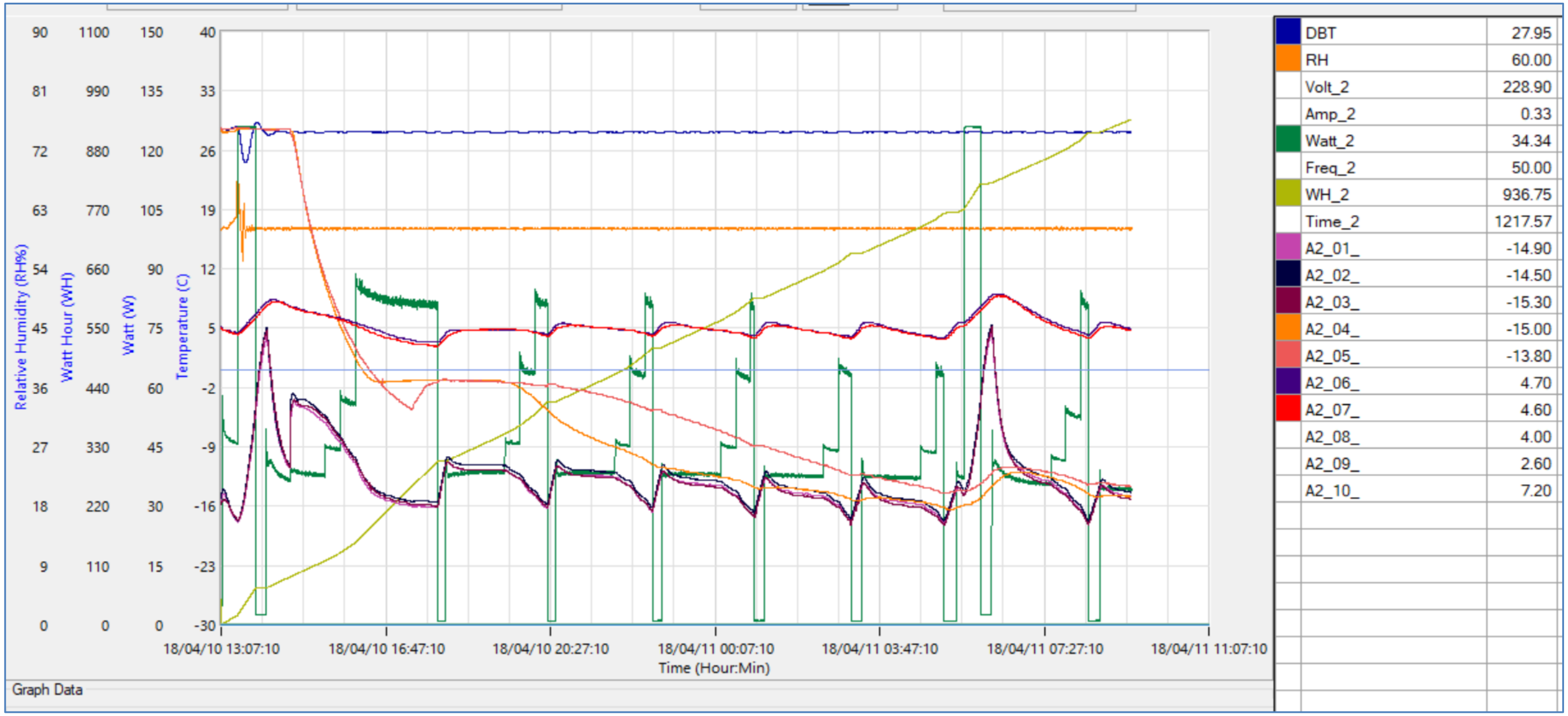


Figure 27: Test Results of 220IN refrigerator

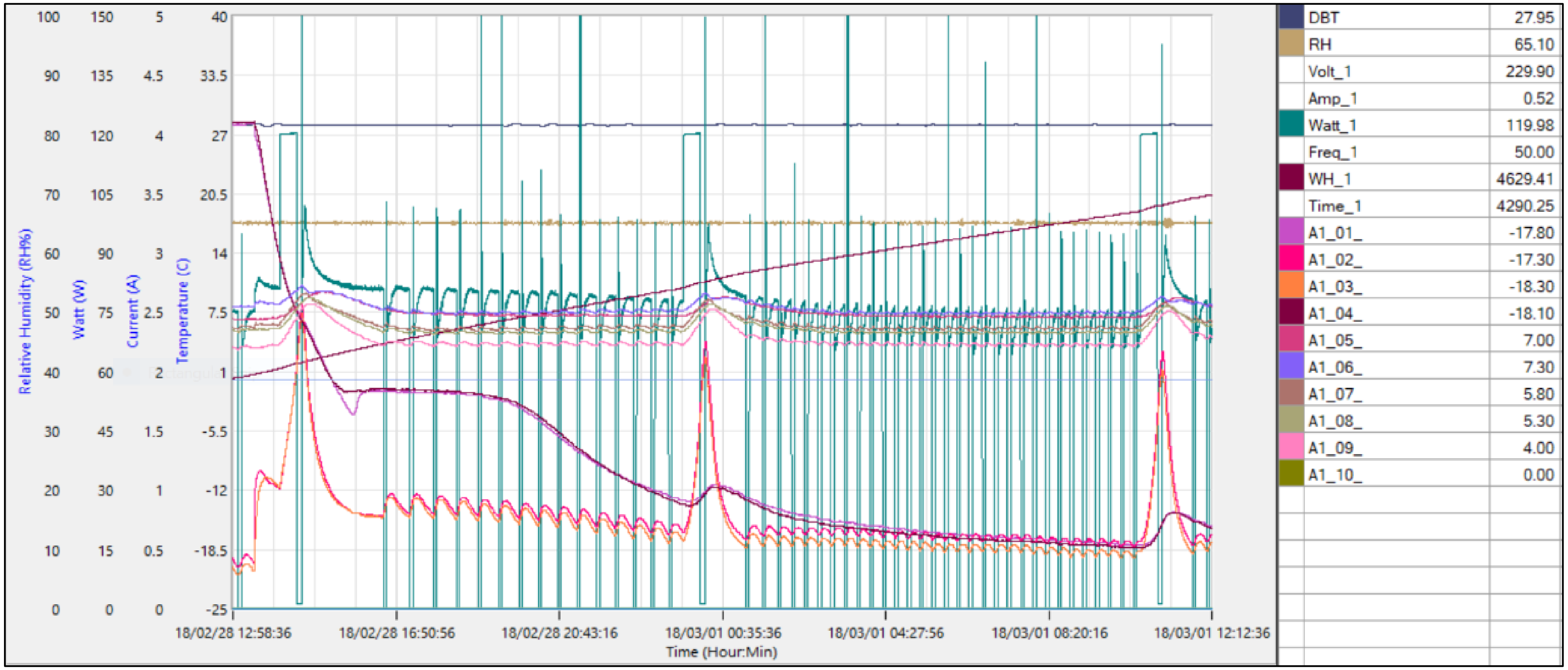


Figure 28: Test Results of 250NON refrigerator

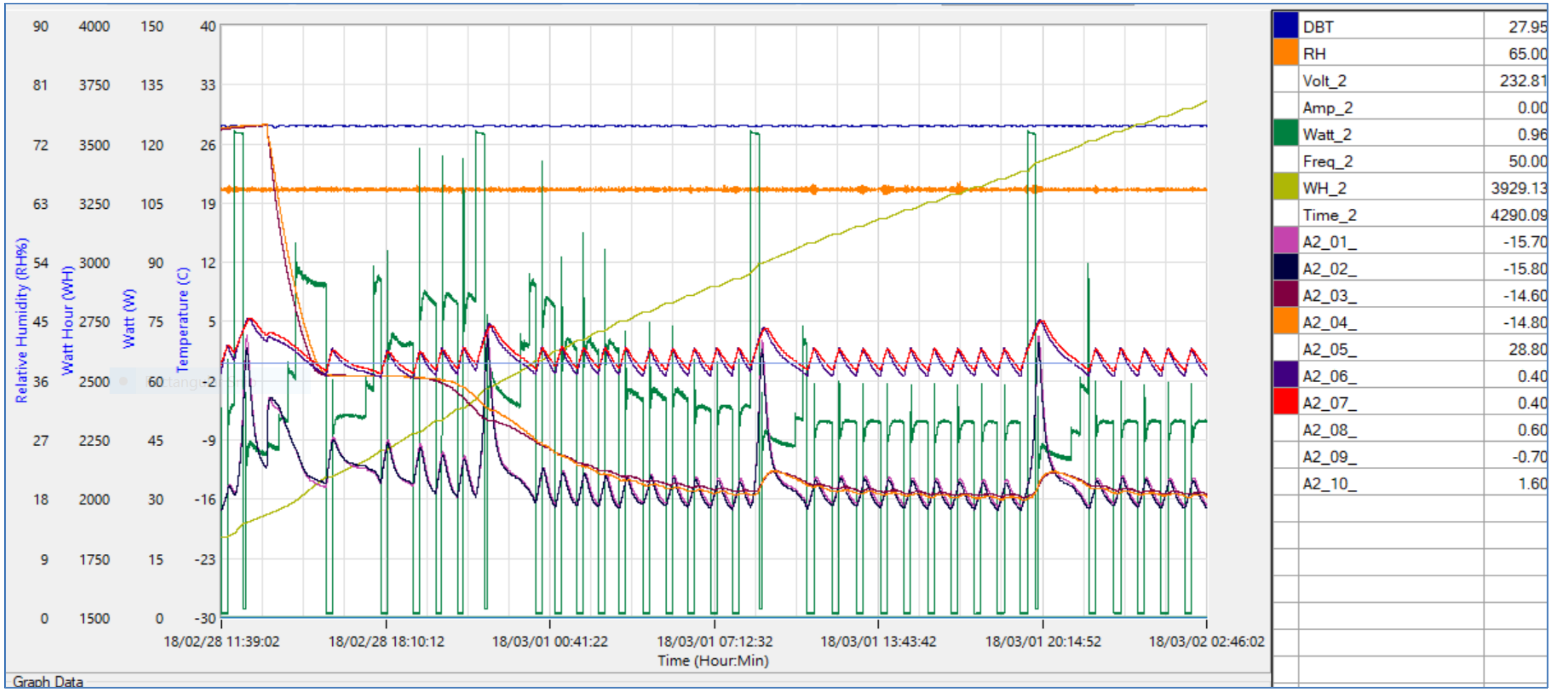


Figure 29: Test Results of 250IN refrigerator

4.2 Cooling Time of test load

Table 5: Cooling Time

Refrigerator	220NON	220IN	250NON	250IN
Time taken to reach -15ºC (h: min)	10.36	17.30	13.12	16.06

Cooling time is the time taken by the added load of 3kg to reach the required temperature of $-15°C$. Cooling rate which depends on cooling time is more critical in food preservation. The time durations were obtained from the test graphs and tabulated in Table 5 and plotted as shown in Figure 30. Cooling characteristics has three phases. First phase is within first 2h and 30min from loading, the temperature of the load was drastically dropping to 0°C from ambient temperature. Second phase is where temperature is stable at 0°C over the next 2h and 30min to 3h, temperature is stable, value is around -2.5°C , may be due to the latent heat absorption by the load. Third phase is the last segment of the graph where temperature drops to -15°C gradually during 5 to 12 hours.

Inverter refrigerators had total cooling time of 3hour to 7 hours slower than non-inverters. Which means, in terms of health and hygiene, the food that is expected to preserve will continue to degrade over three to seven hours as it is not kept in the prescribed temperature. However, in terms of energy use there is a saving as explained in section 4.4. The users should be made aware of the average time taken to cool a given load in the refrigerator as this parameter gives an alarm on food preservation and protection of texture. Simply this result illustrates the time taken by food to reach the temperature at which the activities of microorganism’s retardate.

