

Development of a novel hybrid frost detection and defrost system for refrigeration systems and its applications

by

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**Development of a novel hybrid frost detection and defrost system for
refrigeration systems and its applications**

Koç University

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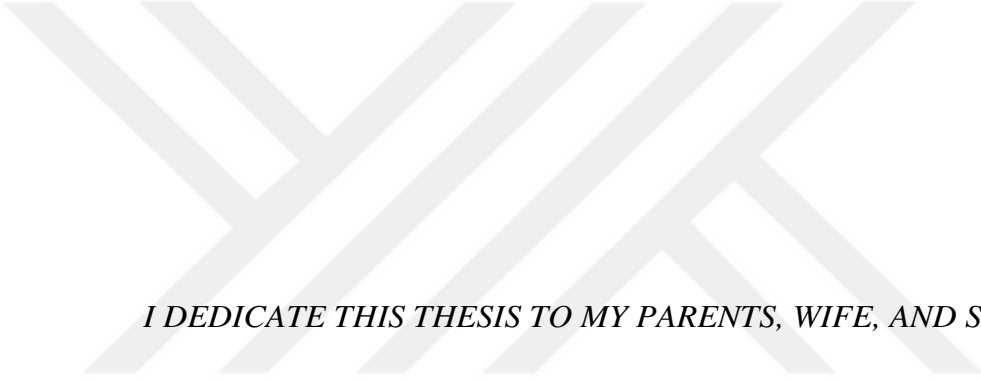
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I DEDICATE THIS THESIS TO MY PARENTS, WIFE, AND SON

ABSTRACT

The repetitive collection of biological samples and their preservation for analyses at a later stage is a key aspect of biomedical research. Millions of samples collected every day around the world may degrade if proper storage conditions are not provided. Therefore, it is imperative to have a storage facility that is efficient enough to preserve the integrity of these samples over time. Refrigeration systems play a crucial role in delaying the degradation process of samples by maintaining suitable thermal conditions in storage facilities. However, the unremitting operation of the refrigeration system and the presence of moisture inside the storage facility may result in frosting on the surface of the evaporator.

The frosting is a phenomenon most detrimental to the performance of refrigeration systems, as it directly affects the heat transfer process inside the refrigerator cabin. The workload on the compressor increases many folds under frosting conditions and the refrigerator struggles to maintain the desired temperature. Consequently, the energy consumption and the probability of stored samples degradation over time increases. The commercial refrigeration systems use a blind and periodic defrosting cycle without any quantification of frost, which leads to lower efficiencies. Therefore, there is a need for an intelligent system that not only detects the presence of frost but also takes countermeasures to defrost the evaporator on-demand, without affecting the quality of stored samples.

In the first part of this research study, a hybrid frost detection – defrosting system (HFDDS) is developed that is comprised of a novel photo-capacitive sensing technique and a dual-purpose additively manufacturable sensor and defrosting heater. The HFDDS can detect the formation of frost, measures the thickness of frost from 1.3 to 8 mm with a 5% margin of error, and triggers a defrosting response once a critical frost thickness is attained. The HFDDS is targeted to provide a defrosting on-demand instead of the inefficient blind and periodic defrosting for the refrigeration systems.

In the second part of this research study, a novel real-time thickness of the frost-based defrost-on demand technique is presented for refrigeration systems. The hybrid frost detection and defrost system developed in the first part, is employed to quantify the thickness of frost in real-time and to defrost the evaporator using a 12 W heater. The effect of the thickness of

the frost-based defrost threshold on the energy consumption of the refrigerator is evaluated. The defrost threshold of 6 mm yields the maximum energy conservation of 10% as compared to the default blind and periodic defrost strategy of the test refrigerator.

In the third part of this research study, a novel, frost feedback-based distributed defrosting approach to minimize the defrost desynchronization is proposed. The evaporator is divided into three regions based on the frost distribution pattern. Each of these regions was equipped with an additively manufactured low-powered defrost heater controlled by an optical frost feedback sensor. The frost feedback-based distributed approach proved to be effective in eliminating the defrosting desynchronization. The frost feedback enables the system to terminate defrosting as soon as the frost in the discretized region melts, which reduced the defrost energy significantly. The distributed approach minimizes the rise in the cabin temperature during defrosting and therefore, leads to the reduction of energy spent in the subsequent recovery cycle. The results of the frost feedback-based distributed approach were compared to the default temperature-based strategy using a single defrost heater. The frost feedback-based operation of the three distributed defrost heaters at 6 W each demonstrated maximum overall energy conservation of 18.9% as compared to the default temperature-based strategy.

ÖZET

Biyolojik örneklerin tekrar tekrar toplanması ve daha sonraki bir aşamada analizler için korunması, biyomedikal araştırmanın önemli bir yönüdür. Uygun saklama koşulları sağlanmazsa, dünya çapında her gün toplanan milyonlarca numune bozulabilir. Bu nedenle, bu numunelerin zaman içinde bütünlüğünü koruyacak kadar verimli bir depolama tesisine sahip olmak zorunludur. Soğutma sistemleri, depolama tesislerinde uygun termal koşulları koruyarak numunelerin bozunma sürecini geciktirmede çok önemli bir rol oynamaktadır. Ancak, soğutma sisteminin aralıksız çalışması ve depolama tesisi içinde nem bulunması, evaporatör yüzeyinde buzlanma ile sonuçlanabilir.

Buzlanma, buzdolabı kabini içindeki ısı transfer sürecini doğrudan etkilediğinden, soğutma sistemlerinin performansına çok zarar veren bir durumdur. Kompresör üzerindeki iş yükü, buzlanma koşullarında çok artar ve buzdolabı istenen sıcaklığı korumak için yüksek efor sarfeder. Buna bağlı olarak, enerji tüketimi ve depolanan numunelerin zamanla bozulma olasılığı artar. Ticari soğutma sistemleri, herhangi bir buz tespit çalışması olmaksızın tek taraflı/geri beslemesiz ve periyodik bir buz çözme döngüsü kullanır, bu da daha düşük verimliliğe yol açar. Bu nedenle, yalnızca buz varlığını tespit etmekle kalmayan, aynı zamanda depolanan numunelerin kalitesini etkilemeden istenildiği anda evaporatörün buzunu çözmek için önlemler alan akıllı bir sisteme ihtiyaç vardır.

Bu çalışmanın ilk bölümünde, yeni bir foto-kapasitif algılama tekniği ve eklemeli üretimle üretilebilir sensör ve buz çözme ısıtıcısından oluşan bir hibrit buz algılama – buz çözme sistemi (hybrid frost detection – defrosting system: HFDDS) geliştirilmiştir. HFDDS don oluşumunu algılayabilir, %5 hata payıyla 1,3 ila 8 mm arasında buz kalınlığını ölçebilir ve kritik donma kalınlığına ulaşıldığında bir defrost tepkisini tetikleyebilir. HFDDS, soğutma sistemleri için verimsiz kör/tek taraflı ve periyodik buz çözme yerine isteğe bağlı bir buz çözme sağlamayı hedefler.

Bu araştırmanın ikinci bölümünde, gerçek zamanlı buz kalınlıklarını kullanan soğutma sistemi için istenen anda çalışan yeni bir buz çözme yaklaşımı sunulmaktadır. İlk bölümde geliştirilen hibrit don algılama ve buz çözme sistemi, gerçek zamanlı olarak don kalınlığını ölçmek ve 12 W'lık bir ısıtıcı kullanarak evaporatörün buzunu çözmek için kullanılmıştır. Donma bazlı defrost eşiğinin kalınlığının buzdolabının enerji tüketimine etkisi

değerlendirilmiştir. 6 mm'lik buz çözme eşiği, test buzdolabının varsayılan kör ve periyodik buz çözme stratejisine kıyasla maksimum %10 enerji tasarrufu sağlar.

Bu araştırma çalışmasının üçüncü bölümünde, defrost uyumsuzluğunu en aza indirmek için yeni, donma geri beslemesine dayalı dağıtılmış bir buz çözme yaklaşımı önerilmiştir. Evaporatör, donma dağılım modeline göre üç bölgeye ayrılmıştır. Bu bölgelerin her biri, bir optik donma geri besleme sensörü tarafından kontrol edilen, eklemeli üretilmiş düşük güçlü bir buz çözme ısıtıcısı ile donatılmıştır. Donma geri bildirimine dayalı dağıtılmış yaklaşımın, buz çözme senkronizasyonsuzluğunu ortadan kaldırmada etkili olduğu kanıtlanmıştır. Donma geri bildirimi, dağıtılmış/ayrıklaştırılmış bölgedeki buz erir erimez sistemin defrost işlemini sonlandırmasını sağlar, ve bu da defrost enerjisini önemli ölçüde azaltır. Dağıtılmış yaklaşım, buz çözme sırasında kabin sıcaklığındaki artışı en aza indirir ve bu nedenle sonraki döngüde harcanan enerjinin azalmasına yol açar. Donma geri beslemesine dayalı dağıtılmış yaklaşımın sonuçları, hali hazırda varolan tek bir buz çözme ısıtıcısı kullanılan sıcaklığa dayalı stratejiyle karşılaştırıldı. Ayrı ayrı konumlandırılan üç defrost ısıtıcısının 6 W'ta donma geri beslemesi temelli çalışması, sıcaklığa dayalı stratejiye kıyasla maksimum toplam enerji tasarrufunun %18,9 olduğunu gösterdi.

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NOMENCLATURE

A	area [m^2]
ASHP	air source heat pump
COP	coefficient of performance
D	defrost threshold [mm]
DAQ	data acquisition [-]
DD	demand defrost
DIW	direct ink writing
d	distance [m]
E	energy consumption [Wh]
FFF	fused filament fabrication
FC	freezer cabin
FFC	fresh food cabin
F_t	frost thickness [mm]
GUI	graphical user interface
H	heat [W]
HFDDS	hybrid system
H_1	top defrost heater
H_2	middle defrost heater
H_3	bottom defrost heater
I	current [A]
IR	infrared radiations
L	inductance [H]
LC	inductor-capacitor [-]
NI	National instruments [-]
PITT	periodically initiated temperature terminated
P_1	refrigerators defrost heater power [W]
P_2	total power of distributed defrost heaters [W]
P_c	compressor power [W]
P_h	defrost heater power [W]
PLA	polylactic acid
R	resistance [ohm]
RH	relative humidity [%RH]
RPM	revolutions per minute
R^2	coefficient of determination
S_2	electrically controlled switch [-]
t	the thickness of frost [mm]
V	voltage [V]
V_1	output voltage of optical sensor top [V]
V_2	output voltage of optical sensor middle [V]
V_3	output voltage of optical sensor bottom [V]

Subscripts

in

input

ss

supply

out

output

c

compressor

cc

constant current supply

r

receiver

t

transmitter

Greek Letters

Ω

ohm

Δ

the change in

ϵ_0

permittivity of vacuum [F/m]

ϵ_r

dielectric constant

Chapter 1 : INTRODUCTION

1.1. Overview

The research in the field of biological sciences is critically dependent on the repetitive collection of specimens from different living organisms. According to an estimate around 1-billion, biological samples are stored worldwide for research purposes [1]. These biological specimens are preserved for subsequent examination by delaying their degradation process. The degradation process can be delayed by using the thermal stabilization technique in which ultra-low and low temperatures are used to slow down the enzymatic activity and bacterial growth [2]. Typically, biological specimens are preserved under different temperature ranges for short-term and long-term storage. The preservation techniques under different temperature ranges are termed as cryopreservation (-196°C to -80°C), lyopreservation (-20°C to 4°C), and hypo-preservation (ambient temperature) [3]. The cryopreservation technique is a long-term storage technique that employs liquid nitrogen to maintain ultra-low temperatures [2]. The lyopreservation and the hypo-preservation are the short-term storage techniques that make use of refrigeration systems to maintain the required temperatures. Owing to the simpler operation lyopreservation and the hypo-preservation of the biological specimens such as blood serum, plasma, reagent, antibodies, and DNA are the most widely adopted techniques by the medical facilities. Refrigeration systems work continuously to provide the required temperatures to delay the degradation process of the biological specimens. However, several factors limit the performance of refrigeration systems which if not addressed may directly influence the quality of the stored biological specimens. Furthermore, the continuous working of the refrigeration systems consumes a huge amount of energy and results in an excessive amount of carbon emissions [4].

1.2. The Refrigeration Cycle

The refrigeration systems are employed to remove heat from the surroundings. The typical refrigeration system is based on reversed Carnot refrigeration cycle that is a four-stage process and is also known as vapor-compression refrigeration cycle as illustrated in Figure 1.1.

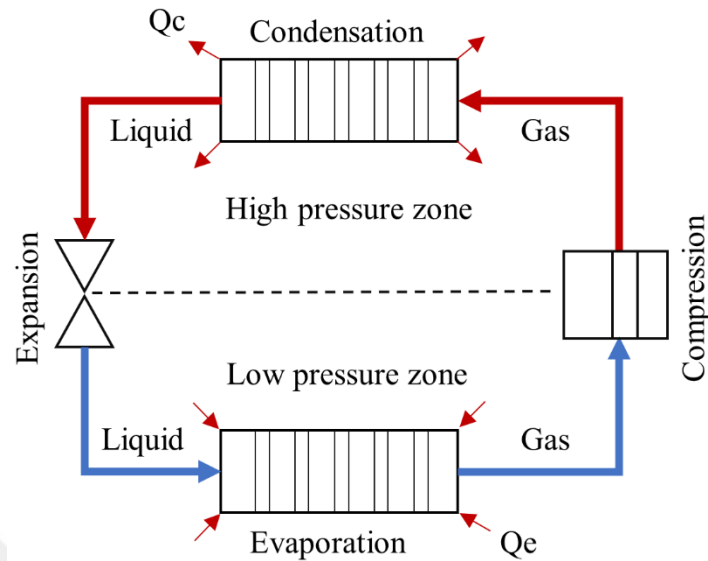


Figure 1.1: The four stages of a reversed Carnot refrigeration cycle

The four stages of the refrigeration cycle are named compression, condensation, expansion, and evaporation [5]. The working fluid is known as the refrigerant and typically in most commercial and domestic refrigeration systems either R-134a or HC-R600a is utilized. There are four main components inside a refrigeration system termed as a compressor, condenser, expansion valve, and evaporator. The compressor and the expansion valve change the pressure and temperature of the refrigerant whereas the condenser and the evaporator are responsible for changing the state of the refrigerant from gas to liquid and vice versa [6]. The refrigeration cycle starts with the compression stage where a compressor is used to compress the refrigerant by doing work. This increases the pressure and temperature of the refrigerant. The refrigerant passes through a condenser to dispose of heat into the circumambience before entering the expansion valve, resulting in a significant decrease in pressure and temperature. The refrigerant at low temperature and pressure is then passed through the evaporator to absorb the heat from the surrounding air. The evaporator is installed inside the refrigerator cabin to absorb the heat and to create cooling. A fan is installed inside the refrigerator cabin to create an air flow around the evaporator for heat transfer through forced convection. The refrigerant after exiting from the evaporator at low temperature and pressure enters the compressor in the gaseous state to complete the cycle and this way the process continues [7].

1.3. Factors Affecting the Performance of Refrigeration Cycle

Typically, the refrigeration cycle based on reversed Carnot cycle is considered as one of the most efficient cycles as compared to other refrigeration cycles [7]. However, the reversed Carnot cycle is prone to several factors that limit its efficiency. The efficiency of the refrigeration systems is measured in terms of the coefficient of performance (COP). The COP is defined as the ratio between the total amount of heat removed from the refrigerator cabin to the total work done by the compressor to remove heat. The COP of the refrigeration systems depends on the following factors [6,8].

1. The operating temperatures of the compressor/evaporator
2. The quality of the equipment used such as compressor, condenser, evaporator, and expansion valve.
3. The refrigerant type.
4. Friction losses in the compressor
5. Compressor leakage/failure
6. Choking of the condenser due to dirt
7. Choking of the evaporator due to frost

The aforementioned factors from 1-6 can be neglected if proper service and maintenance of the components of the refrigerator are carried out periodically. However, the deposition of frost on the surface of the evaporator is considered as one of the major contributors that significantly reduces the coefficient of performance and in some cases, it may even lead to a complete shutdown of the refrigeration systems [9]. Therefore, to maintain the rated performance of the refrigeration systems, removal of the frost from the surface of the evaporator is mandatory [10]. Furthermore, the energy consumption of the refrigeration system can be reduced by triggering the defrost system based on the quantification of frost [11].

1.4. Why defrosting using frost detection is crucial?

Frost growth is a dynamic process that depends on multiple parameters [12]. The deposition of frost on the evaporator of the refrigeration system is extremely detrimental to the refrigeration cycle [9]. Defrosting the evaporator could maintain the performance however, the blind and periodic defrosting operation could affect the coefficient of

performance in a reverse manner [13]. Considering the dynamic nature of frosting, the periodic actuation of defrost system may end up the heating of the refrigerated cabin. The rise in the cabin temperature may directly affect the quality of stored biological specimens. Furthermore, the refrigeration system results in the wastage of excessive amount of energy that is required to maintain the temperature of the refrigerator cabin in the subsequent recovery cycle [14]. Therefore, control of a defrost system should be based on the quantification of frost. The frost can be quantified by interfacing a frost detections sensor along with the defrosting system.

Different types of defrosting and frost detection systems have been proposed in the literature. However, the defrosting systems which are adopted by the commercial refrigeration systems have a high rated power consumption. Furthermore, the frost detection systems in the commercial refrigeration systems are still based on a combination of periodic and temperature sensing. This type of defrosting and frost detection system may perform inefficiently under different operating environments [15].

The depletion of fossil fuels and carbon emissions has recently drawn the attention of humankind towards efficient use of the resources. The regulations have been made to reduce the use of fossil fuels and to improve the energy efficiency of electrical appliances [16]. The European Union has introduced an energy labeling system for electrical appliances[17]. Refrigeration systems are one of the major energy consumers across the globe. The refrigeration systems play a vital role in improving the quality of human life. There are roughly five billion refrigeration, air conditioning, and heat pump systems in operation worldwide. The global electricity demand for refrigeration systems including air conditioning systems is expected to increase more than 200% by the year 2050 [18]. The energy consumption of these systems can be reduced by improving their coefficient of performance which is greatly influenced by the frost deposition on the evaporator. The development of smart frost detection and defrost systems would greatly improve energy conservation and at the same time allows the medical facilities to store the biological specimens for a longer duration.