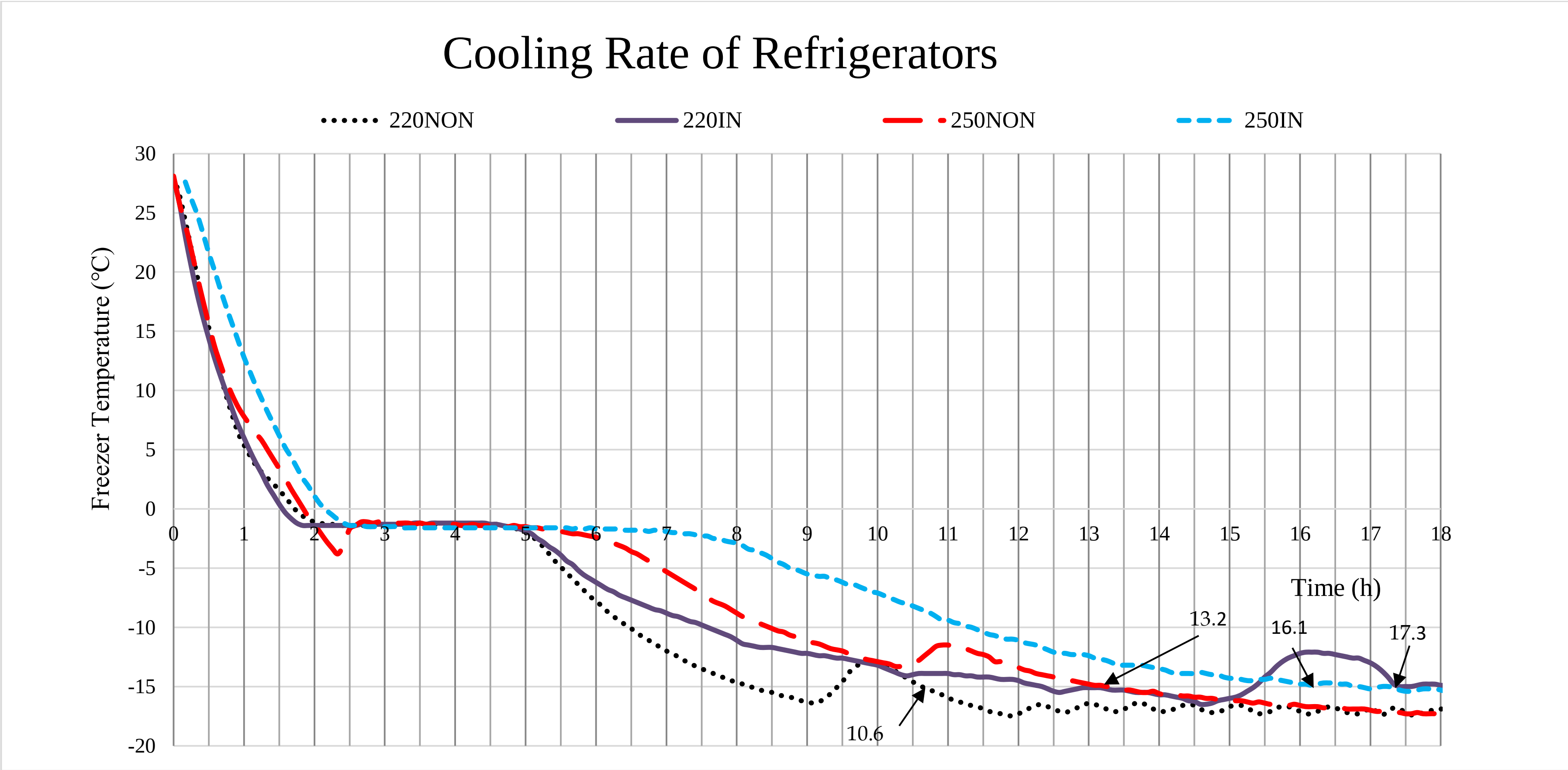


Figure 30 : Refrigerator Cooling Time

4.3 Energy Consumption per unit Volume

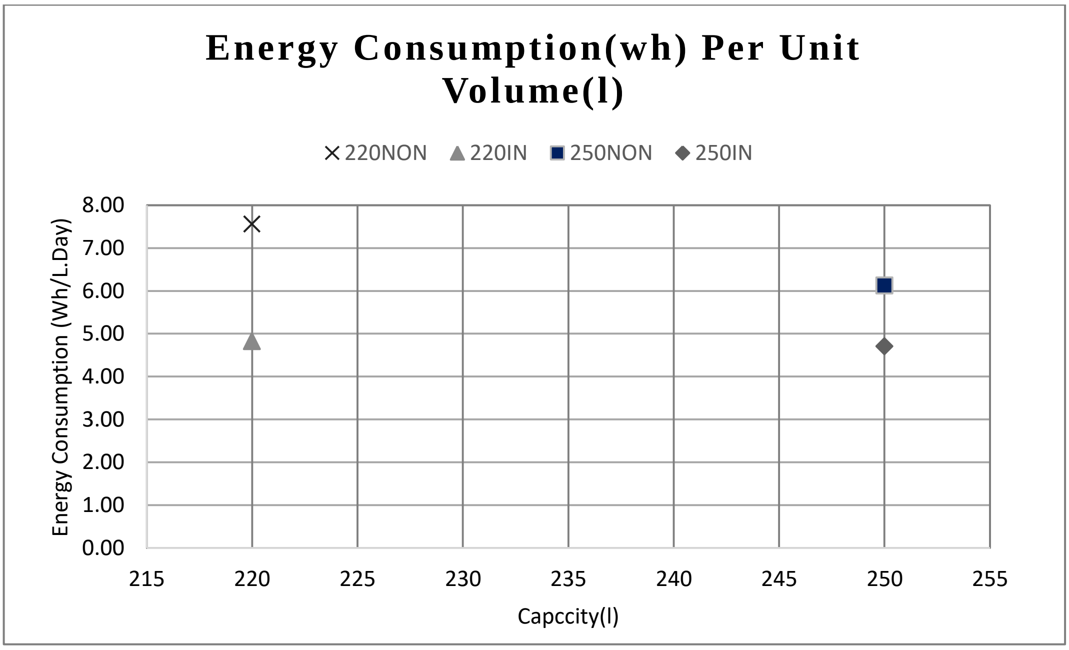


Figure 31: Energy consumption per unit volume per day

Energy consumption (Wh) during this period and for 24 hours was obtained from the test graphs of each refrigerator. Energy consumption per unit volume was calculated and displayed in Table 4. It was observed that inverters had low energy consumption than non-inverters (Figure 31). Minimum or least difference between inverter and non-inverter refrigerator in energy consumption is 1.42Wh/L/day and it is average of 23% energy saving by inverter refrigerator (refer Table 6).

Table 6 : Percentage Energy Consumption

Refrigerator	Energy Consumption (Wh)/L	Difference in Energy Consumption (Wh)/L	% saving
220IN	4.83	2.73	36
220NON	7.56		
250IN	4.71	1.42	23
250NON	5.66		

Energy Consumption per day or 24 hours will not give a clear image of energy conversion or in other words cooling efficiency. Further energy consumption per unit volume is not accurate to compare with different volumes of compartments in many models of refrigerators because energy consumption per unit volume depends on the volumes of the freezer and the fresh food compartment. So, if refrigerator had a comparatively small freezer and big fresh food compartment the Energy consumption per unit volume will less than same overall volume with comparatively large freezer.

4.4 Energy Efficiency Rating

Energy Efficiency Rating, E_r explains how efficiently energy was utilized by the refrigerator during its operation. Energy efficiency makes the bridge, input to the output of the appliance. It tells how much energy is needed to produce one unit of output. This concept is useful measurement if energy saving is concern. E_r was calculated by using equation 17 and illustrated in Table 7.

Table 7: Percentage Saving for Efficiency Rating

Refrigerator	E_r with load (Wh/kJ)	Difference in E_r	% saving
220IN	0.98	0.53	35
220NON	1.51		
250IN	1.12	0.32	22
250NON	1.44		

E_r of inverters are less than non-inverters, and it is further showed that E_r of 220IN is less than 250IN. In order to study the variance of E_r due to volume variation, more test data will be needed in order to compare the difference. It was observed in Table 7 that each refrigerator pair had two different percentage of energy saving 220 pair had 35% saving and 250 pair had 22% saving. Volume Ratio will be the reason and volume ratio are the volume (measured) of fresh food compartment is divided by volume (measured) of freezer compartment.

Volume ratios of 220 capacity refrigerators were 2.80 and that of 250 capacity refrigerators were 3.27 (Table 8). Variation of volume of freezer has an impact to energy consumption, because refrigerator needs energy to condition each compartment. Energy consumption will depend on volumes of refrigerator compartments and its compartment temperatures.

Table 8: Volume ratio of refrigerators

Refrigerator	**220NON**	**220IN**	**250NON**	**250IN**
Measured Freezer comp. Volume, Vf (l)	55.13	55.13	56.00	56.00
Measured Fresh Food Comp. Volume, Vc (l)	154.44	154.44	183.00	183.00
Total measured Volume (l)	209.57	209.57	239.00	239.00
Volume ratio	2.80	2.80	3.27	3.27

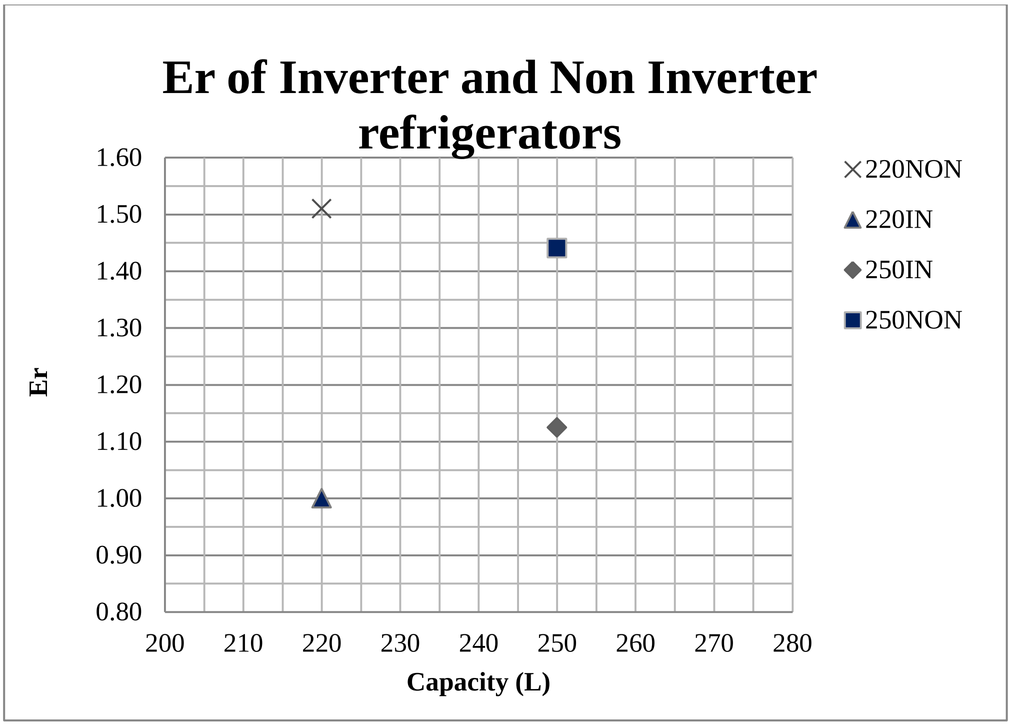
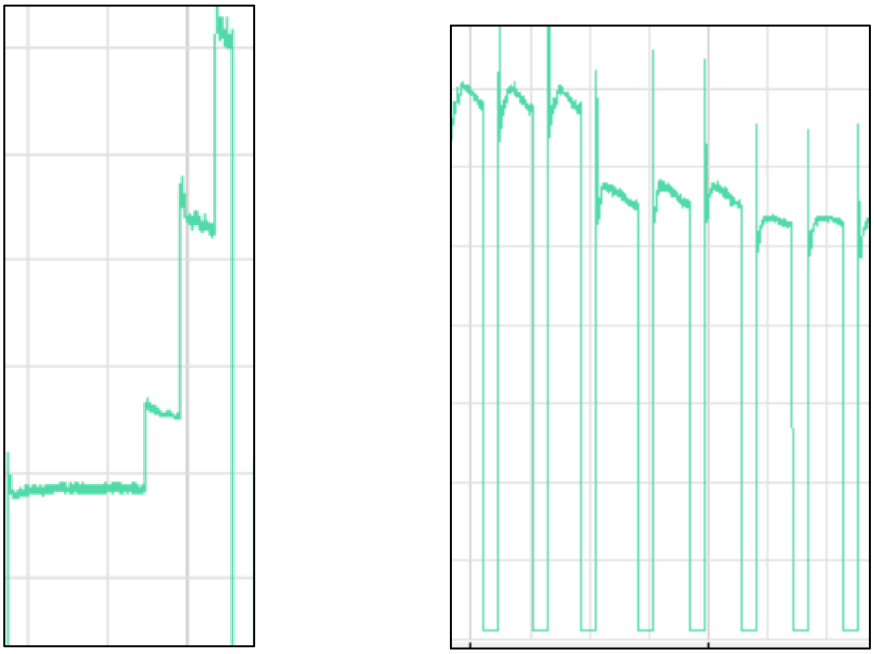