1.5. Thesis Outline

The research work presented in this thesis is as follows: A detailed literature review on frosting in refrigeration systems, different types of defrosting and frost detection systems and the state of the art is provided in chapter 2. The development of a hybrid frost detection and defrost system, its calibration and validation are presented in chapter 3. The application of the hybrid frost detection and defrost system in the energy conservation of a refrigeration system is presented in chapter 4. The application of a frost feedback-based distributed defrost system for the energy conservation of a refrigeration system is presented in chapter 5. The application of a hybrid system as a smart disinfection control system to contain the spread of SARS-CoVid-19 is presented in chapter 6. In the end, the conclusion is presented to summarize all the research work.

Chapter 2 : LITERATURE REVIEW

2.1. *Frosting on the Evaporator*

The frosting is an inevitable phenomenon known to mankind for ages [19]. Frost is a porous medium made up of frozen water vapors. In winters, when the ambient temperature falls during nighttime, the moisture content present in the atmosphere settles down onto the cold surfaces and form a transparent white thin layer of ice. This thin layer of ice is commonly known as frost. The frosting is a detrimental phenomenon for living as well as non-living things. Frosting disrupts the normal working operation of every system from the aviation industry to wind turbines, the health of plants to degradation of food items, and road safety to depreciating coefficient of performance of the refrigeration systems, the negative effects of frosting are ubiquitous [12,20,21].

In refrigeration systems, frost is considered one of the bottlenecks in improving energy efficiency. Frost deposits on the surface of the evaporator when the water vapors present in the humid environment of the refrigerator cabin interact with the cold surface of the evaporator [22]. The air inside the refrigerator cabin has a high content of water vapors due to moisture migration from the stored products, periodic door openings, and door gasket leakage [23]. The water vapors initially condense on the surface of the evaporator when the surface temperature of the evaporator falls below the dew point of the air. The temperature difference between the dewpoint of air and the surface of a cold body is termed a supercooling degree [14]. The condensed water droplets are later converted into frost when the surface temperature of the evaporator further decreases below the water freezing point. Eventually, the dewpoint falls below 0°C causing the water vapors to de-sublimate [9]. Hayashi et al. [19] classified the frost growth process into three distinct stages named crystal growth period, frost layer growth period, and frost layer full growth period. Shen et al. [24] described the frost growth process in different periods starting with the condensation or solidification period in which droplets collide and become solidified on a cold surface. The next period is termed the crystal tip growth period in which crystal tips start to grow in a perpendicular direction as compared to a cold surface. The crystals grow on top of the solidified water droplets. The next period is described as the frost layer growth period in

which the crystal tips grow enough to fill the gaps between the neighboring crystal tips. After that, the crystals started growing like the branches of trees in all directions and traps the air in between them to form a porous structure, this period is termed as the frost layer full growth period as illustrated in Figure 2.1.

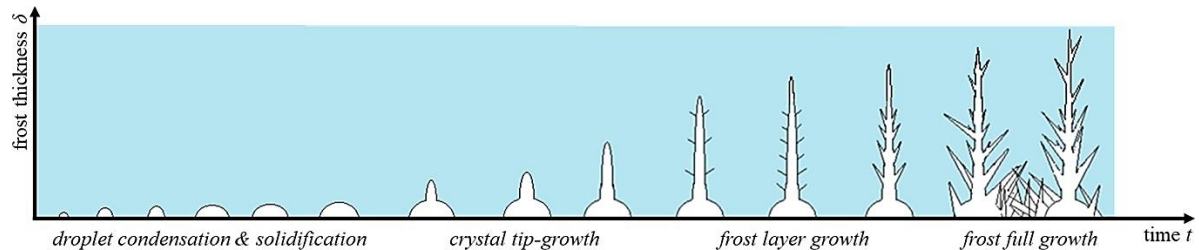


Figure 2.1: The different stages of frost growth [24]

The growth of frost can be related directly to the operation of the compressor, the moisture content inside the refrigerator cabin, the air velocity, and the temperature difference between the evaporator's surface and the air inside the refrigerator cabin [25]. The frost grows in an uncontrolled manner if the suitable conditions for frosting prevail. The growth of frost on the evaporator blocks the passage of air that is responsible for the convective heat transfer inside the refrigerator cabin. Furthermore, the layer of frost on the surface of the evaporator acts as a thermal resistance between the cold surface of the evaporator and the circumambient air inside the refrigerator cabin. Therefore, the coefficient of performance and the rated cooling capacity of the refrigerator falls significantly [12]. Consequently, the compressor keeps on operating until the desired temperature is maintained inside the refrigerator cabin [26]. This would not only affect the quality of the stored biological specimens but also results in excessive energy consumption. It is, therefore, critical to defrost the evaporator to maintain the rated coefficient of performance and the quality of the stored items inside the refrigerator cabin.

It is pertinent to mention here that the initial layer of frost improves the performance of the evaporator by decreasing the contact resistance between the fins and the tube of the evaporator. Furthermore, the surface roughness and the surface area of the evaporator increase due to the frosting which improves the convective heat transfer initially. However, the increase in the thickness of frost leads to either partial or in extreme cases, the complete blockage of airflow which deteriorates the performance of the evaporator in the later stages

of frost formation [12,27]. Therefore, the initial layer of frost is desirable as it slightly improves the performance. Concerted efforts have been made to study the effect of the accumulation of frost on the overall energy consumption of refrigeration systems. Da Silva et al. [9] experimentally recorded a drop of 40% in the cooling capacity after 30 minutes of frosting operation. Brian et al. [28] also reported a 40% reduction in the heat flux because of frost deposition. The cooling capacity of the refrigeration system deteriorates after a critical level of frost deposition [29]. Therefore, to maintain the rated performance of the refrigeration systems and the quality of the stored biological specimens the defrosting of the evaporator before the critical level of frost deposition is of key importance.

2.2. Defrosting of the Evaporator

Defrosting is the process in which the deposited frost on the surface of the evaporator is removed by using different techniques. The defrosting techniques are comprised of either active or passive types [15]. The active type defrosting techniques consumes additional energy to defrost as compared to passive type defrosting techniques that do not require extra energy to operate. The active defrosting techniques are based on chemical, electrical, mechanical, thermoelectric, or thermal actuators that operate on the external energy source to remove the frost. Contrary to this, the passive defrosting techniques rely on surface treatment methods to restrain the frost deposition or in rare cases to partially remove the frost.

2.2.1. Passive Defrosting Techniques

The passive defrosting techniques are mainly comprised of the following surface treatment methods:

- Varying the surface geometry (flat, wavy, louver)
- Surface texturing (grooves, inclined)
- Surface morphology (anti-frosting paint, hydrophobic coating, hydrophilic coating, superhydrophobic coating)

The effect of different surface geometries of the evaporator's fins (flat, wavy, and louvered) under frosting and defrosting conditions on the performance of the air source heat pump is investigated by Huang et al [30]. They concluded that flat fin surfaces had the best

thermal efficiency as compared to wavy and louvered surfaces. They reported an improvement of 9%, 17.1%, and 7.6% in the COP, heating capacity, and energy consumption, respectively. Rahman and Jacobi analyzed the performance of the micro-grooved aluminum and copper surfaces under frosting and defrosting [31]. They concluded that the micro-grooved surfaces reduce the retaining of melted frost on a cold surface by 56% as compared to flat surfaces. However, microgrooves could result in increasing the thickness of the frost layer by 5-25% in multiple frost-defrost cycles. The effect of anti-frosting paint on the heat transfer performance of a surface is investigated by Liu et al [32]. They concluded that the frost formation is delayed by 15 min at least by using an anti-frost paint. They further reported that under a relative humidity of 60% the surface remains frost-free as compared to uncoated copper plate. Seki et al [33] investigated the rate of frost formation on the hydrophilic and hydrophobic surfaces and concluded that the frosting rate is faster on the hydrophilic surface as compared to the hydrophobic surface. Liu et al. experimentally analyzed the performance of superhydrophobic surface having a contact angle of 162° and found that the frost growth rate is delayed by 55 min as compared to plain copper surface. Moallem et al. [34] conducted an experimental investigation to study the effect of frosting on the hydrophilic and hydrophobic surfaces. They summarized that as compared to uncoated surfaces, the coated surfaces have shown better performance in restraining the frost growth and reported an improved heat transfer by 15%. The passive defrosting techniques have been researched extensively for different applications however, owing to their complexity of retrofitting, high installation cost and the limitations of completely removing the frost from the surface of the evaporator makes them an infeasible option for the commercial refrigeration systems.

2.2.2. Active Defrosting Techniques

The active type defrosting techniques are mainly comprised of an actuator that consumes energy to remove the deposited frost. The different types of active defrosting techniques proposed in the literature are as follows:

- Electro-hydrodynamics type
- Ultrasonic vibrations and oscillations

- On-Off type defrosting
- Reverse cycle defrosting
- Electric heater defrosting

The electrohydrodynamic-based active defrosting technique employs a high voltage electric field to restrain the growth of frost. The control of frost using the electrohydrodynamic technique was first discovered by Schaefer [35]. He observed a direct impact on the growth of frost when a high voltage electric field is applied. Marshal and Gunn [35] experimentally investigated the effect of electric fields on frost growth. They concluded that frost grows in a disordered form in the presence of a weak electric field. Molki et al. [36] applied an intermittent electric field at a higher frequency to investigate frost growth. They showed that the intermittent application of electric field performed well in restraining the growth of frost for 1 h operation. Munakata et al. [37] applied a high voltage electric field of 7.5kV and reported an appreciable reduction of 30% in the frost deposition. Tudor et al. [38] shown experimentally that the AC electric field was more effective in attenuating the frost growth in comparison with DC electric field. They have further shown that with the application of an AC electric field the frost accumulation was decreased by 46% at the supplied voltage of 14.5kV. The polarity of voltage also impacts the frost growth, as the negative voltage polarity resulted in a thinner frost layer as compared to the positive polarity as illustrated in Figure 2.2. The thickness of frost is reduced by 20% in the presence of a -15kV electric field whereas a 14% reduction in the frost thickness was observed in the presence of a +15kV electric field.

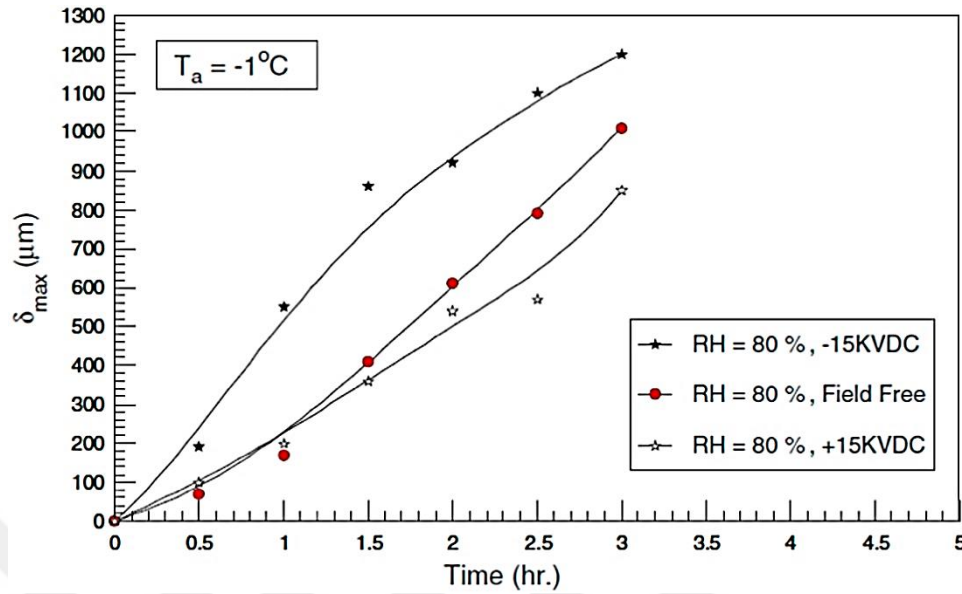


Figure 2.2: The variation in the thickness of frost with respect to time under the influence of changing electric polarity [39]

The application of the electrohydrodynamic technique in restraining the growth of frost has proved to be useful in research facilities. However, for practical real-life applications such as refrigeration systems, the electrohydrodynamic-based defrosting technique is not considered a feasible technique.

The use of vibrations to suppress the growth of frost is an ultrasonic vibration-based active defrosting defrost technique. Several researchers have investigated the application of vibrations at different amplitudes and frequencies to attenuate frost growth. Cheng and Shiu [39] studied the effects of oscillation at a low range of varying amplitudes and frequencies and reported that the frosting pattern alters significantly in the presence of low-frequency mechanical vibrations. Wu and Webb [40] also investigated the effects of low-frequency vibrations on frost growth and their results were relating to the results of Cheng and Shiu [39]. It was further investigated that the low-frequency vibrations are not able to remove the frost from the hydrophobic surface. Adachi et al. [41] reported a drop of 60% in the frosting by applying a high frequency (37 kHz) ultrasonic vibration. Wang et al. [42] investigated the effect of high frequency (28.2 kHz) ultrasonic vibrations in combination with the hydrophilic coating applied on the tube and fin-type evaporator. They showed that 2/3 of the fin gaps were unblocked after 92 min exposure to the high-frequency ultrasonic

vibrations. The influence of ultrasonic vibrations on the frost is illustrated in Figure 2.3 (a) and the comparison between the growth of frost in the absence and presence of ultrasonic vibrations is illustrated in Figure 2.3 (b).

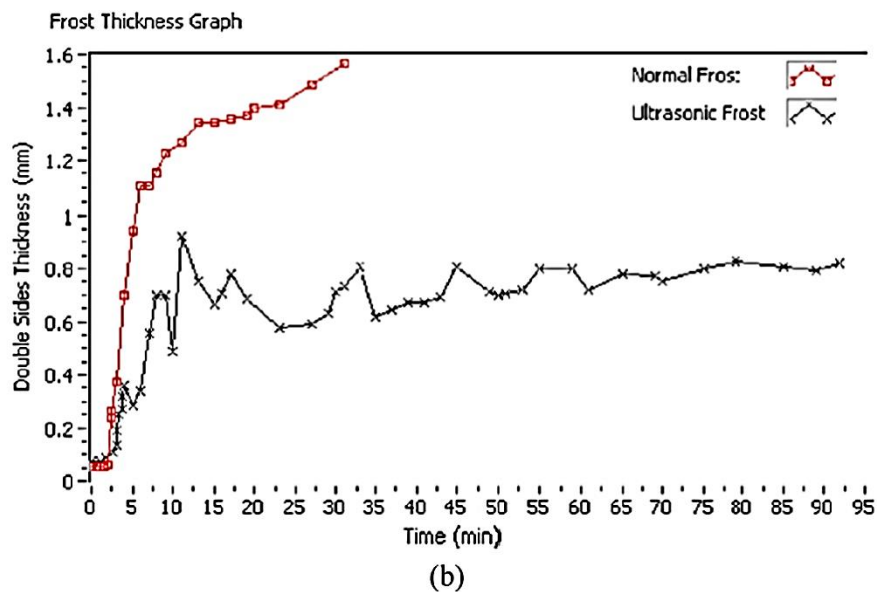
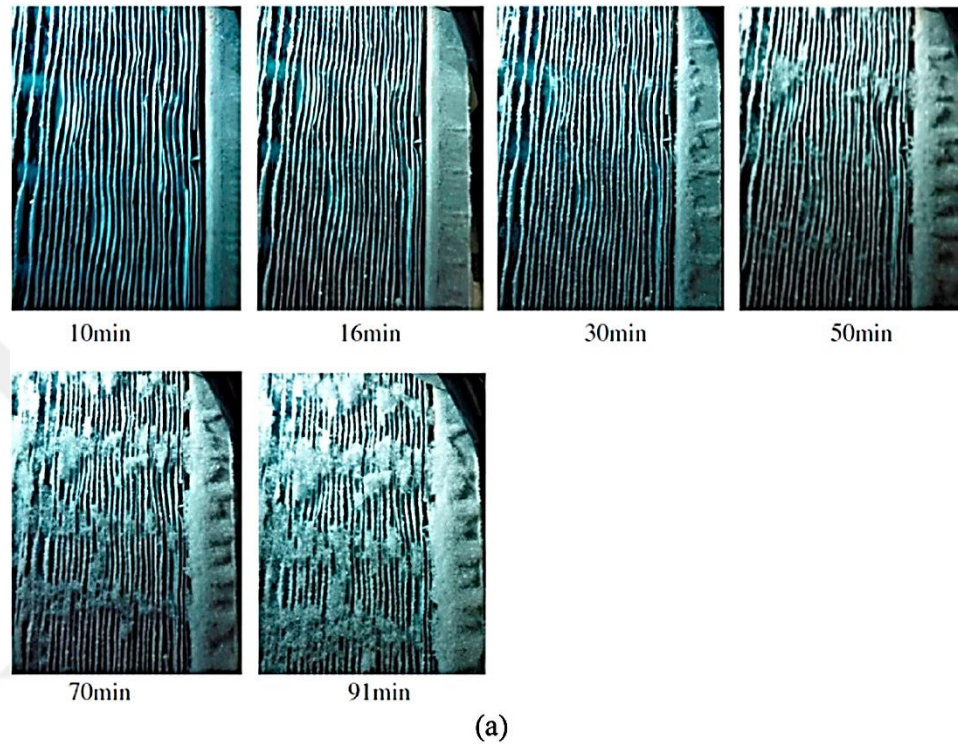


Figure 2.3: (a) The influence of ultrasonic vibrations on frost layer thickness. (b) the comparison between the growth of frost in the absence and presence of ultrasonic vibrations [43]

The difference in the frost growth in the presence and absence of ultrasonic vibrations is explicitly visible in Figure 2.3 (b). Tan et al. [43] studied the effect of intermittent ultrasonic vibrations at a high frequency on the frost deposition at the fin-tube evaporator. They not only observed a change in the height of frost crystals but also noted that under the influence of ultrasonic vibrations the frost crystals were prone to collapse. The active type defrosting-based ultrasonic vibrations are proved to be an efficient alternative to the electrohydrodynamic-based defrosting technique. However, the research work carried out in this field is still naïve and needs further elaboration, especially regarding the real-life application. The high energy expenditure to generate ultrasonic vibrations is one of the bottlenecks in the adaptation of this defrost technique in commercial refrigeration systems [15].