Figure 32: Er of Inverter and Non-Inverter refrigerators

The E_r of refrigerators were shown in Table 7 and plotted in Figure 32.It can be observed that E_r of Inverter refrigerators are lower than Non-Inverter refrigerators. The minimum, difference was 0.32Wh/kJ and as a percentage it is at least 22%. That means to produce a unit of cooling output; work input was less in inverter refrigerators by 22%. Further, 220IN inverter refrigerator is energy efficient than 250IN inverter refrigerator. Two inverter refrigerators had two different patterns of power consumption behavior as shown in the graphs in Figure 27 and Figure 29. Two refrigerators had two different characteristics of power consumption due to the behavior of the compressor. Figure 33 shows the difference of two inverter refrigerators. 250IN had varying peak values at some of ON positions of the compressor while 220IN had four numbers of steps at each compressor ON and due to this 220IN had limited ON s and OFFs than 250IN.



(a)Stepped (b) many peaks

Figure 33: Characteristics of compressor ON/OF

Calculated average power consumption during cooling was illustrated in Table 9 which shows that inverter refrigerators had comparatively low power consumption than non-inverter refrigerators, 220IN has the lowest out of inverters. Here it can be considered that cooling output of each refrigerator pair is almost equal because identical compartment volumes and identical cooling load. Then energy efficiency rating will directly depend on energy consumption. In other words, calculated average power will be the factor for prioritizing the refrigerator performance as in Table 9.

Table 9: Average Power of Refrigerators

Refrigerator	220NON	220IN	250NON	250IN
Energy Consumption, (Wh) in 24 hours	1664.13	1025.94	1413.92	1196.92
Average Power (W)	69.34	42.75	58.91	49.87

4.5 Average Temperatures of refrigerator Compartments

Average equilibrium temperatures of freezer compartments of each refrigerator were plotted in a graph as in Figure 34. All four refrigerators were compatible with standard temperature where T ≤-15℃.

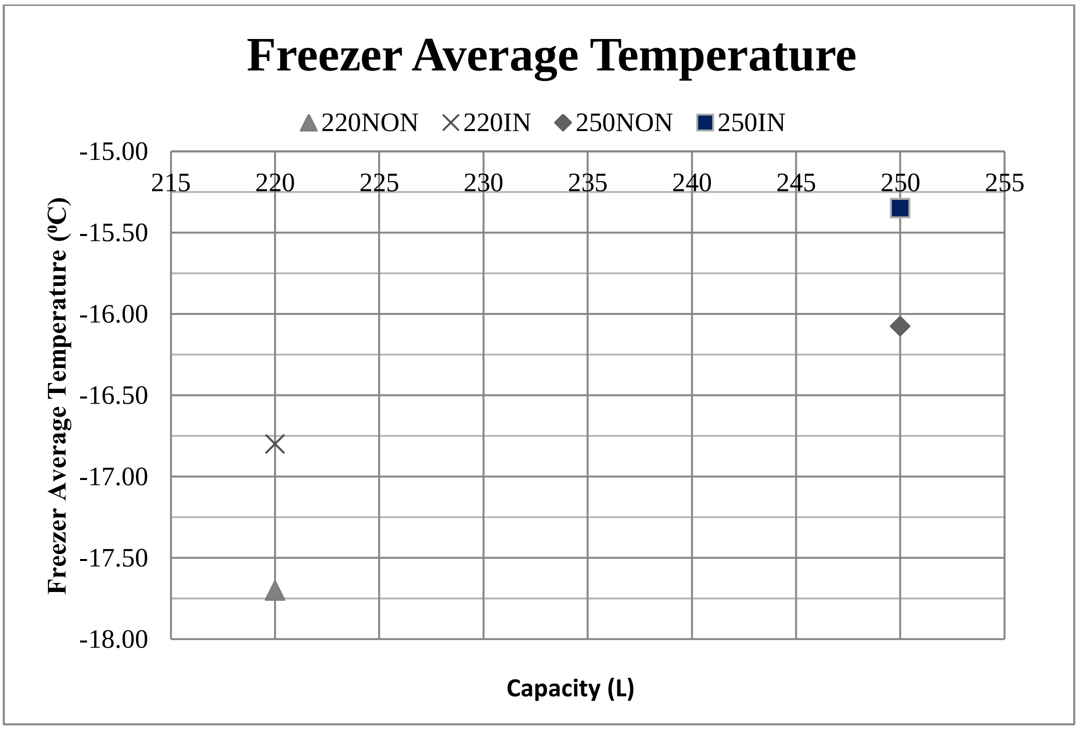


Figure 34: Freezer Average Temperatures

By analyzing, it was understood that inverter refrigerators had the temperature readings close to the target value of -15℃ than non-inverters. This indicates non-inverters were over designed for compartment temperatures, which in turn increases the energy consumption of the appliance.

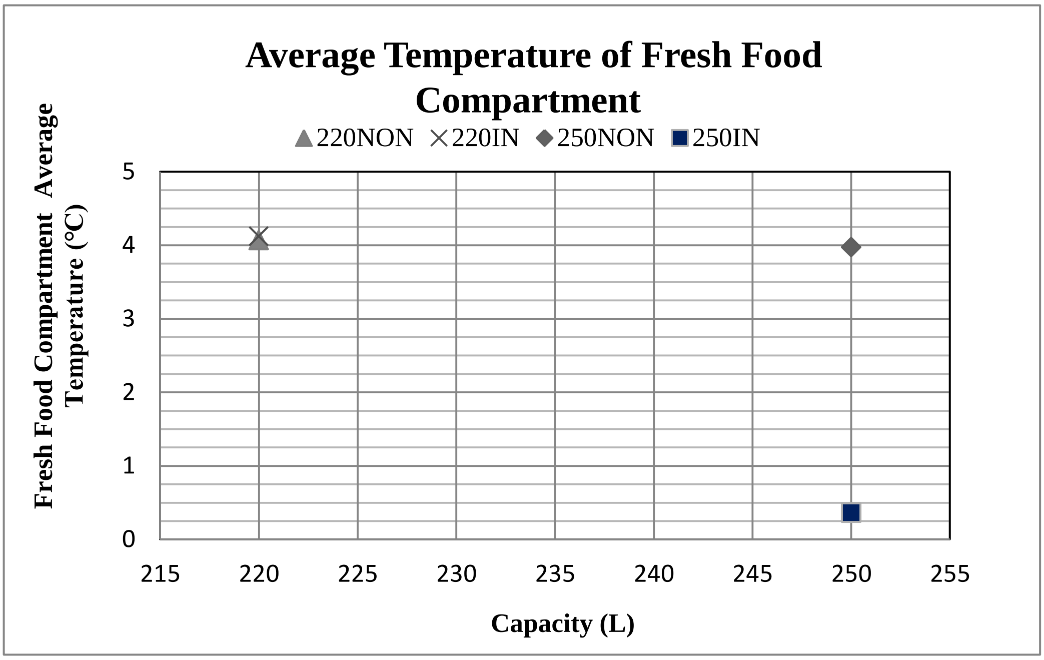


Figure 35: Average Fresh Food Compartment Temperatures

All refrigerators were maintaining freezer temperature and fresh food compartment temperature within the SLSI1230:2003 recommended levels. Fresh food compartment temperature of inverter and non-inverter of the refrigerators of 220NON and 220IN were almost the same while that of 250NON and 250IN showed a difference. Therefore, the 250IN refrigerator may be consuming an additional amount of energy over the other refrigerators, which is a disadvantage.

4.6 Temperature increment at Defrosting Heating

All refrigerators were automatic defrosting refrigerators and defrosting is a cyclic process where initiation of defrosting results increase in temperature as shown in graphs of tested refrigerators. Average temperature increment of 4°C could be observed at defrosting peaks of the refrigerators during the testing period.

Defrosting duration is shown in Table 10. The effect of temperature fluctuation in refrigerator compartment due to defrosting may have impact of food preserved in the refrigerator, especially foods stored in the freezer which are highly sensitive to growth of food spoilage bacteria. Depend on this behavior total food preserving period should be recognized. Food quality testing is required in order to go ahead of this area, and remain for future studies.

Table 10: Defrosting Time Duration

Refrigerator	220NON	220IN	250NON	250IN
Load Temperature (^{0}C) at defrosting peak	-12.80	-12.20	-11.2	-12.80
Defrosting Time duration (h:min) above -15^{0}C	2:16	2:56	1:17	3:26

4.7 Percentage Cooling Load to Total Energy Consumption

Table 11 shows percentage energy consumption to cool 3kg of load to the expected temperature to the total energy consumed during the period. 220NON refrigerator had highest energy consumption after door opening and the inverter of the same model had the lowest. Defrosting initiation, and air circulation speed and time inside the freezer may have possible connection for these results. In order to further analysis many more test data will be required.

Table 11: Percentage Energy consumption for door opening and loading

Refrigerator	220NON	220IN	250NON	250IN
Cooling Time (h:min)	11.41	14.61	13.25	16.85
Event 1:Energy Consumption (Wh) with loading	1040.91	674.81	953.50	927.47
Event2: Energy Consumption (Wh) without loading	564.41	545.85	567.78	635.14
Difference in Energy (Wh) consumed in Event 1 and Event 2	476.50	128.96	385.72	292.33
% increase energy use due to loading	45.78	19.11	40.45	31.52

Inverter refrigerators consumed 20-40% of its total energy to cool 3kg of test load, while non-inverters consumed 60-80% of its total energy.

4.8 Comparison of Energy Efficiency Ratings with SLS 1230:2003

220NON, 220IN, 250NON and 250IN refrigerators were tested according to the SLS 1230:2003 testing procedure for energy rating which is without load. Results obtained for E_r without load and with load were plotted as per Figure 36.

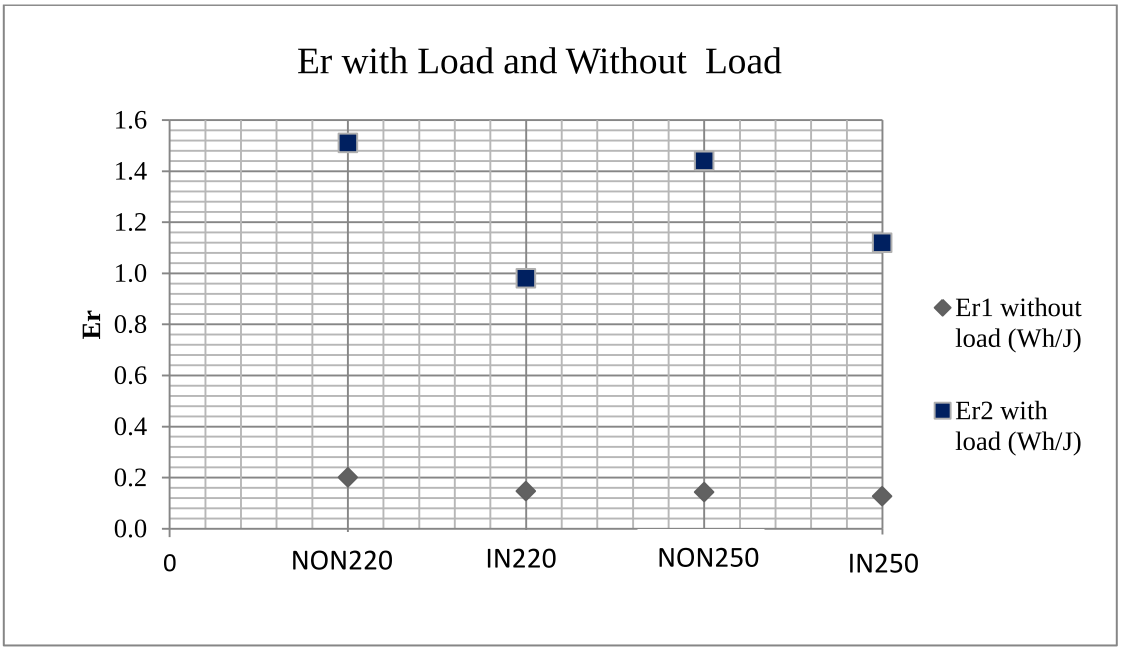


Figure 36: Er values under current testing standard and under proposed test method

Results were tabulated in Table 12, where E_{r1} is with load, and E_{r2} is without load. Inverter refrigerators consumed less energy than non-inverters weather it was loaded or not but, when refrigerators were loaded the difference is high.

Table 12: Er with load and without load

a. For 220*l* refrigerators

	220NON	220IN	Difference of Er
E_{r1} without load (Wh/kJ)	0.201	0.147	0.054
E_{r2} with load (Wh/kJ)	1.510	0.980	0.530

b. For 250*l* refrigerators

	250NON	250IN	Difference of Er
E_{r1} without load (Wh/kJ)	0.143	0.127	0.016
E_{r2} with load (Wh/kJ)	1.440	1.120	0.320

The difference of Er between non-inverter-based refrigerators and inverter- based refrigerators is shown in the Table 12. Difference of Er was 10 times greater for capacity of $220\,l$ refrigerator and it was 20 times greater for capacity of $250\,l$ refrigerator. Then it was observed that when tested at loaded condition, the 'Energy Efficiency Rating' (Er) which is the refrigerator energy performance indicator shows a greater difference between refrigerators than when tested at no load condition. It is around 11% increment. This means inverter refrigerators performs well with loading situation than without load situation. Further, due to many door openings and loadings at real situation the difference of Er between inverter-based refrigerators might increase further.

E_{r1} and E_{r2} of 250IN, 250NON, 220IN and 220NON refrigerators have a relationship of energy rating pattern. The shift of E_r values under no load situation between inverter and non-inverter refrigerator of same model was clear in load situation. In other words, there was a clear variation of E_r between 250NON and 250IN in load situation but it is slight when no load situation. This is same for the 220NON and 220IN. Result points of E_{r1} and E_{r2}were mapped and the shift of inverter refrigerators had high value with minimum of 1.3 and the shift of non-inverters to the same direction had the minimum of 0.83.

This shows shift of E_r with load from without load is similar and slight change for Inverter refrigerators and similar and highly shifted for non-inverter refrigerators. Further the deviation of Energy Rating variation of E_r of load situation is clear than without load situation between inverter and non-inverter refrigerators.

4.9 Potential National Energy Saving

As inverter refrigerators dominate 22% energy saving than non-inverter refrigerators, it is recommended to arrange programs and policies under national level to promote inverter refrigerators in Sri Lanka.

Possible energy saving can be calculated as follows;

Assumptions;

Average volume capacity of a refrigerator = 220 L

Population of households = 3.8million [42]

60% of total population can afford a refrigerator.

Minimum energy saving of inverter refrigerators during 24h

= (1532-1178) Wh

= 354Wh *30 days

= 10.62kWh (electricity units per month per household)

Total number of electricity units can be saved in national level

= 10.62 *(3.8M*0.6)

= 22.8 million electricity units

Summary

Cooling rate, Energy consumption per unit volume, energy efficiency rating, average power consumption for cooling 3kg of test load, freezer and fresh food compartments' effective temperatures after equilibrium, Defrosting heating of load in the freezer, comparison of Er when tested with load and without load, and expected national savings, were analyzed.