Commercial refrigeration systems need a type of defrosting technique that has low cost, ease of retrofitting, and simpler operation. Therefore, in actual refrigeration systems, defrosting is achieved by using either an on-off type defrosting, a reverse cycle defrosting, or an electric heater-based defrosting. The on-off type of defrosting, as the name implies works on the principle of turning the compressor off for a pre-determined duration of time until all the accumulated frost melts away. The compressor will return to its normal working condition after defrosting. The on-off type of defrosting technique can be found in old refrigeration systems. The main advantage of the on-off type of defrosting technique is the ease of operation and the low cost.

In reverse cycle defrosting the refrigeration cycle is reversed with the help of a solenoid bypass valve to direct the superheated refrigerant from the compressor towards the evaporator. This type of defrosting technique is complex and expensive; however, the defrosting efficiency is significantly higher which makes this method is the most widely accepted defrost technique in large-scale refrigeration systems such as air source heat pumps. Defrosting using the reverse refrigeration cycle has been investigated vastly. For example, Hoffenbecker et al. [44] shown experimentally that the application of the reverse cycle defrosting technique reduced the defrosting time by 5.7%, and the COP was improved by 8.5%. Byun et al. [44] injected the liquid refrigerant and the hot gas manually from the suction side of the compressor to investigate reverse cycle defrosting. The results of the

Byun et al. were in line with the results of the Hoffenbecker et al. [44], as they have also reported an improvement of 5.7% and 8.5% in the heating capacity and the COP respectively. Dopazo et al. [45] shown that the time needed to defrost was 842 s as compared to the on-off type defrost control that approximately takes around 20 min to completely defrost the evaporator. The images of the evaporator during reverse cycle defrosting are shown in Figure 2.4.

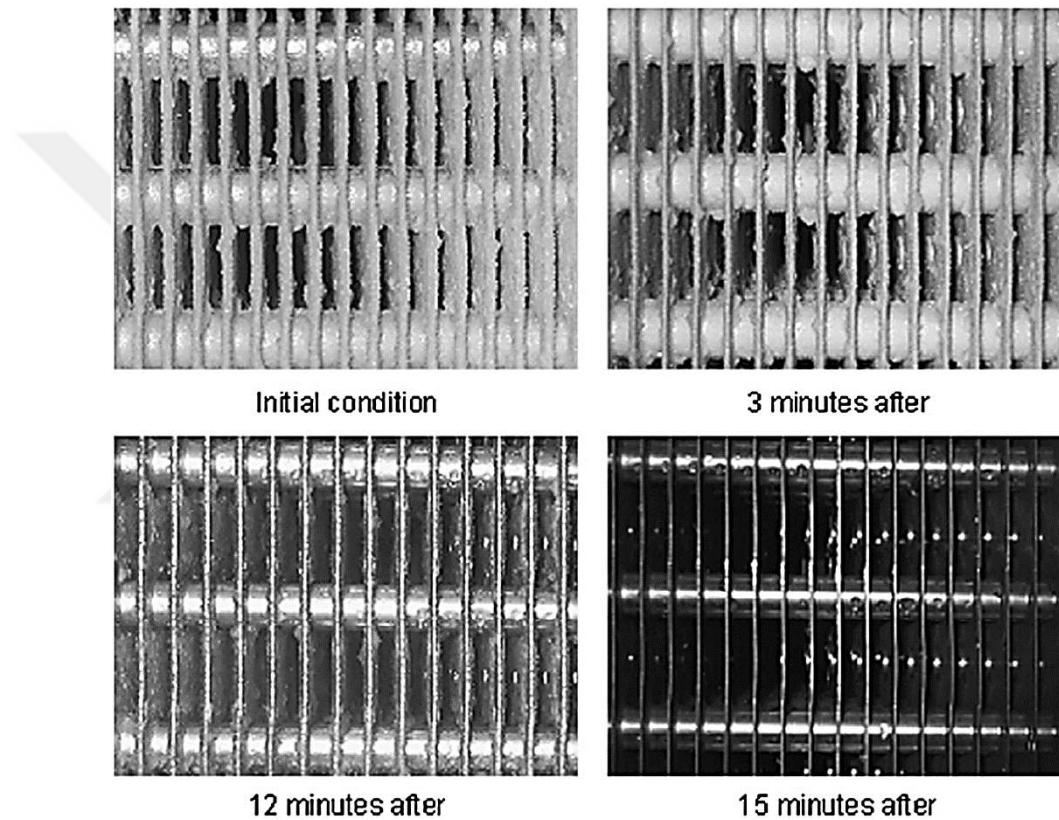


Figure 2.4: The images of the evaporator showing the different stages of the reverse cycle defrosting [46]

Briley [46] proposed a methodology to optimize the reverse cycle defrosting technique by combining the hot gas with other methods such as electricity, water, and air to achieve maximum cooling performance. Cho et al. [47] investigated the performance of the reverse cycle defrosting technique and compared it with the on-off type defrosting for a showcase system that was comprised of multiple evaporators. They reported 75% opening of the expansion valve as an optimum operation during the reverse cycle as compared to on-off defrosting. Furthermore, the defrosting time was reduced significantly as illustrated in Figure 2.5 (a). The reduction in defrosting time leads to a stable storage temperature as

compared to the on-off cycle as shown in Figure 2.5 (b).

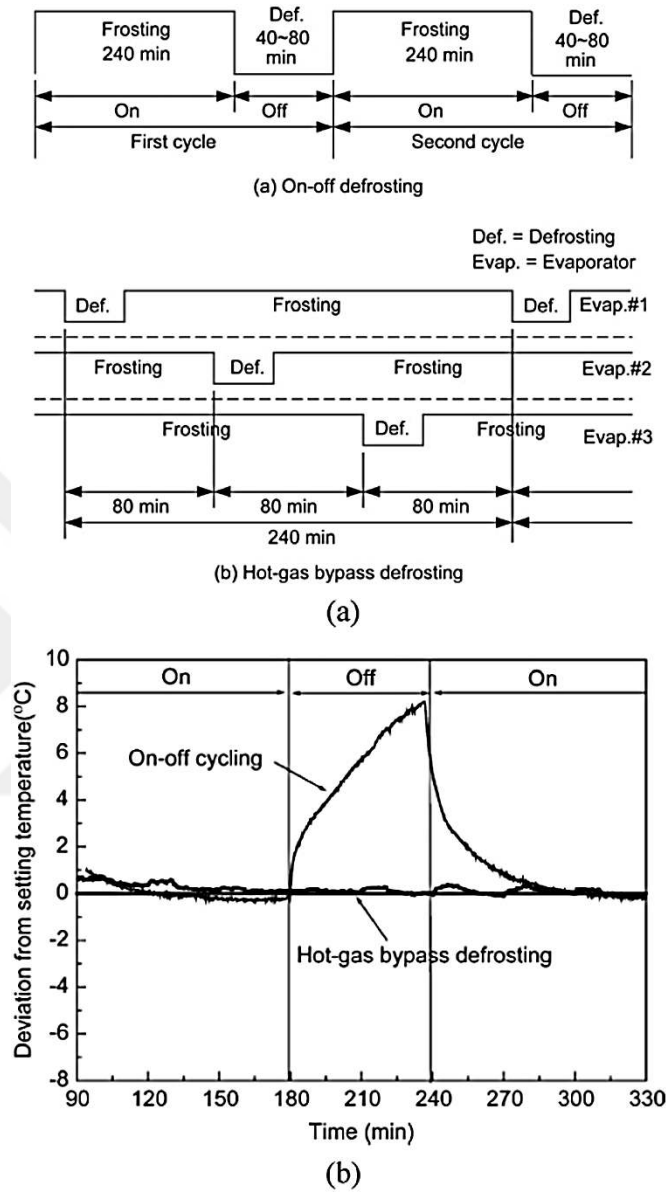


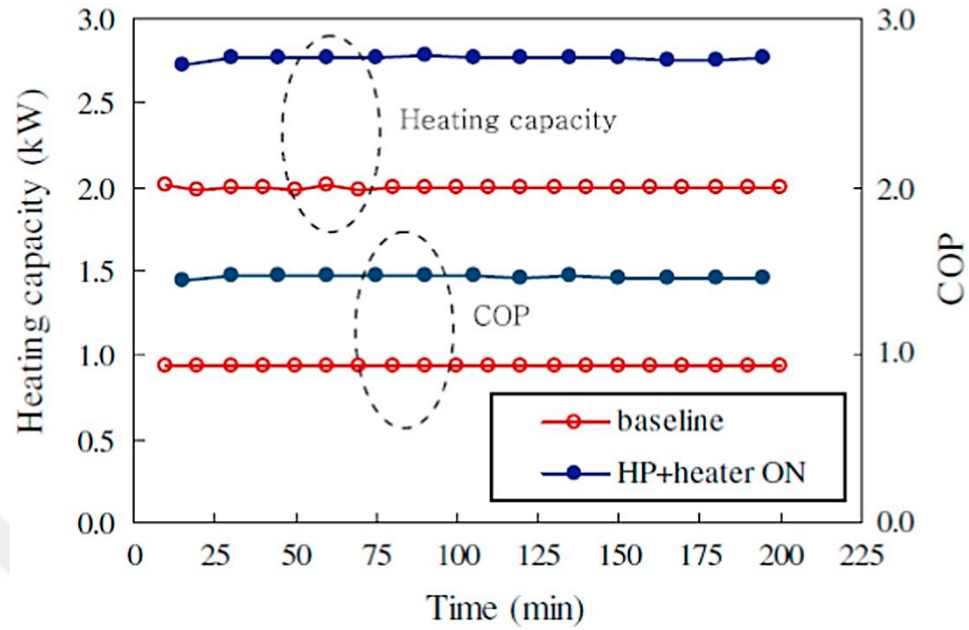
Figure 2.5: (a) The comparison between the reverse cycle defrosting and the on-off defrosting technique. (b) The comparison in terms of storage temperatures for both defrosting techniques. [48]

In the electric heater-based active defrosting an electric heater is installed either along with the tubing of the evaporator or placed at the bottom of the evaporator. However, most of the heat generated by the electric heater is lost to the surrounding air and only a small fraction of heat is spent on defrosting. Bansal et al. [48] shown experimentally that only 30.3% of the heat generated by the electric heater is utilized for defrosting while the rest is utilized to raise the temperature of the air inside the refrigerator cabin. Zhao et al.

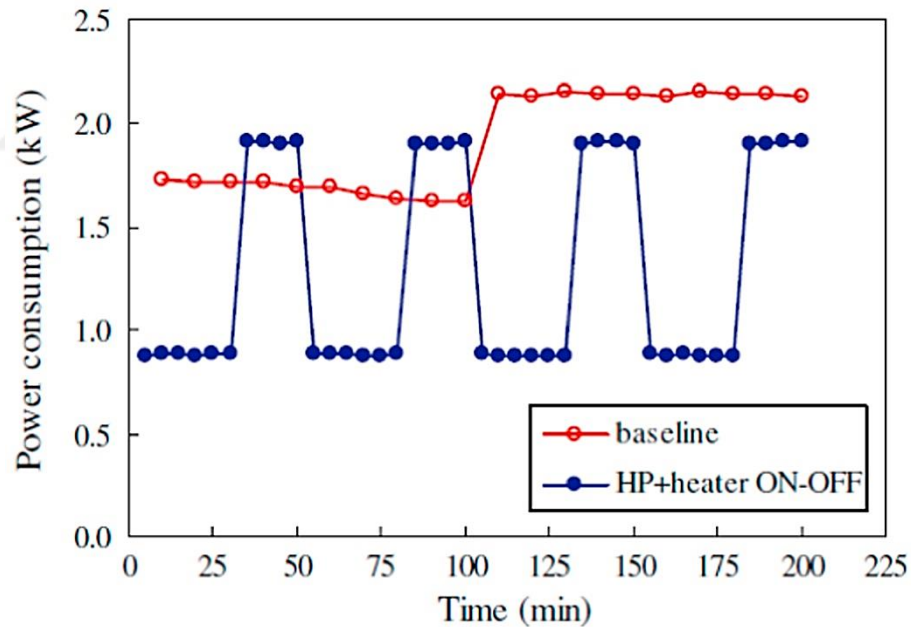
[49] performed defrosting using the EHD system in a refrigerator and found the 12.6°C rise in the cabin temperature.

The rise in the temperature of the cabin during defrosting leads to the increase in the energy consumed by the compressor of the refrigerator in the subsequent refrigeration cycle, the so-called recovery cycle. The overall defrost energy is defined as the sum of the energy spent by the heater in the defrost cycle and the energy spent by the compressor in the recovery cycle. Therefore, both these energy expenses must be taken into consideration for the minimization of the overall defrost energy.

Kwak and bai [50] experimentally investigated the performance of the electric heater in defrosting the outdoor evaporator of a heat pump. They concluded that electric heater-based defrosting is an economic and efficient alternative to the reverse cycle defrosting technique. They further reported an improvement of 38% in the heating capacity and 57% in the COP of the heat pump as illustrated in Figure 2.6 (a). The outdoor placement of the electric heater offered a reduction of 11.7% in the power consumption when the ambient temperature was around 2°C as depicted in Figure 2.6 (b).



(a)



(b)

Figure 2.6: (a) The coefficient of performance (COP) and the heating capacity with respect to time. (b). The power consumption of heat pump and defrost electric heater with respect to time of a heat pump. [51]

The ease of retrofitting, fast defrosting, and efficient operation make the electric heater-type defrosting technique a strong contender to the rest of the defrosting techniques. Commercially available low-capacity refrigeration systems are mostly equipped with an

electric heater to defrost the evaporator at periodic intervals. However, the electric heater type defrosting system consumes a significant amount of power during its operation which is considered as a tradeoff between energy cost and the installation cost.

2.3. Defrost Control Strategies

The consumption of extra energy by the active type defrosting techniques adversely affects the performance of refrigeration systems. Therefore, different types of defrost control strategies have been designed and implemented to minimize energy consumption. These control strategies include periodically initiated and periodically terminated defrosting, periodically initiated and temperature terminated defrosting, temperature, humidity, and time-dependent defrosting, and periodically initiated and pressure difference terminated defrosting [51–53]. The inefficiency of the periodic defrost control strategies has been reported in several experimental studies in the literature [15]. A defrost control strategy based on direct detection of frost, the so-called demand defrosts can significantly improve the energy conservation of the refrigeration systems [54]. The demand defrost technique has been investigated vastly for heat pumps using different types of frost detection methods and active type defrosting techniques [55]. However, the literature on the application of demand defrost on domestic refrigerators is scarce. The examples of the application of the demand defrost technique on different refrigeration systems from the literature are summarized in Table 2-1.

Table 2-1: Examples of the demand defrost technique from the literature.

Reference	System	Method	Defrosting system	Defrost demand
[56]	ASHP	Photoelectric sensing (detection at discrete points)	Reverse cycle bypass	Saturation of the sensors.
[57]	ASHP	Temperature-humidity-time based	Reverse cycle bypass	Time-based threshold.
[13]	ASHP	Photoelectric sensing (detection at discrete points)	Reverse cycle bypass	Saturation of the sensors.
[58]	ASHP	Photoelectric sensing (detection at discrete points)	Reverse cycle bypass	Saturation of the sensors.
[59]	ASHP	Photoelectric sensing (detection at discrete points)	Reverse cycle bypass	Saturation of the sensors.
[60]	ASHP	The superheating degree of refrigerant is detected by temperature and pressure sensing	Reverse cycle bypass	Decrease in the superheating degree of refrigerant
[61]	ASHP	Controlled deposition of frost	Reverse cycle bypass	Time-based threshold.
[62]	ASHP	Tube encircled photoelectric sensors (detection at discrete points)	Reverse cycle bypass	Saturation of the sensors.
[63]	ASHP	Controlled deposition of frost	Reverse cycle bypass	Time-based threshold.
[64]	Display freezer cabinet	Refrigerant flow instability detection by monitoring the operation of the thermostatic expansion valve (TEV)	Electric heater	Refrigerant flow instability

Byun et al. [56] implemented the demand defrost technique in ASHP using photoelectric sensors, without quantifying the thickness of frost and reported an improvement of 5.5% in the heating capacity. Zhu et al. [57] proposed a novel temperature-humidity-time (T-H-T) based criterion to implement the demand defrost technique in ASHP

and shown an improvement in the average COP by 4.6% to 5.3% under different environmental conditions. Ge et al. [13] utilized tube encircled photoelectric sensors and reverse cycle defrosting to implement the demand defrost technique in ASHP without quantifying the thickness of frost and shown the improvement in the performance coefficient by 10.9%. Wang et al. [58] employed the demand defrost technique using photoelectric sensors and reported an improvement of 5% in the performance coefficient and 6% in the heating capacity of an ASHP. Song et al. [61] experimentally analyzed the defrosting performance of the ASHP at different frost accumulations without using any frost detection sensors and reported a peak defrosting efficiency of 46.05% while removing the 930 g of frost accumulation. Lawrence and Evans [64] proposed the implementation of demand defrost in freezer cabinets using refrigerant flow instability sensing and reported a reduction in the number of defrost cycles.

However, neither of these studies presents a demand defrost system, that relies on the real-time quantification of the thickness of frost, as the triggering criterion for defrosting. The defrost threshold must be based on the real-time thickness of frost to capitalize on the improvement in performance, offered by the early stage of frosting [12,65]. Premature defrosting may also lead to frequent defrost cycles which in turn will increase energy consumption [14]. On the other hand, belated defrosting allows the clogging of the evaporator that not only deteriorates the performance but also increases the energy required for defrosting. The real-time thickness of frost-based demand defrost has not been studied previously and therefore, its application for the energy conservation of refrigeration systems must be investigated.