5 DISCUSSION AND CONCLUSION

Discussion with research findings and test procedures were figured first. Then conclusion was conversed with, key findings, recommendations, limitations and future studies.

5.1 Discussion

Energy consumption of refrigerators is the critical parameter used in energy labelling schemes. Therefore, accurate procedures of assessing energy consumption should be followed in testing methods. SLS 1230:2003 is the refrigerator testing standard practicing in Sri Lanka to guide consumers for selecting suitable energy efficient refrigerators. In this method, the empty refrigerators are tested for energy performance. This is in contrast to the actual usage of refrigerators where, it is always loaded with food and beverages. Therefore, the aim of this research was to investigate the effect on energy performance when the refrigerators are tested with loading and to propose a test procedure to increase the accuracy of performance measurement of domestic refrigerators. This may be used to amend the Test Standard 1230:2003. The performance was found to be different at actual situation and the reasons were understood by analyzing the loading effect.

In this study, inverter-based and non-inverter-based refrigerators were tested and compared to differentiate the effect of loading. Therefore, a pre-defined load was selected for the refrigerator freezer. The predefined load was decided by considering practical possibility of achieving required cooling result within limited time span of 24hours. Two pairs of inverter and non-inverter type, two door refrigerators were tested having capacity of $220\ l$ and $250\ l$. First, the refrigerators were allowed to reach their set temperatures of, -15^0C in the freezer and $+5^0C$ in the fresh food compartment. Then the test load ($3\ kg$) at room temperature of 28^0C was loaded to the freezer. The time duration for loading was $40s$. Data on temperature of load, air temperature of freezer compartment, power consumed, temperature and relative humidity of surrounding were logged until the freezer compartment reached its set temperature.

5.1.1 Cooling Rate

Results showed that cooling-time for the test load in non-inverter and inverter pairs of $220\ l$ and $250\ l$ were$10, 17\ and\ \ 13, 16$ hours respectively. The results showed that, the air temperature of the freezer compartment reached -15^0C within 3 hours while the cooling time of freezer load was more than ten hours for $3kg$ of test load, from room temperature to -15^{o}C.

Another important outcome obtained from the research was the cooling rates of test loads. By analyzing cooling rates, it was understood inverter-based refrigerators were minimum of 3 hours slow coolers than non-inverter-based refrigerators. This fact should not be ignored, because cooling rate derived from test results provides basic parameter applicable for food preservation. As an example, foods like meat and fish will need fast cooling in order to immediate slowdown of bacteria reaction on them. Unfortunately, this is not addressed in the SLS 1230:2003 test procedure, which only focuses on energy consumed.

5.1.2 Comparison of Energy Efficiency Rating

Then it was observed that when tested at loaded condition, the 'Energy Efficiency Rating' (E_r) which is the refrigerator energy performance indicator shows a greater difference between refrigerators than when tested at no load condition. For example, for $220\ l$ refrigerators the difference of E_r between inverter and non-inverter refrigerators, when tested with loading was 10 times more than that when tested with empty refrigerators. This is 20 times more between the $250\ l$ refrigerators. Therefore, testing with loaded refrigerators clearly differentiate the energy performance of inverter-based refrigerators against non-inverter-based refrigerators. This is because inverter-based refrigerators consume energy according to the level of loading [37].

The energy consumption of refrigerators which were loaded was identified and results showed that energy efficiency of inverter-based refrigerators were 11% high when they were tested with load.

5.1.3 Power Profiles

Energy consumption patterns of refrigerators were explained in the graphical results obtained for refrigerators. Interestingly, the two inverter-based refrigerators have two different profiles, one has step up increase at each ON of the power profile (Figure 33 on page 50) and the other had many ON/OFF but different peaks. The latter showed, 14.2 % increase in E_r. This may due to the different manufacturer and may be that the former mode of operation is better than that of the latter.

The average power consumption in Watt, during cooling time of refrigerators was calculated and average power consumption of inverter-based refrigerators was 30% lower than that of non-inverter-based refrigerators.

Average temperatures of refrigerator freezer and fresh food compartment showed that, inverter refrigerators have the ability to maintain freezer air temperature near to the target temperatures of the freezer. All the refrigerators had maintained freezer temperature and fresh food compartment temperature within the SLS 1230:2003 recommended levels.

5.1.4 Defrosting

Defrosting occurs in every 8 to 10 hours for the tested refrigerators. The defrost cycle is the time between switching on the defrost heater and the time for the freezer compartment to reach the set temperature. The defrost heater switches off at half way through the time. The effect of temperature variation due to heating for defrosting process on the load in the freezer was obtained and it was observed that the freezer test load temperature was increased by 3℃ during the average of two hours of the defrosting operation. This may cause an adverse effect on food preservation as well as energy consumption of the refrigerator.

5.1.5 Temperature Indicators

Refrigerator compartment settings were fixed as per SLS 1230:2003, and average temperature of freezer was set to -15^0C and that of fresh food compartment was +5^{o}C. As discussed in chapter 2 refrigerators had temperature settings which were either numbered 1-7 or with symbols like dots, and not the temperature itself. Due to this reason compartment temperatures were set by trial and error method by observing the temperature sensor readings. This facility is not available for the users, as almost all the refrigerators do not display temperatures.

This experiment can combine with field surveys in order to include the actual domestic situation of refrigerators and to identify other key parameters like effect of environmental conditions to energy performance of refrigerators.

5.1.6 Suggestion for SLS 1230:2003

In the SLS 1230:2003 refrigerator test standard, energy consumption test is explained in section 8.7 (page 29) and the installation of sensors in refrigerator is given in 8.2.7 (page 19 and 20) and Appendix B (page 53) explains the locations of temperature sensors in each compartment of the refrigerator. There it neither indicates to use empty refrigerator nor to use the loaded refrigerator. However, in section 8.7, table 4 (page 30) it clearly shows that only the air temperature readings are recorded and in section 8.7 freezer volume has to be maintained for maximum energy consumption. Therefore, this indicates that the empty refrigerators have to be tested for energy performance labeling, which is the current practice.

Based on the results of this research it is suggested to load the freezer in accordance with the loading ratio explained in Chapter 3. Then carryout test as described below.

1. Load the freezer compartment to half of the volume with freezer test packages and allow the refrigerator to reach equilibrium set temperature.
2. Positioning of temperature sensors has to be in accordance with the section 8.2.7 of the SLS 1230:2003 standard.
3. Open the door of the freezer and within $40\ s$ install the $3\ kg$ of test packages with the internal temperature sensors and close the door.
4. Record the sensor readings until the 3kg of test packages reach the set temperature of -15^0C .
5. Follow the procedure as given in the Chapter 3, section 3.2.1 of this research to calculate the E_r value.

5.2 Conclusion

By analyzing energy performance of domestic refrigerators this research delivered comparative outcome between inverter-based refrigerators against non-inverter-based refrigerators. Results consists with two key findings which are not addressed in the SLS 1230:2003 refrigerator testing standard and it was suggested to amend the standard SLS 1230:2003 according to section 5.1.6 of the discussion. Proposed test method considers pre-defined volume of test load for the freezer and indicated practical possibility of achieving required energy and cooling results. Test samples of $220\ l$ and $250\ l$ capacities of refrigerators were tested with $12\ kg$ of test load during $24\ hours$ of test period. Test procedure follows the test standard 1230:2003 and additionally incorporated door opening, loading and cooling effect to the test procedure. Response of inverter-based refrigerators to the load variation and cooling rate was grasped from the results. Energy Efficiency Rating (E_r) was calculated to compare the energy performance of each refrigerator. Smaller the value of E_r better is the energy performance of the refrigerator. Based on the analysis of the results, key findings, recommendations, and limitations and future work are explained as below.