Low-capacity refrigerators have the biggest share in the total refrigeration systems in operation worldwide, contributing roughly 25% whereas air source heat pumps contribute only 2% [18]. The adaptation of the new energy labeling system by the European Union from 2021 enforces the manufacturers to improve the energy consumption of their existing [16]. The low-capacity refrigerators currently being sold still employ the inefficient periodically initiated and temperature terminated defrost control strategy using a conventional 20 W – 50 W heater in the fresh food cabin and a 150 W – 200 W heater in the freezer cabin. The temperature, humidity, time-dependent defrost control strategies have

been investigated in previous studies [66]. However, defrosting the evaporator based on the conditions of the cabin such as the humidity and the temperature may lead to the erroneous triggering of defrosting and therefore, may result in excessive energy consumption.

Various challenges hinder the successful application of the demand defrost technique in low-capacity refrigerators. The conventional defrost heater of the refrigerator is not suitable for the application of the demand defrost technique as it causes a significant rise in the cabin temperature. Therefore, the refrigerator must spend extra energy to achieve the target temperature in addition to the energy spent on defrosting. The successful application of the demand defrost technique requires low-power heaters that can defrost the evaporator while minimizing the rise in the cabin temperature. The detection and quantification of frost on the evaporator's surface is another challenge due to the high humidity inside the refrigerator cabin.

2.4. Frost Detection System

Several frost detection strategies have been reported in the literature that can be categorized into either direct or indirect detection methods [67]. The direct detection method detects a change in a physical quantity such as inductance, impedance, capacitance, thermal or electrical conductivity, and reflective properties, due to the formation of frost. The indirect methods estimate the frost accretion by using deterministic or empirical models. Table 2-2 shows examples of different frost detection methods from the literature.

Table 2-2: Examples of frost detection and defrost control methods from the literature.

Reference	Detection type	Sensing technique
[68]	Direct	Photoelectric sensing
[58]	Direct	Photoelectric sensing
[24]	Direct	Capacitance sensing
[20]	Direct	Capacitance sensing
[69]	Direct	Resistive sensor
[70]	Direct	Fiber-optic sensor
[71]	Direct	Laser displacement gauge sensor
[72]	Direct	Piezoelectric sensor
[73]	Direct	Ultrasonic based sensor

[74]	Indirect	Empirical model
[75]	Indirect	Empirical model
[14]	Indirect	Optimal defrost control cycle
[11]	Indirect	Optimal defrost control cycle

The direct estimation of the frost-based defrost control strategy relies on a frost detection sensor to monitor the frost deposition. The sensor detects a change in the physical quantity such as inductance, impedance, capacitance, thermal or electrical conductivity, and reflective properties, due to the formation of frost [67]. A sensor developed for frost detection in refrigeration systems has cost as a decisive factor. Therefore, any prototype to be developed must be inexpensive and has reasonable accuracy and reliability. Additionally, size and complexity also play a significant role in the frost detection sensor to be implemented in refrigeration systems. There are different types of frost detection sensors proposed in the literature which include photoelectric, capacitive, resistive, ultrasound, fiber optic, piezoelectric, laser displacement, piezoresistive, and resonance type [67].

Photoelectric-based frost detection, which works on the principle of reflection of light from a target surface, is an inexpensive technique, has shown promising results in terms of accuracy. However, it can be used effectively only for frost detection at discrete points [58]. On the other hand, capacitive type frost sensors are practical for monitoring frost growth on a complete surface [20,76]. Resistive sensing methods are reliable for the detection of frost but fail in quantifying the thickness of the frost layer [69]. Fiber-optic-based frost detection has shown good agreement in terms of accuracy and reliability, but it fails to achieve economic convenience [77]. Detection of frost using a laser displacement gauge sensor is another complex and expensive method that has been investigated in refrigeration systems. Additionally, voids between the frost layer result in an ineffective laser reflection and consequently fails the measurements [71]. Piezoelectric sensor-based frost detection is proved to be an accurate approach, but it can be used effectively for frost detection at specific points [72]. Ultrasonic-based ice sensors have been implemented successfully in aircraft and wind turbines, but the high cost and complex installation procedures limit the application of such sensors in refrigeration systems [73]. Considering

the size, complexity, accuracy, reliability, and power consumption of different frost detection techniques mentioned in the literature, the capacitive sensing technique seems suitable for the application in refrigeration systems.

The capacitive sensing technique works on the change in capacitance between two oppositely charged electrodes, based on the relative permittivity of the materials between these electrodes. The relative permittivity of frost is 3 times greater than that of the air; therefore, the capacitive sensors can detect the change in capacitance as frost starts to appear on the evaporator [78]. However, the presence of water on the surface of the evaporator at the initiation of frost and during defrosting causes erroneous results as the relative permittivity of water is 25 times higher than that of frost [79]. The high relative permittivity of water causes the capacitance to drastically change with even a small amount of water [20] causing erroneous measurements.

The electrodes used in the capacitive sensing technique are electrically conductive structures that can be converted into resistive heaters for defrosting if their resistance can be controlled. This conversion can be achieved by conducting electricity through either one or both electrodes by bypassing the sensing circuit. Therefore, a hybrid system that can detect frost as well as defrost can be developed using a capacitive sensing technique as its core. However, such a hybrid system is unable to detect frost while working in defrosting mode, as the sensing circuit is bypassed. Hence, the defrosting will remain time terminated. This can be addressed by the addition of a secondary sensor at discrete points of the evaporator to provide feedback on the complete melting of frost in the defrosting mode. Photoelectric-based frost detection sensors are the most suited for the detection of frost as they are insensitive to the presence of water on the target surface [56]. The incorporation of a secondary sensor will also increase the reliability of the sensing system as demonstrated by [80,81]. Unconventional manufacturing techniques can facilitate the development of electrodes that can be converted to heating elements for the application in hybrid frost detection and defrosting system [82].

Additive manufacturing (AM) technology can produce geometries that are impossible to manufacture using conventional manufacturing techniques. With the progress in AM, new materials are being developed for various functional properties such as electrical, chemical,

and optical. Selectivity between various functional properties within one AM build can be achieved using the multi-material additive manufacturing (MAM) technique. With the selectivity between electrically conductive and insulating regions, electrically functional parts such as resistors, electrodes, and capacitive sensors can be manufactured [83].

2.5. *Uneven Frost Distribution*

The uneven distribution of frost on the surface of the evaporator is a typical phenomenon found in refrigeration systems that attenuates the efficiency of the defrosting system. Knabben et al. [22] studied the frosting and defrosting processes on the evaporator of a domestic refrigerator and reported that frost accumulates mostly on the top central rows due to higher humidity gradient and tends to decrease down the length of the evaporator. Therefore, the top portion of the evaporator needs more heat as compared to the bottom one. The desynchronization between the defrost heat and the frost distribution leads to waste of energy during defrost cycle, and the rise in the temperature of the refrigerator cabin, as reported in several studies [84,85].

The use of multiple heaters has been proposed in the literature to reduce the rise in the temperature of the refrigerator cabin during defrosting due to the uneven distribution of the frost. Zhao et al. [86] reported a decline of 1.1°C rise in the temperature of the refrigerator cabin with a reduction of 3.3 minutes in defrost duration using two defrost heaters. However, the study relied on the temperature-based defrosting termination criterion. The energy efficiency of a multiple heater system could be further improved by the integration of a frost feedback system.

The feedback on the status of frost on the evaporator can be obtained using different types of frost detection sensors as described in section 2.4. Furthermore, the energy spent on defrosting can be reduced by replacing the high-powered electric heater in the electric heater-based defrost system with an additively manufactured low-powered electric heater as reported by [82]. Therefore, there is a potential for improvement in the defrosting performance and energy conservation by discretizing the evaporator into regions and using distributed defrost heaters controlled individually with a frost feedback sensor for each region.

2.6. *Summary*

In summary, frosting is the most detrimental phenomenon to the efficiency of refrigeration systems. Frost accumulates on the evaporator of a typical refrigeration system. During the early stages of frost formation, the coefficient of performance of the refrigeration systems increases. However, as the frost layer gets thicker, it starts to block the evaporator which results in the disruption of the airflow required for the convective heat transfer. Furthermore, the thick layer of frost acts as a thermal resistance between the cold surface of the evaporator and the surrounding air. Consequently, the working duration of the compressor increases which results in excessive energy consumption. To address this problem, several types of defrosting systems have been proposed in the literature which is comprised of either active or passive type methods. The passive type defrosting methods are comprised of surface treatment techniques to restrain or partially remove the frosting. Contrary to this the active type defrost methods consume additional power for defrosting. The passive defrost systems are not adopted by refrigeration system manufacturers due to their complex installation, high cost, and complexity of retrofitting. The active type defrosting techniques are widely employed in commercial and medical-grade refrigeration systems. Electric heater-based active type defrosting technique is prominent in low-capacity refrigeration systems owing to its low installing cost, ease of retrofitting, and simpler operation. However, the high energy consumption by the electric heater-based defrosting system bottlenecks the overall efficiency of the refrigeration systems.

Therefore, different types of defrost control strategies have been proposed in the literature to control the defrosting systems such that they consume minimum energy while maintaining performance. The demand-actuated defrosting approach based on frost detection sensing is the most efficient defrost control strategy, as it relies on triggering the defrosting system based on a response from a frost detection sensor. The implementation of a frost detection sensor along with the demand-actuated defrost control strategy significantly improve the defrosting efficiency. There are different types of frost detection sensors reported in the literature. However, the photoelectric, piezoelectric, and capacitive types of frost detection sensors have shown the capability to perform well with refrigeration systems. Furthermore, the advent of additive manufacturing technology and the

development of functional materials enabled the customized manufacturing of hybrid systems. These hybrid systems can be utilized as capacitive sensors as well as low-powered defrost heaters.

Frost deposition on the evaporator of a refrigeration system is a completely dynamic process. The frost grows unevenly on the evaporator, consequently, the defrosting systems have shown desynchronization during defrosting. The defrost desynchronization significantly affects the defrosting process. Traditionally, a single defrost electric heater is employed on the evaporator for defrosting, however, the uneven distribution of frost leads to early melting of frost on some regions of the evaporator as compared to others. Therefore, a defrosting system based on distributed defrost heaters controlled through a frost feedback sensor can address this issue.

Chapter 3 : DEVELOPMENT OF A HYBRID FROST DETECTION AND DEFROST SYSTEM

3.1. Overview

The frosting is a phenomenon most detrimental to the efficiency of refrigeration systems. The accumulation of frost blocks the airflow, deteriorating the cooling capacity and the coefficient of performance. The commercially available refrigeration systems use a blind and periodic defrosting cycle without any quantification of frost, which leads to lower efficiencies. Considering the new and tougher energy regulations in refrigerators, nowadays increasing the efficiencies of the refrigerators becomes more critical. In this chapter, a hybrid frost detection – defrosting system (HFDDS) is proposed that comprises a novel photo-capacitive sensing technique and a dual-purpose additively manufacturable sensor and defrosting heater. The HFDDS can detect the formation of frost, measures the thickness of frost from 1.3 to 8 mm with a 5% margin of error, and triggers a defrosting response once a critical frost thickness is attained. The HFDDS is targeted to provide defrosting on-demand instead of the inefficient blind and periodic defrosting cycles.

3.2. Development of hybrid frost detection and defrosting system

3.2.1. Photoelectric sensing module

The photoelectric sensing module (PSM) is comprised of an infrared (IR) transmitter and an IR receiver as shown in Figure 3.1 (a). The transmitter emits IR light beams when powered with a constant voltage supply V_{ss} . The transmitted IR light is reflected off the evaporator surface and falls upon the IR receiver. In the absence of frost, the intensity of IR light arriving at the receiver will be weakened because of the large gap between the transmitter/receiver and the surface of the evaporator. The current I_o will be maintained at the low value while the output voltage V_{out} remains at the maximum value. As the thickness of the frost layer increases, the distance between the IR transmitter and the evaporator surface decreases, which results in an increased intensity of reflected IR light. This increase minimizes the internal resistance between the collector and the emitter junction of the IR receiver. Therefore, the amount of current I_{out} increases and the V_{out} decreases gradually till the saturation point occurs and the frost accumulation fills the gap between the IR transmitter

and the evaporator surface as shown in Figure 3.1 (a). The output voltage is calculated from the receiver current I_{out} using Kirchhoff's voltage law (KVL) with the following Equation (3.1).

$$V_{out} = V_{ss} - I_{out}R_{out} \quad (3.1)$$

where, V_{ss} is the regulated supply voltage of the receiver circuit and R_{out} is the collector resistance. The gradual decrease in the PSM voltage signal V_{out} , during the transition between no-frost to frost, was used to determine the starting point of the frost accumulation. The decreasing output voltage response of the PSM is shown in Figure 3.1 (b). The PSM module is embedded inside an additively manufactured housing. The position of the IR transmitter, IR receiver, and the circuit board inside the PSM housing is shown in the computer-aided model (CAD) of the PSM illustrated in Figure 3.2.

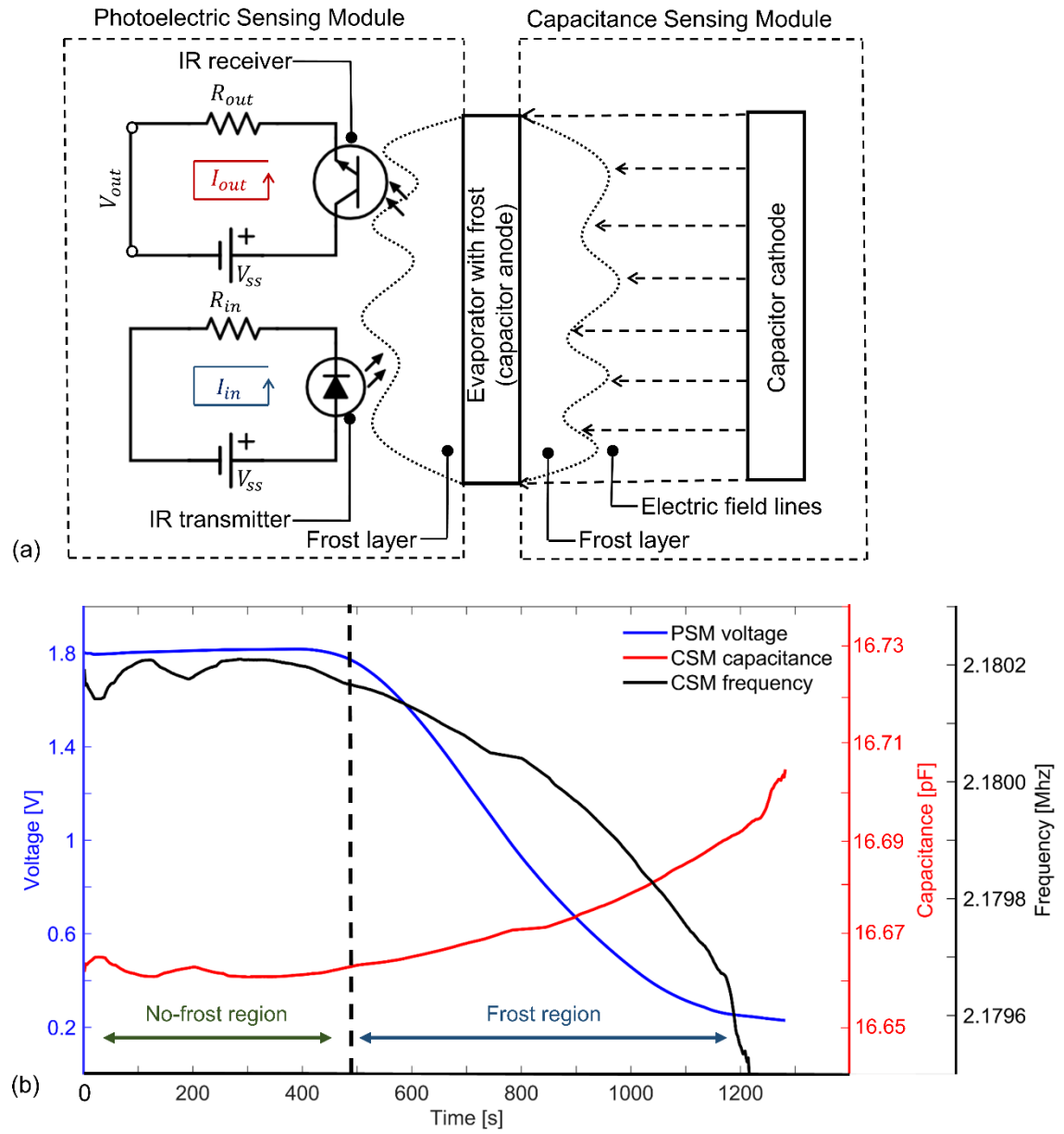


Figure 3.1: (a) Schematics of the photoelectric and the capacitive based frost sensing, and (b) responses of the photoelectric (PSM) and capacitive sensing module (CSM) in the presence of frost on the evaporator surface.

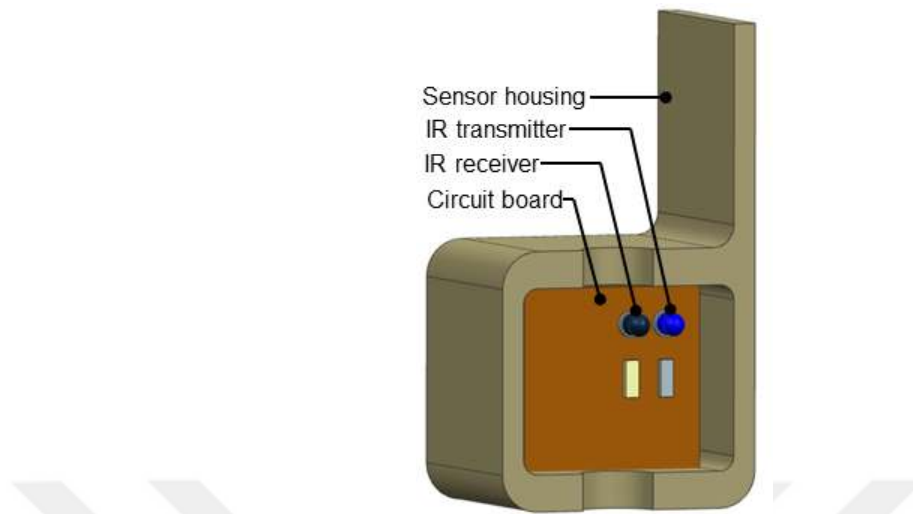


Figure 3.2: The CAD model of the photoelectric sensing module (PSM).

3.2.2. Capacitive sensing module

The capacitive sensing module (CSM) works on the principle of change in capacitance between two parallel and oppositely charged electrodes. The evaporator body was used as the capacitor anode while an additively manufactured electrode was used as the cathode of the CSM. When the alternating voltage is applied among parallel placed cathode and the anode, an electric charge begins to store in between both electrodes in the form of an electric field as illustrated in Figure 3.1 (a).

The cathode was manufactured using robotic MAM by combining the fused filament fabrication (FFF) head and direct ink writing (DIW) head mounted on a Mitsubishi Electric robot. The FFF head was used to deposit PLA which is an insulating thermoplastic that yields insulating regions inside the build. The DIW head was used to deposit an ePMC ink having an electrical conductivity of 128 S.m^{-1} . The development of ePMC ink was reported in our previous work [82]. The combination of FFF and DIW heads yields selectivity between electrically conductive and insulating regions within one build. Exploiting this selectivity, the outer insulating shell of the cathode was manufactured using PLA and the inner electrically conducting region ($140 \times 20 \times 5 \text{ mm}^3$) was made using ePMC ink. The manufactured electrode was left to dry overnight at ambient conditions. The electrical resistance of the additively manufactured cathode was 12Ω . Figure 3.3, illustrates the MAM of the capacitive electrode using a conductive material.

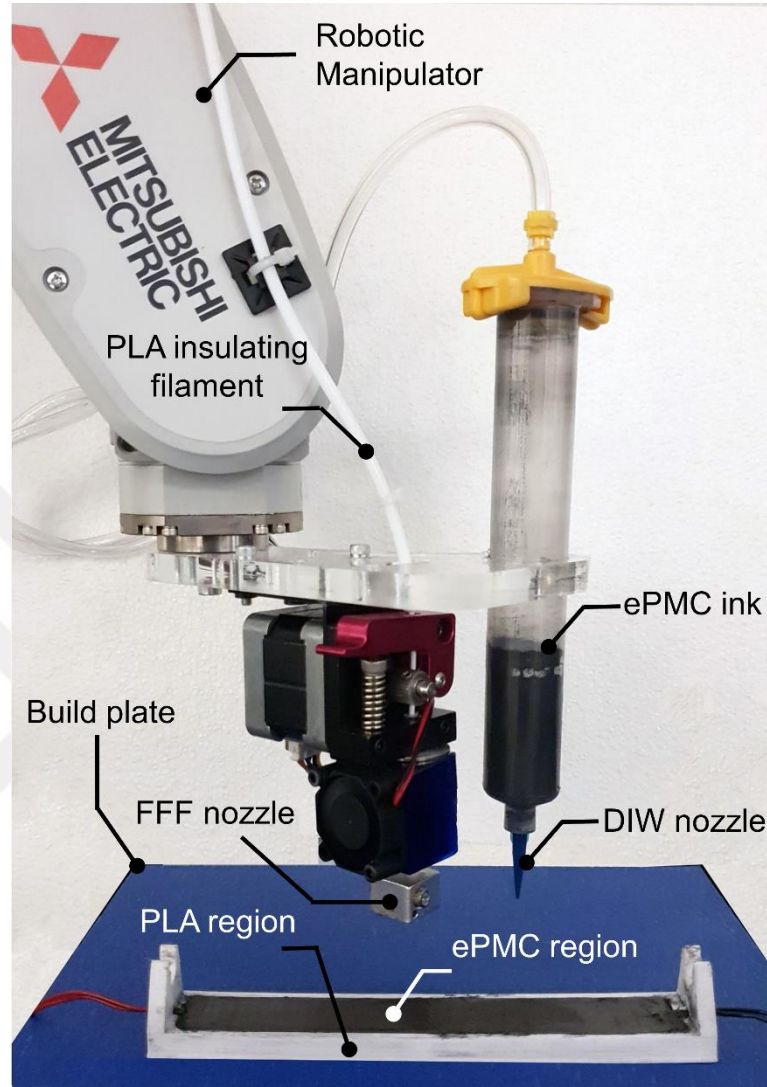


Figure 3.3: Multi-material additive-manufacturing setup for an additively manufactured cathode (AMC).

The frost accumulation on the surface of the anode (evaporator) disturbs the electric field of lines as shown in Figure 3.1 (a) that would change the capacitance of the parallel placed electrodes incrementally as shown in Figure 3.1 (b). This incremental change can be attributed to a directly proportional relationship between the capacitance and the dielectric constant of the material between two electrodes, considering all other factors being constant. The capacitance is calculated as,

$$C = \varepsilon_o \times \varepsilon_r \times A/d \quad (3.2)$$

where, ε_o is the permittivity of free space, ε_r is the relative permittivity or the dielectric constant of the material between electrodes, A is the area of electrodes and d is the distance between the electrodes. The electric field lines are most dense between the parallel electrodes (cathode and anode) of the capacitor [20] therefore, any obstruction of electric field lines due to the stored items inside the refrigerator will be insignificant. The described CSM is integrated as a variable capacitor in the inductor-capacitor (LC) based resonating circuit. The resonating frequency of the LC circuit depends on the combined values of inductance and capacitance. The changing value of capacitance because of frost accumulation between the sensing electrodes brings a shift in the resonating frequency. The frequency is determined as,

$$f_m = \frac{1}{2\pi\sqrt{LC}} \quad (3.3)$$

where, f_m is the measured frequency, L is the inductance and C is the capacitance of the CSM. A commercially available frequency-to-digital (FDC) converter is used to measure the frequency of the resonating circuit. This measured frequency will be converted into equivalent capacitance using Equation (3.3). The parasitic capacitance of the electrical circuit will be subtracted from the total capacitance. The capacitance and the frequency change response of the CSM during no-frost and frosting condition is illustrated in Figure 3.1 (b).

3.2.3. Defrost module

Initially, the additively manufactured cathode (AMC) acts as a sensing electrode to measure the thickness of frost. The AMC and the evaporator (anode) are connected to the FDC using the normally closed configuration of the multiway switch S1 whereas, the switch S2 remains open in the sensing mode as shown in Figure 3.4. Virtuous to the moderate resistance of the AMC, it can be used dually in a heating mode for defrosting, as an electrically resistive heating element. Figure 3.4 illustrates the schematic of the switching-off of the AMC between the sensing and the defrosting modes.

Defrosting mode is activated by actuating the switch S1 from a normally closed state to the open state that disconnects the AMC from the FDC. In the open state of switch S1, AMC stays connected with the positive terminal of the direct current (DC) power supply. The electrical connection between the evaporator (anode) and the negative terminal of the DC power supply is established by actuating switch S2 from open to a closed state. When

used as a heating element, the AMC draws an average of 1 A of current at 12 V thus consuming an average of 12 W of power. However, the power consumption during the sensing mode is much lower as compared to the heating mode.

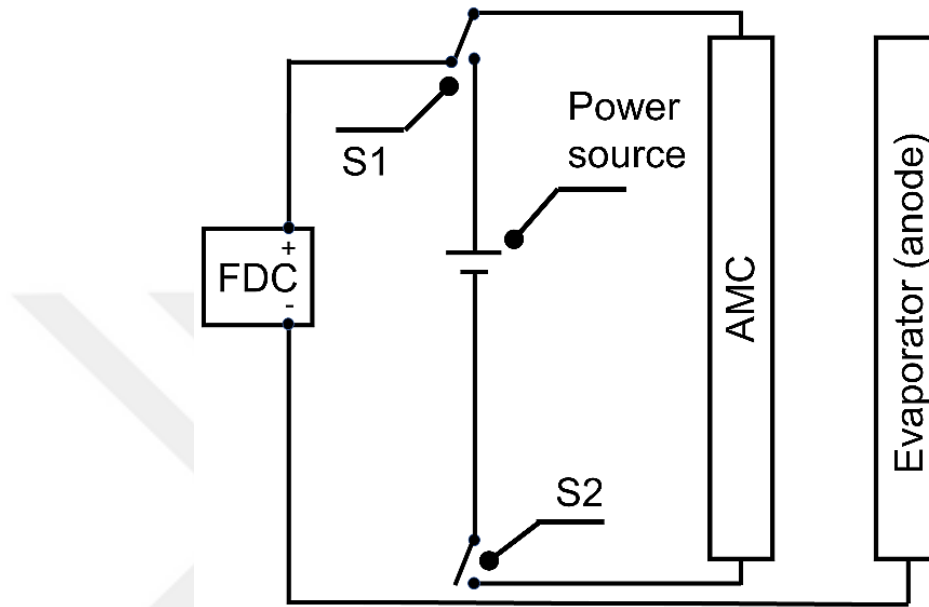


Figure 3.4: Schematic of the additively manufactured cathode (AMC) switching between frequency to digital converter (FDC) (sensing mode) and power source for heating (defrosting mode) using control switches S1 and S2.

3.2.4. Defrost on-demand algorithm

Based on the individual modules that are described in section 3.2.1 – 3.2.3, a defrost on-demand control algorithm is developed that incorporates the outputs from the PSM and the CSM modules in conjunction to effectively detect and quantify the total thickness of the frost on the surface of the evaporator. The system triggers the defrosting module once the critical thickness of the frost is achieved. The flowchart of the control algorithm for the initial frost detection, the frost thickness measurement, and the defrost control is illustrated in Figure 3.5.

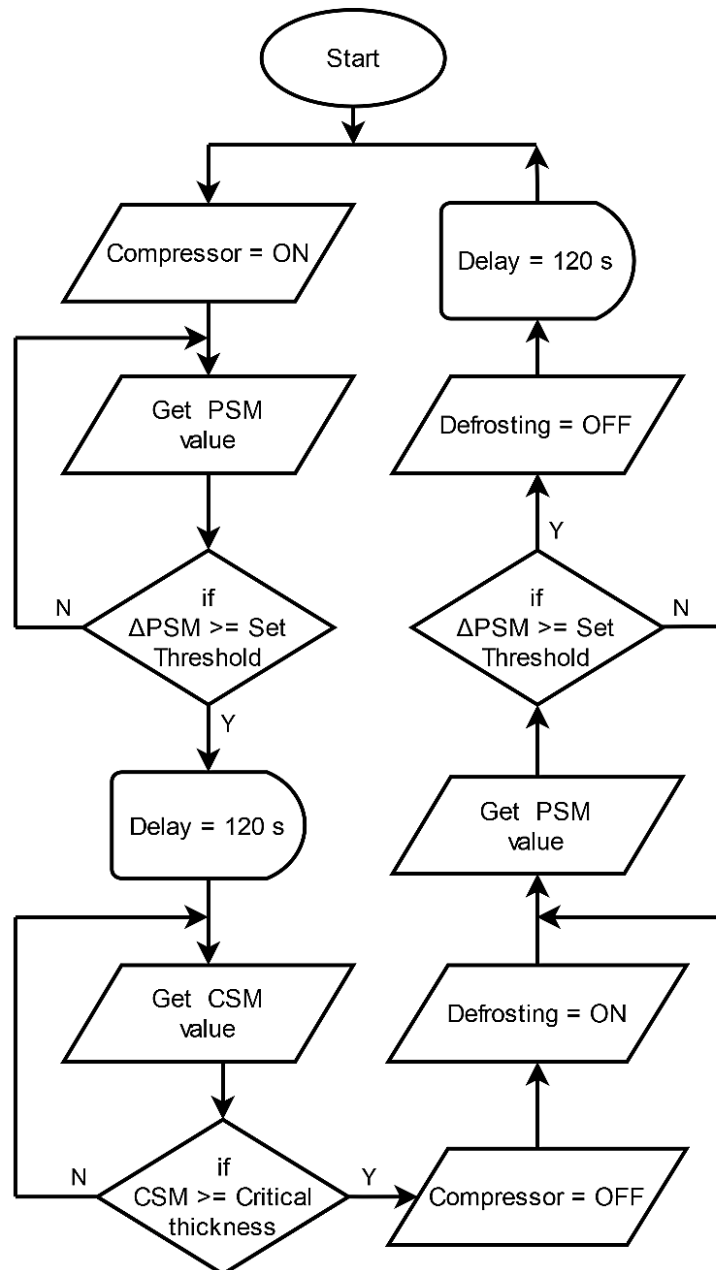


Figure 3.5: The flowchart of the defrost on-demand control algorithm of the hybrid frost detection and defrosting system (HFDDS).

When the refrigerator is powered on, the controller turns on the compressor to achieve the target temperature inside the refrigerator cabin. The controller monitors the state of the evaporator using the PSM output. The controller detects the change in the output of PSM due to initial frosting. A change of 0.2 volts indicates the appearance of frost on the evaporator; however, there is a mixture of condensed water and frost on the surface of the evaporator at

this instant. Therefore, the controller waits 120 seconds to allow the condensate to turn completely into frost before triggering the CSM.

Once triggered on, the CSM monitors the thickness of the frost until the critical value of the frost thickness is reached. Based on the CSM output, the controller first turns off the compressor and then converts the CSM into the defrosting module as illustrated in Figure 3.4. During defrosting, as the frost starts to melt the response of the PSM also changes. The controller detects this change in the PSM output voltage and triggers the defrosting off. The compressor will be turned on after the delay of 120 seconds to ensure that all the melted water is completely drained before the next cooling cycle to prevent re-freezing.

3.3. *Experimental setup*

The experimental facilities applied in this research are illustrated in Figure 3.6. The developed HFDDS was tested in an emptied-out fresh food compartment (FFC) of a bottom-mount type domestic refrigerator. The refrigerator employs an inverter-based variable speed compressor, running an HC R600a working fluid. The FFC has a tube-fin type evaporator where the mode of heat transfer is forced convection by generating an airflow through the evaporator using a fan.

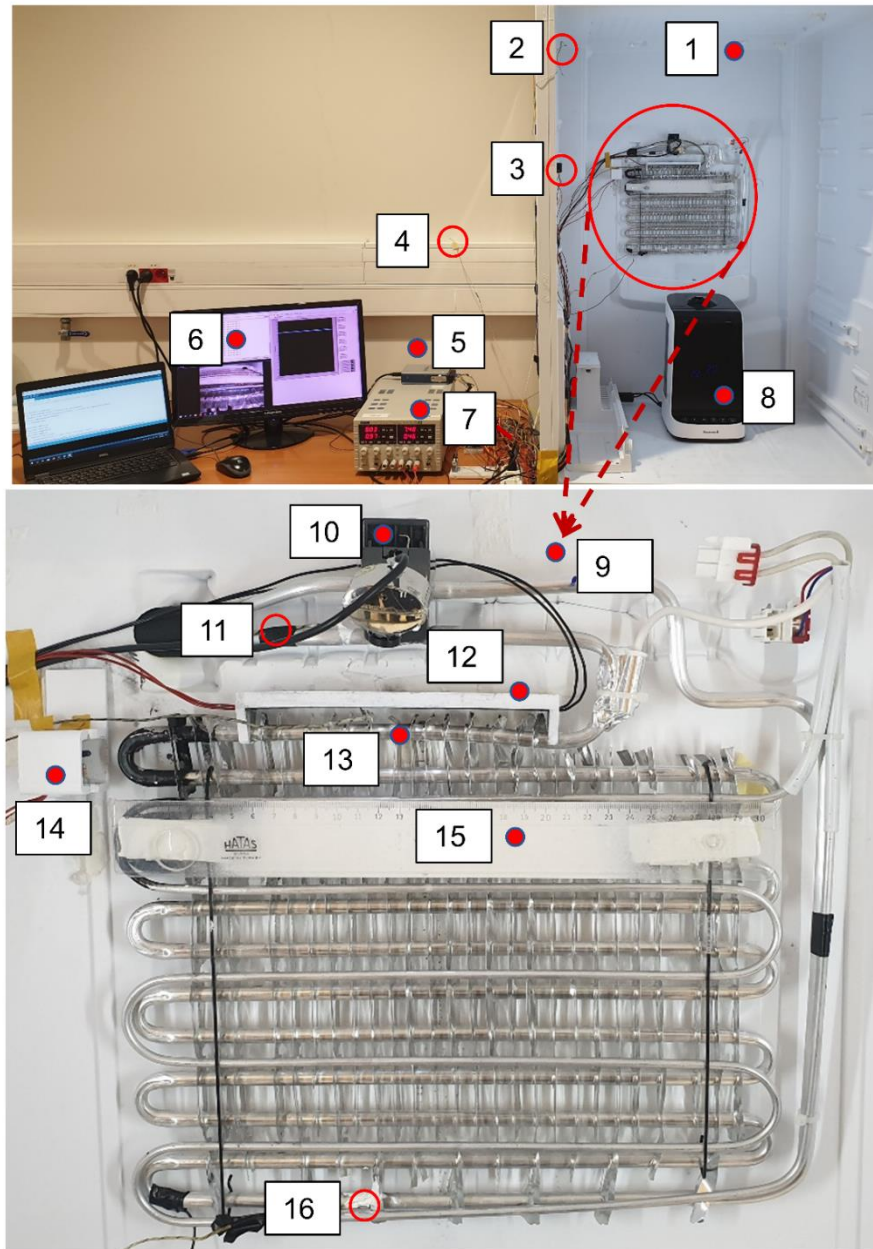
The refrigerator was installed in a test room, under controlled ambient conditions of 20-24°C room temperature and 40-60% relative humidity. The humid air inside the compartment condenses and the condensate freezes rapidly on the cold evaporator's surface. The condensation results in a decrease in humidity causing the release of moisture from the stored items to achieve equilibrium. Humidity inside the compartment is also disturbed when the compartment door is opened by the user. To simulate the changes in humidity of the FFC, a humidifier with controllable humidity was placed inside the compartment.

Pre-calibrated J-type thermocouples were installed to monitor the temperature of the test room, FFC, evaporator's top, and bottom. The current consumption was recorded using a hall effect-based current sensor. The humidity inside and outside of the FFC was measured using a capacitance-based humidity sensor. An 8-bit microcontroller was used to implement the control algorithm, data acquisition and to communicate with the refrigerator's onboard controller. A digital camera with a resolution of 640 x 480 pixels along with a reference scale is attached to the evaporator. The digital camera is installed only for the calibration and

validation of the amount of frost and is not a part of the developed HFDDS. The information of the instruments applied in the experiment is presented in Table 3-1.