5.2.1 Key Findings

- Cooling time of refrigerators for $3\ kg$ of test load from room temperature to -15^0C in the freezer was more than ten hours, which may support pathogen growth in food.
- The cooling rate of inverter-based refrigerators is, 3 to 7 hours slower than non-inverter-based refrigerators which may support pathogen growth.
- Energy consumption per unit volume per day was found to be $23\ \%$ lower than non-inverter automatic defrosting refrigerators and E_r is $22\ \%$ lower in Inverter refrigerators.
- Testing with load gives E_r values for different refrigerators with 10 to 20 times contrast than when testing according to the standard SLS 1230:2003.

- Two different power profiles could be observed for inverter-based refrigerators. Inverter type refrigerators with step by step power profile showed better energy performance than the one with many peaks power profile.
- Freezer test load temperature was observed to increase by 3℃ during the defrosting operation which may support pathogen growth.
- Opening the freezer door while the defrost cycle is in operation the energy consumption of the refrigerator increases.

5.2.2 Recommendations

- A temperature display is necessary to show compartment temperatures of the refrigerator compartment and it should be included as a requirement in the refrigerator test standard.
- The test procedure SLS 1230:2003 to be amended to incorporate loading of refrigerator freezer to obtain E_r and cooling rate of freezer load as explained in Chapter 5, section 5.1.6.
- Testing for quality of food preservation to be incorporated in the test standard. This may be achieved in terms of the cooling rate.
- In order to avoid door opening during the defrost cycle; an indicator needs to be incorporated outside the refrigerator.

5.2.3 Limitations and Future Studies

- Effect of defrosting the freezer and the door opening on the quality of food in the freezer need to be further investigated.
- The cooling rate required for a given food item depends on the growth rate of micro-organisms on that food. Therefore, an analysis of food quality versus retention time for types of food generally stored in the refrigerator has to be carried out, in order to define a minimum cooling rate for refrigerators.
- An analysis of power consumption pattern of inverter-based refrigerators has to be carried out to identify advantages pertaining to each technique.

- To overcome restrictions of effect of air gap between test loads a loading-ratio needs to be introduced after further investigations.
- Actual performance of domestic refrigerators, need to be studied in order to identify, behavioral patterns of door opening and loading, different ambient conditions to make further amendments to adapt the standard test to Sri Lankan context.
- The Sri Lankan domestic refrigerator's operation cycle can also be derived from the above study which may change the behavioral patterns of domestic consumers towards national energy savings.

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Appendix A: Properties of R600a

As per ASHRAE Standard 34-2013[13] refrigerants can be classified for safety is as follows.

Increasing Flammability

High Flammability	A3	B3
Low Flammability	A2	B2
No Flame Propagation	A1	B1
	Lower Toxicity	Higher Toxicity

Increasing Toxicity

ASHRAE ; classification of R600a refrigerant.

HFC-134a is A2. R600a (Isobutene) and CO_2 are refrigerant taken attention at present. These refrigerants have lower global worming potential and ozone depletion potential.

Properties of R600a

Molecular formula	C_4H_{10}
Molar mass	58.12 g mol−1
Appearance	colorless gas
Density	2.51 kg/m3, gas (15 °C, 1atm) 593.4 kg/m3, liquid
Ozone depletion potential (ODP)	0
Global warming potential (GWP)	3
Flash point	Flammable gas

CO_2 has good heat transfer coefficient and higher heat exchange capacity. Same way it is a high-pressure refrigerant and at high operating pressure CO_2 is efficient.

So, systems should design such that to withstand high pressure up to 9barAlso CO_2 has a lesser compression pressure ratio of 20 which is 50% less than HFCs and Ammonia [42]]. Due to this it is still not used in commercial refrigeration. Major disadvantage of CO_2 is tendency of GHG effect. Then hydro carbons were introduced as their GWP is less than 4 but flammable and belong to group A3.

While R600a is demanding as a refrigerant some research works were conducted in parallel considering thermal conductivity.

Appendix B: Efficiency Rating as per SLS 1230:2003

The efficiency rating shall be derived from the following formula and the results rounded off to three decimal places.

$$\boxed{\mathbf{E_r = EC / V^1}}$$

Where,

$V^1 = V_f \times K_f + V_c \times K_c$

V_f = Volume of frozen food storage compartment in liters

V_c = Volume of fresh food storage compartment in liters

EC = Energy consumption in kWh / year

$K_f = 32 - T_f$

$K_c = 32 - T_c$

T_f = Temperature of frozen food storage compartment in °C

T_c = Temperature of fresh food storage compartment in °C

Appendix C: Data Sheet of Test Packages

1. Product and Manufacturer Identification

Commercial name: TEST PACKAGE o PACCO TEST

Use: for performance tests on Household Cooling Appliances, according to ISO 15502, ISO5155, ISO 7371, ISO 8187,ISO 8561, and relevant Amendments, and on

Commercial Cooling Appliances, according to EN Standards 441-4, 441-5, UNI EN ISO

23953-2:2006 and relevant Amendments.

Manufacturer: **MADI S.r.l.** - Via delle Industrie, 2/4 – 26838 TAVAZZANO C/V (LO) – Italy
Phone: +39 0371 477880
Fax: +39 0371 477073
Phone number for urgent callings:
+39 349 5620917

2. Composition/Information of Ingredients

Substances container in the product (percentage over 1%), considered dangerous according to the European Directive CEE 67/548 and relevant amendments,

Freezing point	- 1°C
oxyethylmethylcellulose	23,0%
sodium chloride	0
water	76,4%
sodium chloride	0.5%
chloro-m-cresol	0.08%

Appendix D: Estimation of Uncertainty of Measurements

E_r can be written as;

$$Er = \frac{Wh}{(MmCm + Vf - (Vn + Vo) * (Tr - Tf) + Vc * (Tr - Tc))} \tag{16}$$

Where, W is power measurement in Watt and h is the time measurement in hours.

Combine Uncertainty, U(E_r) can be written as a function of partial derivatives of all the measuring parameters;

$$\begin{aligned} U^2\ (Er) = \left(\frac{\partial Er}{\partial W}\right)^2 U^2\ (W) + \left(\frac{\partial Er}{\partial h}\right)^2 U^2\ (h) + \left(\frac{\partial Er}{\partial Mm}\right)^2 U^2\ Mm \\ + \left(\frac{\partial Er}{\partial Vf}\right)^2\ U^2(Vf) + \left(\frac{\partial Er}{\partial Vn}\right)^2\ U^2(Vn) \\ + \left(\frac{\partial Er}{\partial V0}\right)^2\ U^2(V0) + \left(\frac{\partial Er}{\partial Vc}\right)^2\ U^2(Vc) \\ + \left(\frac{\partial Er}{\partial Tr}\right)^2\ U^2(Tr) + \left(\frac{\partial Er}{\partial Tf}\right)^2\ U^2(Tf) \\ + \left(\frac{\partial Er}{\partial Tc}\right)^2\ U^2(Tc) \end{aligned} \tag{17}$$

Where;

$U^2\ (Er)$ - Uncertainty of estimation of E_r

$U^2\ (W)$ - Expanded uncertainty of Power measurement

$U^2\ (h)$ - Expanded uncertainty of Time measurement

$U^2\ (Mm)$ - Expanded uncertainty of Weight measurement

$U^2\ (Vf)$ - Expanded uncertainty of Freezer volume measurement

$U^2(Vn), U^2(Vo)$ - Expanded uncertainties of test packages volume measurement

$U^2(Vc)$ - Expanded uncertainty of fresh food compartment volume measurement

$U^2(Tr)$ - Expanded uncertainty of ambient temperature measurement

$U^2(Tf)$ - Expanded uncertainty of freezer temperature measurement

$U^2(T)$ -Expanded uncertainty of fresh food compartment temperature measurement

$\frac{\partial Er}{\partial W}$, $\frac{\partial Er}{\partial h}$, $\frac{\partial Er}{\partial Vf}$, $\frac{\partial Er}{\partial Vn}$, $\frac{\partial Er}{\partial Vo}$, $\frac{\partial Er}{\partial Vc}$, $\frac{\partial Er}{\partial Tr}$, $\frac{\partial Er}{\partial Tf}$ and $\frac{\partial Er}{\partial Tc}$ are sensitivity coefficients.