The working fluid enters the evaporator from the top and exits from the bottom; hence, it was assumed that the formation of frost would start from the top of the evaporator. Therefore, to detect the initial frost formation the sensing modules of HFDDS were installed on the first tube of the evaporator. The PSM was installed with a clearance of 25 mm from the evaporator tube in a finless region. The dual-purpose capacitive sensing and the defrosting modules were placed on the evaporator with a fixed clearance of 10 mm from the fins.





- | | |
|--------------------------------|---------------------------------------|
| 1 Fresh food compartment (FFC) | 9 Evaporator zoomed view |
| 2 FFC temperature sensor (T3) | 10 Digital camera |
| 3 Humidity sensor for FFC | 11 Evaporator top temperature (T1) |
| 4 Room temperature sensor (T4) | 12 AMC (capacitor cathode) |
| 5 NI DAQ system | 13 Evaporator (capacitor anode) |
| 6 Graphical user interface | 14 PSM |
| 7 DC power supply | 15 Reference scale |
| 8 Humidifier | 16 Evaporator bottom temperature (T2) |

Figure 3.6: Experimental setup including the FFC of the refrigerator, data acquisition system, humidifier, and the zoomed view of the evaporator (anode) with thermocouples, digital camera, additively manufactured cathode (AMC), and the photoelectric sensing module (PSM) placement on the evaporator.

Table 3-1: Specifications of the instrumentation used in the experiment.

Description	Quantity	Measurement Range	Uncertainty	Model
Thermocouple	6	-60 to 400°C	$\pm 0.4^{\circ}\text{C}$	J-type
Current Sensor (for compressor)	1	-5 to 5 A	$\pm 0.075\text{A}$	ACS712
Humidity sensor	2	0 to 99.9% RH	$\pm 3\%$	AM2301
Infrared transmitter	1	-	-	940 nm
Infrared receiver	1	-	-	940 nm
Frequency to digital convertor	1	10 kHz to 10 MHz	-	FDC2214
Camera for frost thickness measurement	1	0 mm to 6 mm	$\pm 0.16\text{ mm}$	Generic digital camera
Humidifier	1	40 to 90% RH	-	WHC752
Reference scale	1	0-100 mm	$\pm 1\text{ mm}$	-

3.3.1. Experimental procedure

The conducted experiments are categorized as either calibration experiments or validation experiments. For calibration experiments, the triggering of defrosting was disabled to deposit a significant thickness of frost on the evaporator. However, for the validation experiments, a critical thickness of 3 mm was defined to trigger defrosting. The rest of the procedure remains the same for both types of experiments. The refrigerator and the humidifier were turned off before the start of every experiment. The door of the FFC was left open for 1 hour to maintain an equilibrium in the temperature and humidity of the FFC with the ambient conditions of the test room. This makes the surface of the evaporator completely dry and free from any residual frost or condensation.

The experiment begins after closing the door of the FFC and turning on the refrigerator. The humidifier is set to maintain a constant humidity level of 65% inside the FFC through an inbuilt humidity level controller of the humidifier. When the humidity level inside the FFC drops below the set threshold, the humidifier will be turned on automatically. The evaporator fan remains disabled throughout the experiment to accelerate the frost formation on the surface of the evaporator. The temperature of the evaporator surface (top and bottom), FFC, and the test room are measured using the J-type thermocouples with National Instruments data acquisition system (NI-DAQ) and displayed on the computer screen using a graphical user interface (GUI). The output responses of the humidity sensor,

PSM, and CSM are collected by the data logger at the intervals of 5 seconds and then automatically written into a text file for subsequent analysis. Meanwhile, the digital camera which is directed towards the evaporator continuously records the frost accumulation.

3.4. Results and discussion

The data from the installed thermocouples was acquired to map the temperature profile of the evaporator. The evolution of temperature at discrete locations of the evaporator, the FFC, and the test room for a typical calibration experiment is illustrated in Figure 3.7. The air temperature of the FFC (T3) is significantly higher than the surface temperature of the evaporator and drops down steadily since the evaporator fan is disabled and the air velocity is negligible during the experiments. The condensed water on the evaporator freezes and frost start to accumulate as the temperature of the evaporator fall below 0°C. The working fluid enters the evaporator from the top at a very low temperature, and exchanges heat with the evaporator before exiting from the bottom of the evaporator. A temperature difference is observed in the top (T1) and bottom (T2) of the evaporator which appears to be due to the superheating of the working fluid in the evaporator. However, this temperature difference gradually decreases as the experiment proceeds. Sub-freezing temperature is achieved earlier at the evaporator's top, which initiates the accumulation of frost from the top. Hence the assumption for HFDDS installation on the evaporator top is validated. An increase in the temperature of the air around the refrigerator (T4) is observed due to the operation of the refrigerator.

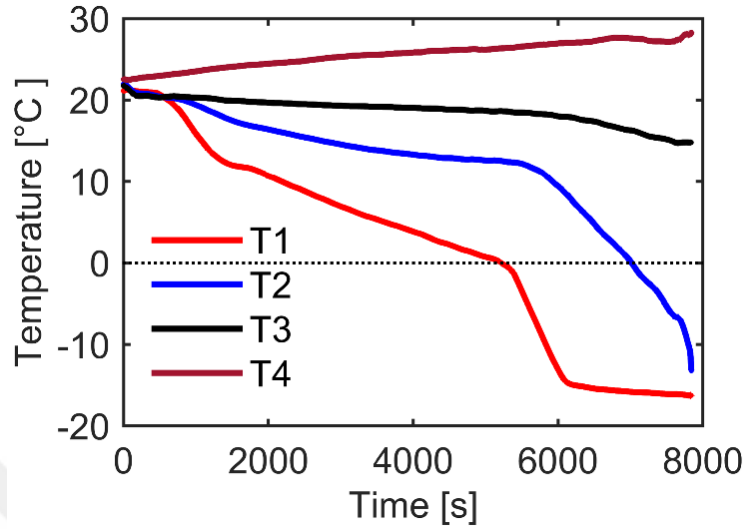


Figure 3.7: Temperature variations of the evaporator's top (T1), evaporator's bottom (T2), the FFC (T3), and the test room (T4) for a typical calibration experiment.

3.4.1. Quantification of frost

Frost accumulation is quite a random process due to the variations of the environmental conditions. Various parameters affect the rate of formation of frost on the evaporator such as the evaporator's temperature, humidity, air velocity, and the temperature inside the FFC. These parameters change constantly throughout the operation of the refrigerator. In a typical experiment, the temperature of the evaporator (top and bottom) varies in the range of 24 to -20°C . The inside air temperature of the FFC varies in the range of 24 to 10°C and the humidity inside the FFC varies in the range of 60 to 99% RH. However, the target of the HFDDS is to detect the presence of frost and measure its thickness regardless of the ambient conditions of the FFC.

To quantify the amount of frost on the surface of the evaporator several experiments were conducted. The two distinct levels of the PSM's output in the absence and presence of frost were verified by the digital camera. To calibrate the thickness of frost with the change in the capacitance, the output of the CSM and images from the digital camera at the interval of every 5 minutes were recorded. The thickness of frost was measured from the digital images using pixels and the reference scale. Figure 3.8 shows samples of images recorded from the start of frosting, along with the thickness of frost measured from the images and the elapsed time (MM: SS).

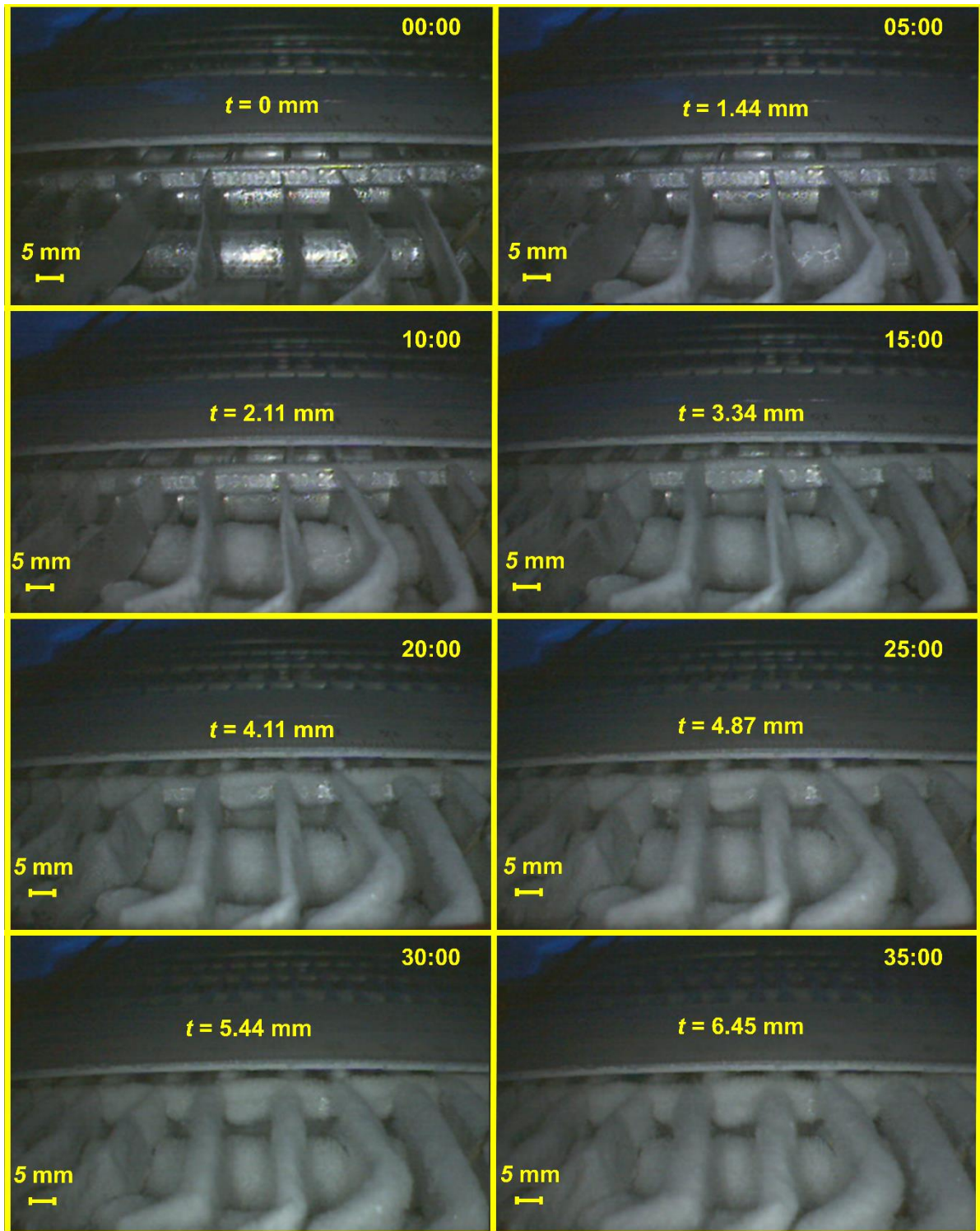


Figure 3.8: The images recorded from the digital camera of the accumulation of frost on the evaporator along with the measured thickness of frost (t) and the elapsed time (MM: SS).

A linear correlation between the change in capacitance and the thickness of frost for 10 experiments was developed using the least-square fit method with the coefficient of determination, r^2 equals 0.97. The final correlation is given as:

$$t = 0.043\Delta C + 1.3 \quad (3.4)$$

where t is the thickness of frost (mm), ΔC is the change in capacitance (fF). The thickness of frost versus change in capacitance with a best-fit line is illustrated in Figure 3.9.

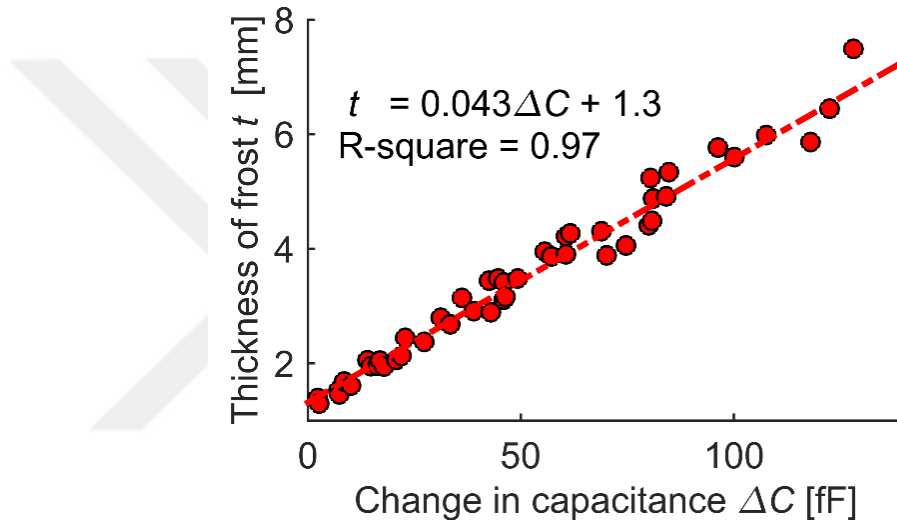


Figure 3.9: Correlation for the thickness of frost versus change in capacitance.

The linear relation between the change in capacitance and the thickness of frost indicates that the thickness of frost on the evaporator is a single-valued function of the change in capacitance. Therefore, the variation in the evaporator temperature, humidity, and temperature of the air inside the FFC does not affect the measurement of the thickness of frost.

The reliability of the correlation is dependent on the thickness of frost measured from the images from the digital camera therefore, a high-resolution camera can be employed to improve this correlation. Reliability can also be increased by increasing the number of experiments.

3.4.2. Validation of the correlation

To validate the frost detection and defrosting of the HFDDS three validation experiments were conducted following the same experimental procedure described in section

3.3.1. The developed HFDDS can cater to the critical thickness of frost in the range of 1.3 mm – 8 mm. However, the critical thickness of 3 mm was selected for the validation tests. Figure 3.10 shows the results of the first validation test.



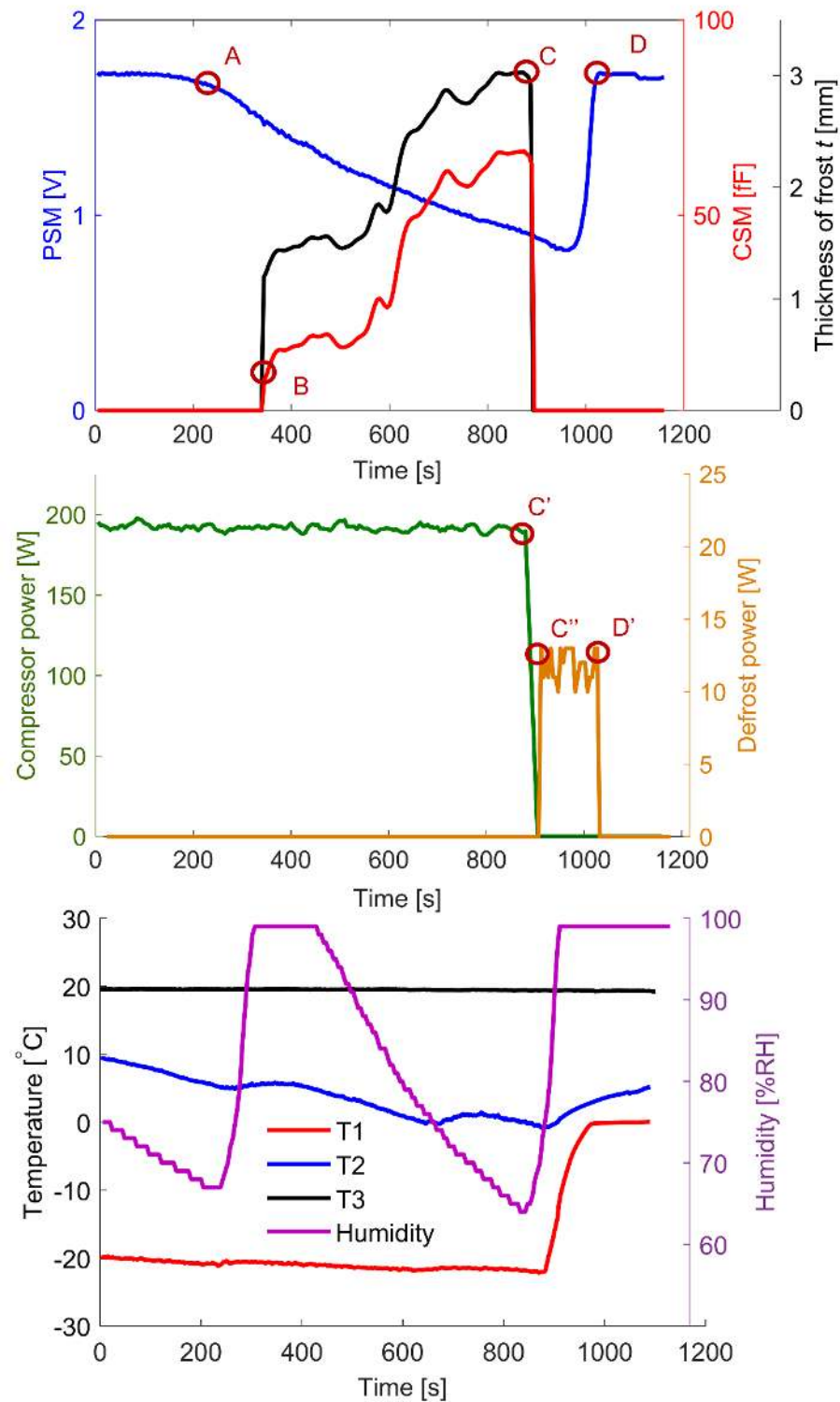


Figure 3.10: Responses of the photoelectric (PSM), capacitive (CSM) modules and the thickness of frost t estimated from the CSM, the power consumed by the compressor and the defrost heater, and the variations in the relative humidity and the temperature inside the FFC of the refrigerator for the first validation experiment.