Assume $$Z = \left(\mathrm{Mm\ Cm} + \mathrm{Vf} - (\mathrm{Vn} + \mathrm{Vo})\right) * (\mathrm{Tr} - \mathrm{Tf}) + \mathrm{Vc}(\mathrm{Tr} - \mathrm{Tc}) \quad (18)$$

$$\frac{\partial Er}{\partial W} = \left(\frac{\mathrm{h}}{Z}\right) \quad (19)$$

$$\frac{\partial \mathrm{Er}}{\partial \mathrm{h}} = \left(\frac{\mathrm{W}}{Z}\right) \quad (20)$$

$$\frac{\partial \mathrm{Er}}{\partial \mathrm{Vc}} = \left(\frac{\mathrm{Wh}}{Z^2}\right) * (\mathrm{Tr} - \mathrm{Tc}) \quad (21)$$

$$\frac{\partial \mathrm{Er}}{\partial \mathrm{Vf}} = \left(\frac{\mathrm{Wh}}{\mathrm{Z}^2}\right) * (\mathrm{Tr} - \mathrm{Tf}) \quad (22)$$

$$\frac{\partial Er}{\partial Tr} = \left(\frac{\mathrm{Wh}}{\mathrm{Z}^2}\right) * \left(\left(\mathrm{Mm\ Cm} + \mathrm{Vf} - (\mathrm{Vn} + \mathrm{Vo})\right) + Vc\right) \quad (23)$$

$$\frac{\partial Er}{\partial Tc} = \left(\frac{\mathrm{Wh}}{(\mathrm{Z})^2}\right) * (Vc) \quad (24)$$

$$\frac{\partial Er}{\partial Tf} = \left(\frac{\mathrm{W}}{\mathrm{Z}^2}\right) * \left(\mathrm{Mm\ Cm} + \mathrm{Vf} - (\mathrm{Vn} + \mathrm{Vo})\right) \quad (25)$$

$$\frac{\partial Er}{\partial Vn} = \left(\frac{\mathrm{Wh}}{\mathrm{Z}^2}\right) * (\mathrm{Tr} - \mathrm{Tf}) \quad (26)$$

$$\frac{\partial Er}{\partial Vo} = \left(\frac{\mathrm{Wh}}{\mathrm{Z}^2}\right) * (\mathrm{Tr} - \mathrm{Tf}) \quad (27)$$

$$\frac{\partial Er}{\partial Mm} = \left(\frac{\mathrm{Wh}}{\mathrm{Z}^2}\right) * Cm * (\mathrm{Tr} - \mathrm{Tf}) \quad (28)$$

Estimation of uncertainty is shown in Table 13, 14 and 15 and Expanded Uncertainty of E_r is ± 0.012Wh/kJ at 90% confident level.

Table 13: Estimation of Uncertainty of Measurements -Part A

`	**Measurement**	**Source**	**Unit**	**Variability**	**Type**	**Distribution**	***Coverage factor (K)**	**Standard Uncertainty (u)**	**Combined Uncertainty (U_C)**	**Expanded Uncertainty (U_E)**	**U_E With professional judgement**
1	Power	Calibration	W	0.0500	B	normal	2	0.0250	**0.0252**	0.050	0.05
		Resolution	W	0.0100	B	rectangular	3.464	0.0029			
2	Time	Calibration	s	0.0800	B	normal	2	0.0400	**0.04031**	0.081	1min
		Resolution	s	0.0100	B	rectangular	3.464	0.0050			
3	Temperature inside refrigerators	Calibration	^0C	0.2600	B	normal	2	0.1300	**0.1301**	0.260	0.3
		Resolution	^0C	0.0100	B	rectangular	3.464	0.0050			
4	Temperature of test chamber	Calibration	^0C	0.3400	B	normal	2	0.1700	**0.1701**		
		Resolution	^0C	0.0100	B	rectangular	3.464	0.0050			
5	weight of Test pieces	Calibration	kg	0.0100	B	normal	2	0.0050	**0.0058**		
		Resolution	kg	0.0100	B	rectangular	3.464	0.0029			

Table 14: Estimation of Uncertainty of Measurements -Part B

	Measurand (xi)	**Detail**	**Values**	**Unit**	**Sensitivity coefficient ($\partial E_r/\partial x_i$)**		**(∂Er/∂xi)^2**	**U^2**	**Uncertainty Component of Er**
1	W	Power (avg.)	49.04	W	∂Er/∂W	0.0229	0.0005	6.3E-04	3.3E-07
2	h	Time	24	h	∂Er/∂h	0.0469	0.0022	1.6E-03	3.6E-06
3	Vc	Volume-Fresh Food	0.145	m3	∂Er/∂Vc	0.0297	0.0009	2.1E-06	1.9E-09
4	Vf	Volume-Freezer	0.055	m3	∂Er/∂Vf	0.0466	0.0022	1.3E-07	2.8E-10
5	Tr	Temperature- Room	28	℃	∂Er/∂Tr	0.0260	0.0007	2.9E-02	2.0E-05
6	Tc	Temperature-Fresh food	0.37	℃	∂Er/∂Tc	0.0002	0.0000	1.7E-02	4.1E-10
7	Tf	Temperature-Freezer	-15.35	℃	∂Er/∂Tf	0.0259	0.0007	1.7E-02	1.1E-05
8	Mm	Mass of Test pieces (TP)	12	kg	∂Er/∂Mm	0.0932	0.0087	3.3E-05	2.9E-07
9	Vn	Volume of TP inserted	0.003	m3	∂Er/∂Vn	0.0466	0.0022	9.4E-09	2.1E-11
10	Vo	Volume of TP inside	0.009	m3	∂Er/∂Vo	0.0466	0.0022	9.4E-09	2.1E-11
11	Wh	Energy consumed	1177						
12	Cm	Specific heat of TP	2						
13	Er	Energy Rating	1.1249						
14	Uncertainty component total								0.00004
15	Combine Uncertainty of Er								0.00592
16	Expanded Uncertainty								0.01184

* K=2 for 90% confident level

Table 15: Estimation of Uncertainty of Volume of Refrigerator Compartments (Type A) by Statistical method

	Freezer				Fresh Food Comp			
Data Set	L(cm)	H(cm)	W(cm)	V(l)	L(cm)	H(cm)	W(cm)	V(l)
1	39.5	22.0	24.0		44.0	81.0	45.0	
2	39.3	22.0	24.0		44.0	81.1	45.0	
3	39.5	22.0	23.5		43.5	81.0	44.5	
4	39.0	22.0	24.0		44.0	81.5	45.0	
5	39.5	22.2	24.0		44.5	81.0	45.0	
6	39.5	22.0	24.0		44.0	81.2	44.5	
7	39.0	22.3	24.0		44.0	81.0	44.8	
8	38.9	22.0	23.9		44.0	79.8	45.0	
9	39.0	22.0	24.0		44.0	81.0	45.0	
10	39.4	22.2	24.0		44.2	81.0	45.2	
Standard Deviation	0.255	0.116	0.158		0.244	0.438	0.231	
Mean	39.260	22.070	23.940	20.743	44.020	80.960	44.900	160.017
Repeatability (@k=2)	0.040	0.018	0.025		0.039	0.069	0.037	
Calibration(@k=2)	0.150	0.150	0.150		0.150	0.150	0.150	
Resolution(@k=2√3)	0.029	0.029	0.029		0.029	0.029	0.029	
uncertainty of volume	0.158	0.154	0.155		0.158	0.168	0.157	
% uncertainty	0.402	0.697	0.647	1.746	0.358	0.207	0.350	0.915
U of volume				**0.362**				**1.464**

Glossary

1) **Freezer** – Separate compartment of refrigerator intend to preserve fish and meet mainly
2) **Fresh Food Compartment** – Separate compartment of a refrigerator purpose to preserve perishable goods; milk, egg, vegetables and fruits.
3) **Testing Chamber** – A Standard Chamber where temperature and humidity inside it can be controlled and refrigerators can be located inside; used for refrigerator testing.
4) **Volume Ratio** – Freezer volume to fresh food compartment volume ratio.
5) **Refrigerator compartments**- Freezer compartment and fresh food compartment.