The photoelectric module outputs between 1.8-2 V, when there is no frost, however, it starts to drop rapidly with the formation of frost on the evaporator. Point A in Figure 3.10 represents the change in the response of the PSM due to the mixture of frost and condensed water on the surface of the evaporator. Point B represents the triggering-on of the CSM after 120 seconds of initial frost detection. The thickness of frost is measured from the CSM's output using the correlation developed in section 3.4.1, and defrosting is triggered on when the critical thickness of frost is reached. Points C, C' and C'' represent the triggering-on of defrosting routine and turning-off of the compressor. The melting of frost is monitored using PSM during defrosting. Defrosting is triggered off when the output of PSM returns to the no-frost level. Points D and D' represent the triggering-off of the defrosting routine. The changes in the temperature of the evaporator's top (T1), evaporator's bottom (T2), the FFC (T3), and the humidity of the air inside the FFC during the validation tests are also illustrated in Figure 3.10. The temperatures are consistent with the calibration experiments as shown in Figure 3.7.

The results of the second and third validation tests are presented in Figure 3.11, and Figure 3.12, respectively. The results are consistent with the results of the first validation test reported in Figure 3.10.

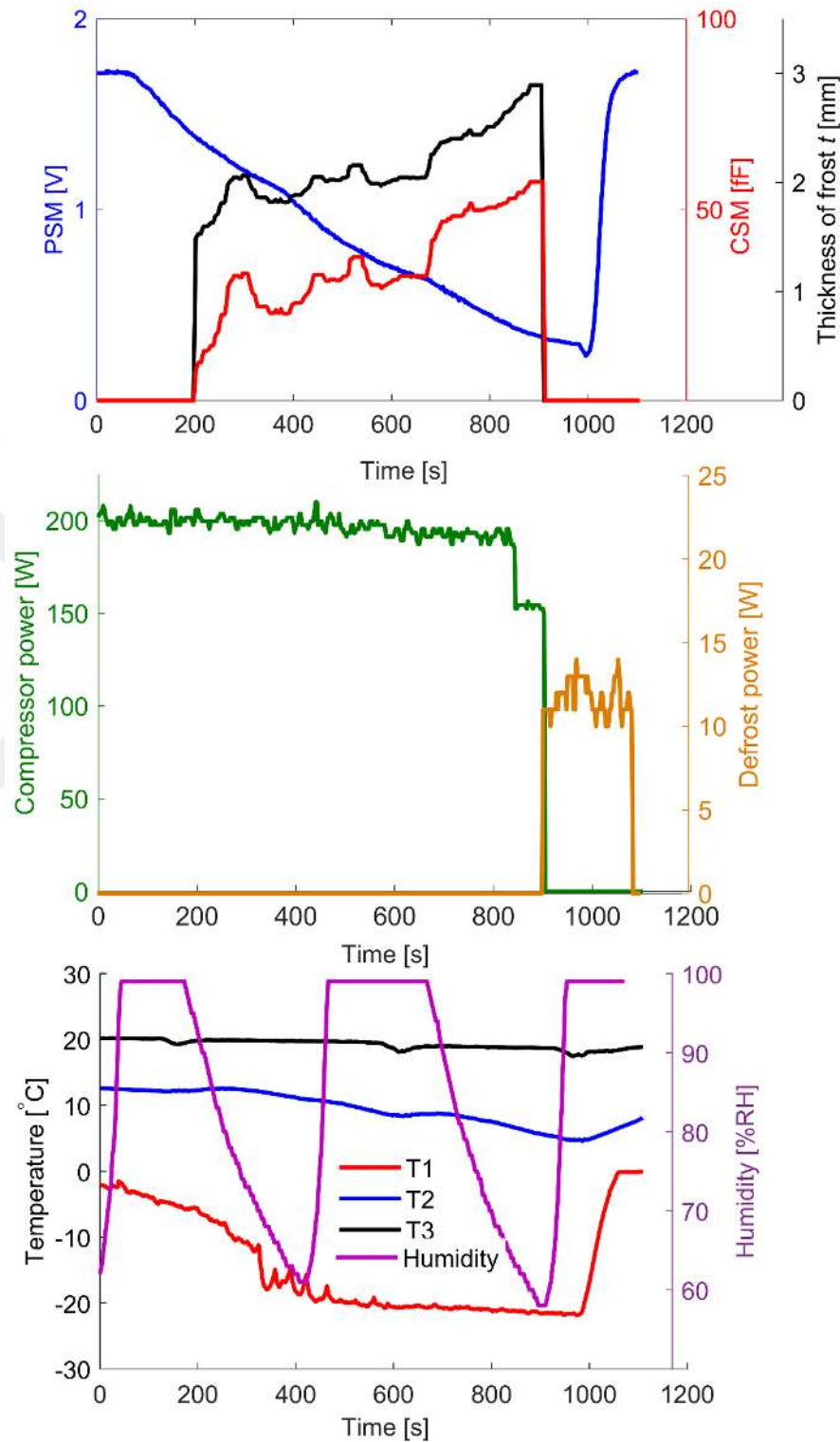


Figure 3.11: Responses of the photoelectric (PSM), capacitive (CSM) modules and the thickness of frost t estimated from the CSM, the power consumed by the compressor and the defrost heater, and the variations in the relative humidity and the temperature inside the FFC of the refrigerator for the second validation experiment.

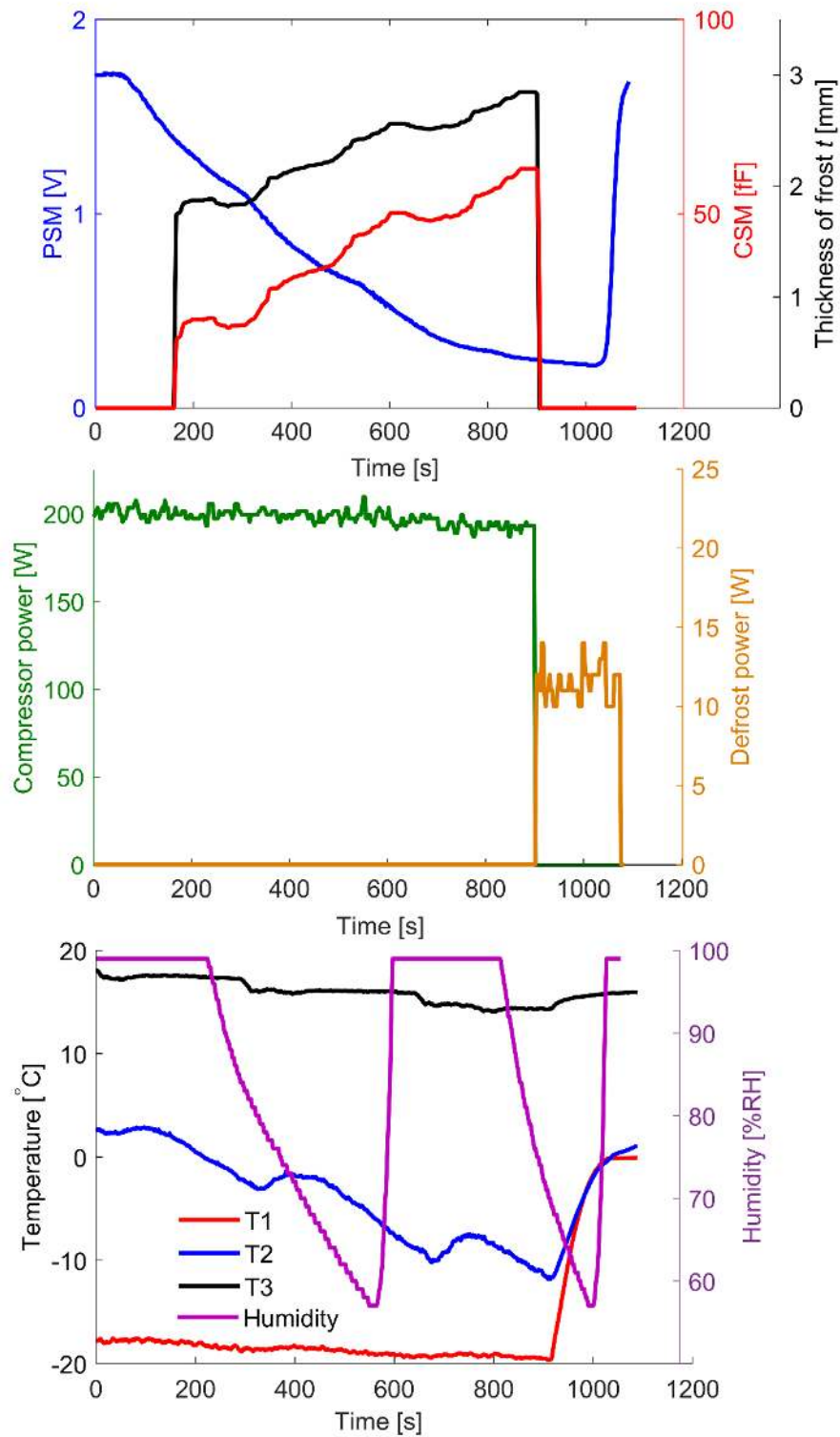


Figure 3.12: Responses of the photoelectric (PSM), capacitive (CSM) modules and the thickness of frost t estimated from the CSM, the power consumed by the compressor and the defrost heater, and the variations in the relative humidity and the temperature inside the FFC of the refrigerator for the third validation experiment.

The actual thickness of frost was measured from the digital images. The estimated thickness of frost versus the actual thickness of frost is presented in Figure 3.13. The estimated thickness of frost is consistent with the actual frost thickness within a relative deviation of $\pm 5\%$ which validates that the correlation produces a good agreement with the measured data of the validation experiments. However, the margin of error can be further reduced by the elimination of parasitic capacitances of the system, implementation of noise filters, optimization of the geometry of the AMC, and its placement on the evaporator.

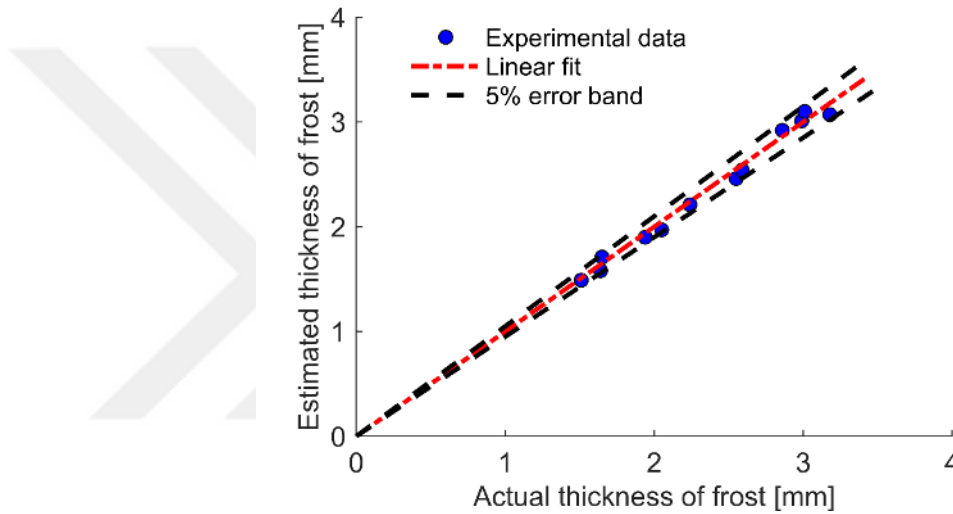


Figure 3.13: The thickness of frost estimated from the correlation versus the actual thickness of frost measured from the images recorded from the digital camera along with 5% error limits.

3.4.3. Efficacy of defrost on-demand

The defrost on-demand technique is a promising alternative to the blind TITT defrosting technique as the heating is performed only when needed [67]. A frost sensor detects and quantifies the amount of frost and triggers defrosting heater based on a pre-defined critical thickness of frost.

The employability of the capacitive sensing technique for the implementation of defrosting on-demand regimes in domestic refrigeration systems is demonstrated by the developed HFDDS. The developed system can detect and quantify the presence of frost with a 5% margin of error. The AMC can be converted into a defrost heater virtuous to the graphite-based material used for the manufacturing of the AMC. The AMC melts a 3 mm thick layer of frost in approximately 200 seconds using 12 Watt of power. The CSM cannot

measure the amount of frost while it is functioning as a defrost heater. Therefore, a secondary PSM module was incorporated into the system to provide feedback on the melting of frost during the defrosting mode. The PSM not only enables the system to detect the complete melting of frost but also increases the overall reliability of the system by giving a starting point of frost for the CSM.

The test refrigerator by default uses a TITT defrosting routine where the 20 W defrost heater is triggered-on for 10 minutes in a 24-hour window. Therefore, the default defrosting regime utilizes 12 KJ of energy every 24-hours. The developed HFDDS draws an average of 12 W of power and takes approximately 200 seconds to melt away a 3 mm thick layer of frost. Therefore, only 2.4 KJ of energy is utilized in one defrost cycle. However, the refrigerator may require multiple defrosting cycles in a 24-hour window due to the variations in the humidity of the FFC. Therefore, the selection of the critical thickness of frost is of key importance. The evaporator's thermodynamic efficiency deteriorates as frost starts to accumulate on its surface. Therefore, the threshold of the critical thickness of frost should be kept at a low value. However, a value too low would increase the number of defrost cycles which would result in an increase in power consumption due to frequent startups of the compressor. On the other hand, a value too high would increase the defrosting time causing the temperature of the FFC to drop significantly, leading to an increase in the compressor's power consumption. A long defrosting time would also increase defrosting energy consumption [14] and [11]. Therefore, improvement in the efficiency of the system requires a multivariate optimization of the critical thickness of frost with respect to the defrost time, the number of required defrost cycles in a 24-hour window, and the decline in the thermodynamic efficiency of the evaporator due to frost. The optimization would be system-specific and remains a challenge for the implementation of the HFDDS in the current refrigeration systems.

The newly developed HFDDS can be adapted for any type of refrigeration system virtuous to the flexibility offered by additive manufacturing which enables the development of application-specific geometries of the PSM and the AMC with minimum lead time. However, the developed correlation in section 3.4.1 is only true for the currently used geometry of the AMC. Nevertheless, the current correlation will help as a starting point to develop a new correlation for different geometries of the AMC. The AM of the AMC is a

bottleneck for the mass producibility of the HFDDS. However, once the application-specific AMC is prototyped by AM and validated, it can be manufactured by mass production techniques such as injection molding.

3.5. *Summary*

In summary of this chapter, a novel hybrid frost detection and defrost system (HFDDS) for domestic refrigerators has been developed using a combination of photoelectric sensing, capacitive sensing, and resistive heating techniques. The frost detection module is comprised of an infrared (IR) based optical couple and a capacitive sensing module (CSM). The evaporator of the refrigerator and an additively manufactured cathode (AMC) were used as a parallel plate capacitor for capacitive sensing. The AMC was manufactured using a graphite-based polymer composite with a moderate electrical conductivity which enables the use of AMC as a resistive heater for defrosting. The frost detection range of the HFDDS is from 1 mm to 8 mm with a 5% margin of error. The HFDDS triggers defrosting when a critical thickness of frost is reached. This critical threshold can be adjusted based on the application. The developed HFDDS is flexible, allowing the use of application-specific geometries of photoelectric and capacitive sensing modules. Additionally, results show that the additively manufactured graphite-based heating elements could potentially be used as a low-power defrosting system for domestic refrigerators.

Chapter 4 : APPLICATION OF THE HYBRID FROST DETECTION AND DEFROST SYSTEM IN ENERGY CONSERVATION OF REFRIGERATION SYSTEMS

4.1. Overview

The typical domestic refrigerator employs a blind and periodic defrost strategy that leads to the clogging of the evaporator between the consecutive defrost cycles. The clogging of the evaporator causes a loss in performance which can be minimized using the demand defrost technique. The demand defrost systems proposed in the literature rely on the detection of frost as the defrost triggering criterion, rather than the real-time quantification of the thickness of frost. The initial frost layer improves the performance and therefore, the thickness of frost must be taken into consideration. Frost becomes detrimental only after it crosses a critical threshold. Defrosting the system at lower thicknesses may lead to frequent defrosting cycles which in turn increases the defrost energy. Therefore, the defrost triggering criterion must be selected tactfully to utilize the benefit of the initial frost layer along with the minimization of the defrost energy. In this chapter, a novel real-time thickness of the frost-based demand defrost technique is presented for a domestic refrigerator. The hybrid system presented in Chapter 3 is used in this study. The hybrid system is comprised of frost detection and defrosting modules are employed to quantify the thickness of frost in real-time and to defrost the evaporator using a 12 W heater. The effect of the thickness of the frost-based defrost threshold on the energy consumption of the refrigerator is evaluated. The defrost threshold of 6 mm yields the maximum energy conservation of 10% as compared to the default blind and periodic defrost strategy of the test refrigerator.

4.2. Hybrid system

The hybrid system is comprised of an additively manufactured frost detection sensing unit that can be converted into a thermal actuator. The capacitive and the photoelectric sensing techniques are merged to quantify frost. The photoelectric sensing is employed using an infrared transmitter-receiver couple whereas, the capacitive sensing is used in a parallelly installed electrode configuration. Figure 4.1 recalls the working principle of the capacitive and the photoelectric sensing techniques for frost detection on the evaporator coil. The hybrid frost detection and defrost system is calibrated and experimentally validated to quantify the

average frost thickness between 1.3 mm and 8 mm with 95% accuracy [87].

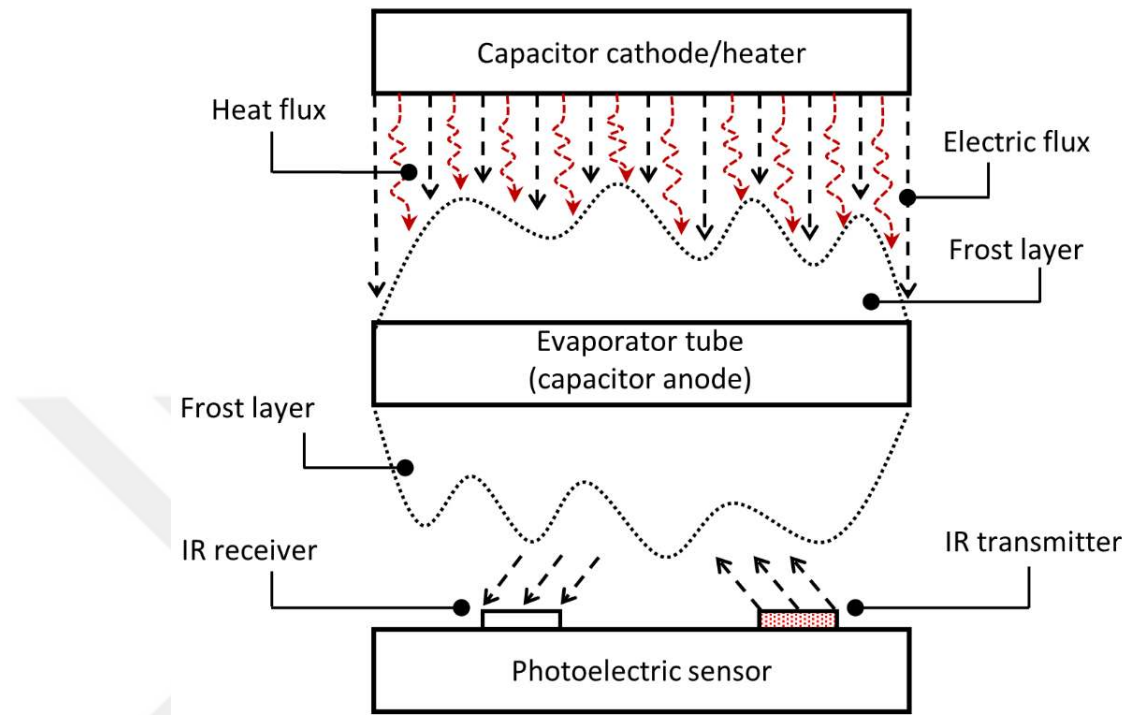


Figure 4.1: Schematics of the hybrid system consisting of a photoelectric sensor and a capacitive sensor/defrost heater.

The hybrid system constantly measures the thickness of frost using a frost sensing module. The defrost module of the hybrid system was triggered once a predefined threshold of the thickness of frost is accreted. The hybrid system defrosts the evaporator using a 12 W heater and terminates the defrosting once the frost sensing module detects complete melting of the frost.

4.3. Experimental setup

4.3.1. Experimental apparatus

The experimental apparatus employed in this research consisted of four major components: the emptied fresh food cabin (cabin) of the domestic refrigerator, the tube fin-type evaporator having a fin pitch of 10 mm, the hybrid system, and the data acquisition system. The refrigerator uses a constant speed compressor and HC-600a as a refrigerant and employs a 20 W defrost heater controlled by the periodically initiated and temperature terminated (PITT) defrost control strategy by default. The detailed specifications of the test refrigerator are listed in Table 4-1. The experimental setup is illustrated in Figure 4.2.

Table 4-1: Specifications of the test refrigerator

Items	Parameter	Items	Parameter
Refrigerator model	Beko 683720 EI	Defrost heater	20W, Aluminum type
FFC Volume	422 L	Defrost control	Time-temperature
FC volume	155 L	Throttle device	Capillary tube
Refrigerant	HC-R600a	Climate class	SN-T
Compressor	Variable-speed inverter	Energy efficiency class	A ⁺⁺
Weight	120 Kg	Sound level	41 dBA

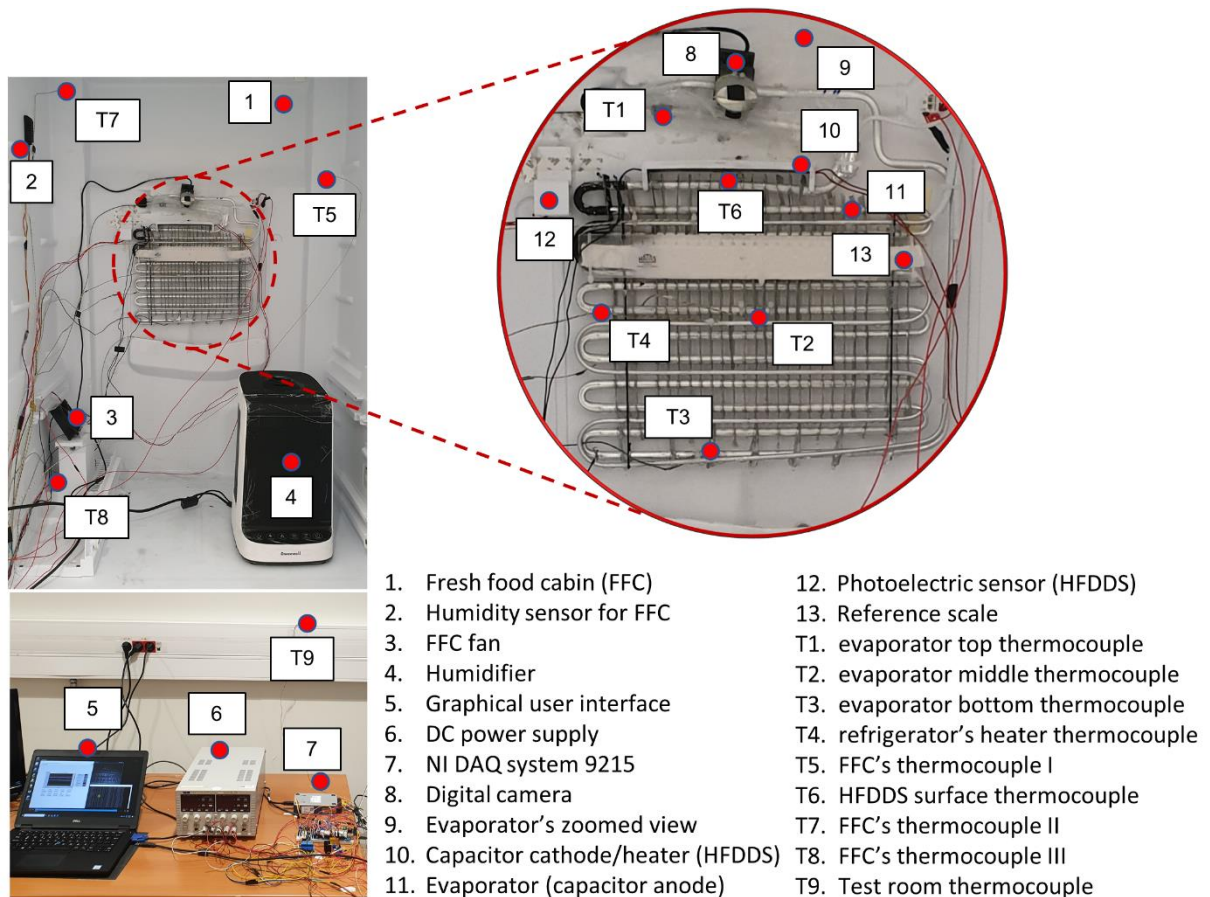


Figure 4.2: Experimental apparatus showing the fresh food cabin (cabin), the humidifier, the graphical user interface, and the evaporator with the hybrid system (HFDDS).

The temperature and the relative humidity of the test room were maintained in the range of 20 – 24°C and 60 – 80 %RH, respectively. The relative humidity level inside the cabin continuously varies because of the release of the water vapors from stored food items and the condensation of these water vapors on the surface of the evaporator. Therefore, a

humidifier with an inbuilt humidity controller was installed to induce humidity inside the cabin of the refrigerator.

A 12V DC fan was installed inside the cabin, to provide a constant supply of airflow for convective heat transfer. J-type pre-calibrated thermocouples were installed on nine different positions, as illustrated in Figure 4.2, to monitor temperature variations including the cabin, the evaporator, the surface of a hybrid system, the drain, and the test room. The power consumption of the compressor during the cooling cycle and the power consumption of the hybrid system during the defrost cycle was measured using current sensors. The change in the relative humidity inside the cabin and the test room was monitored using humidity sensors. A digital camera (640×480 pixels resolution) was installed inside the cabin to monitor the state of the evaporator visually during experiments. Table 4-2 highlights the model type, quantity, accuracy, and measurement uncertainty of the instruments used in the experiment.

Table 4-2: Specifications of the sensors and the instruments used in the experiment.

Instrument	Qty.	Range	Accuracy	Uncertainty	Model
Thermocouple	9	-60 °C to 400 °C	±0.4 °C	-	J-type
Humidity sensor	2	0 %RH to 99 %RH	±3 %RH	-	AM2301
Current sensor	2	-5 A to +5 A	±0.075 A	-	ACS712
Humidifier	1	40 %RH to 90 %RH	-	-	WHC752
Reference scale	1	0 mm to 300 mm	± 1 mm	-	-
Frost detection (hybrid system)	1	1.3 mm to 8 mm	-	±5%	-
12 V DC fan	1	-	-	-	Casing fan

4.3.2. Installation of the hybrid system

The pattern of frost deposition on the evaporator was studied to determine the suitable location of the hybrid system. The digital images of the evaporator at various instances along with the temperature at different points of the evaporator and the humidity changes inside the cabin are illustrated in Figure 4.3. The deposition of frost starts from the top of the evaporator due to the temperature gradient between the inlet (top) and the outlet (bottom) of the evaporator. A significant thickness of frost has already been deposited on the top of the evaporator by the time an initial frost layer appears on the bottom. The frosted top of the evaporator loses its efficiency and therefore, it is selected as the suitable location for the

hybrid system. The installation of the hybrid system at the top of the evaporator ensures early detection of frost and therefore, the defrosting can be triggered before the entire evaporator is covered with frost.

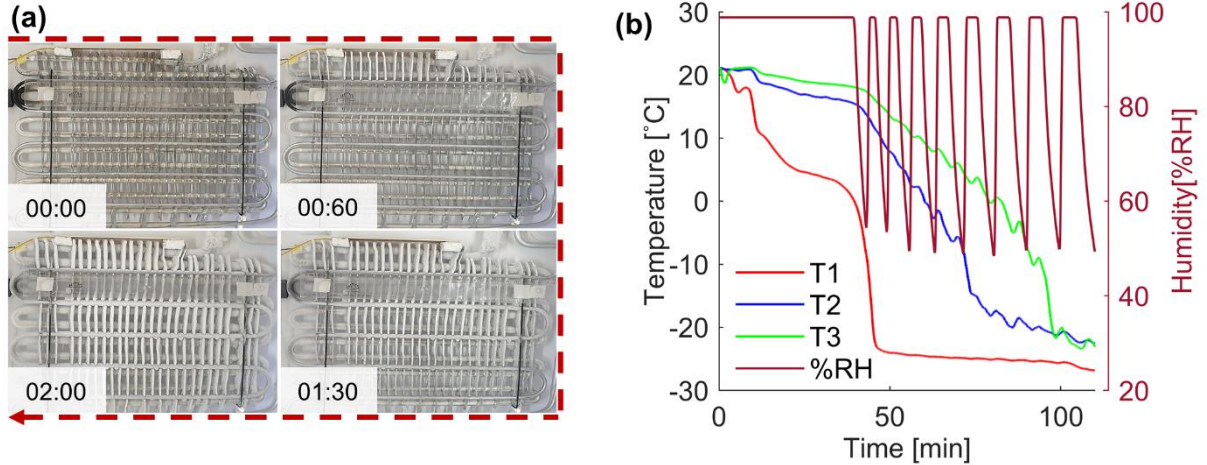


Figure 4.3: (a) Digital images of the evaporator at the various instances during undisturbed operation. (b) The evolution of temperature at various points of the evaporator (T1: evaporator top, T2: evaporator middle, T3: evaporator bottom) and the relative humidity (%RH) inside the cabin.

4.3.3. Experimental protocol

The refrigerator cabin and the test room were allowed to maintain an equilibrium in terms of temperature and humidity by keeping the cabin door open before the start of the experiment. The compressor and the humidifier remained in the off state to drain any residual water from the surface of the evaporator. The experiment started by actuating the compressor, whereas the door of the cabin remained closed throughout the experiment. The compressor operates continuously until the cabin's temperature drops to 0°C in the transient phase. At this instance, the compressor is turned off and the cabin's temperature starts to rise consequently. The compressor is turned back on when the cabin's temperature rises to 4°C. Therefore, the cabin's temperature will keep oscillating between 0°C and 4°C after the transient phase. The refrigerator consumes the most energy in bringing the temperature down to 0°C from room temperature however, the energy consumption minimizes when the refrigerator oscillates between 0°C and 4°C. The transient region of the cabin's temperature between room temperature and 0°C is termed as a major cycle whereas, each of the oscillations between 0°C and 4°C is termed as a minor cycle. The humidifier works intermittently, releasing water vapor into the cabin whenever the humidity inside the cabin

drops below 60 %RH. Therefore, the humidity inside the cabin oscillates between 100 %RH and 60 %RH as illustrated in Figure 4.3 (b). Various experiments were performed to compare the energy consumption of the default PITT defrost control strategy and the real-time thickness of the frost-based demand defrost technique by the application of the hybrid system. The experiments were conducted for 24 hours and repeated thrice to ensure repeatability. The cabin fan and compressor of the refrigerator remain off during defrosting for both cases.

4.3.3.1. Periodically initiated temperature terminated defrost strategy

The PITT defrosting strategy is the default strategy of the test refrigerator where the defrost cycle is triggered once every 24 hours. The default 20 W heater of the refrigerator defrosts the evaporator and terminates defrosting when the temperature of the cabin rises to a predefined defrost termination temperature. Various defrost termination temperatures have been reported in the literature [49,63,66,88] however, 7°C is the lowest of the reported temperature and is, therefore, adopted for this study.

4.3.3.2. Demand defrost technique

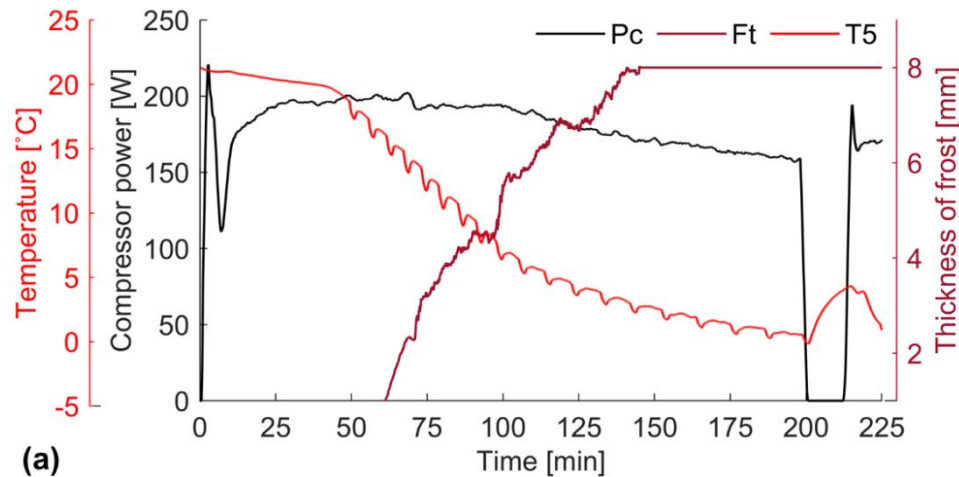
The demand defrost strategy relies on the output of the hybrid system to trigger and terminate the defrosting cycle. The defrost cycle is triggered when the frost deposited on the top of the evaporator reaches a pre-defined defrost threshold irrespective of the system being in the major or minor cycle. Defrosting terminates when the complete melting of the frost on the top of the evaporator is detected by the hybrid system.

4.4. Results and Discussion

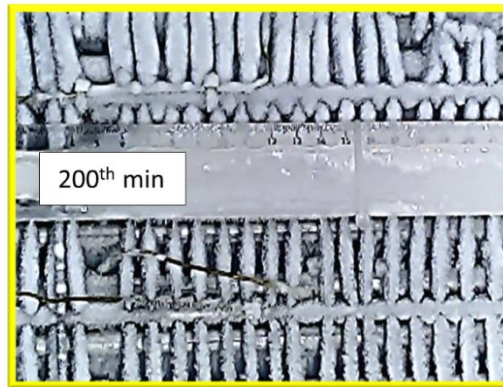
The refrigerator's default PITT defrost control strategy is compared to the demand defrost technique in terms of energy consumption. The demand defrost experiments were carried out for the defrost thresholds of 2 – 8 mm with an increment of 1 mm.

4.4.1. Major cycle

The power consumption of the compressor, the evolution of the cabin temperature, the thickness of frost deposited on the evaporator in the major cycle for the PITT defrost control strategy, and the digital image of the evaporator at the end of the major cycle is illustrated in Figure 4.4.



(a)



(b)

Figure 4.4: (a) The power consumption of the compressor, the thickness of frost, and cabin temperature during the major cycle of the periodically initiated temperature terminated (PITT) defrost control strategy. (b) Digital image of the evaporator at the 200th minute of the PITT experiment (end of major cycle).

The thickness of frost enters the measuring range of the hybrid system after approximately 60 minutes of operation of the compressor and it increases as the experiment progresses as shown in Figure 4.4 (a). Frost grows unhindered and exceeds the maximum measurable thickness of 8 mm of the hybrid system after 146 minutes of operation. At this instant, the target cabin temperature has not been achieved and therefore, the compressor remains on until the target temperature of 0°C is achieved at the 200th minute. A small portion of the frost is expected to melt as the cabin temperature rises during the compressor off-time, but it was not detected by the hybrid system as the frost remains above 8 mm. The compressor restarts at the 213th minute, triggering the minor cycle as shown in Figure 4.4 (a). The total energy consumption of the major cycle of the PITT experiment is 590 Wh. The state of the evaporator at the end of the major cycle is illustrated in Figure 4.4 (b). A

significant amount of frost is carried forward into the minor cycle which will lead to inefficient performance for the next several hours until the scheduled defrost cycle of the PITT strategy.

The power consumption of the compressor, power consumption of the defrost heater of the hybrid system, the evolution of the cabin temperature, and the thickness of frost deposited on the evaporator in the major cycle for the demand defrost technique with the defrost thresholds of 2 mm, 6 mm, and 8 mm are illustrated in Figure 4.5.



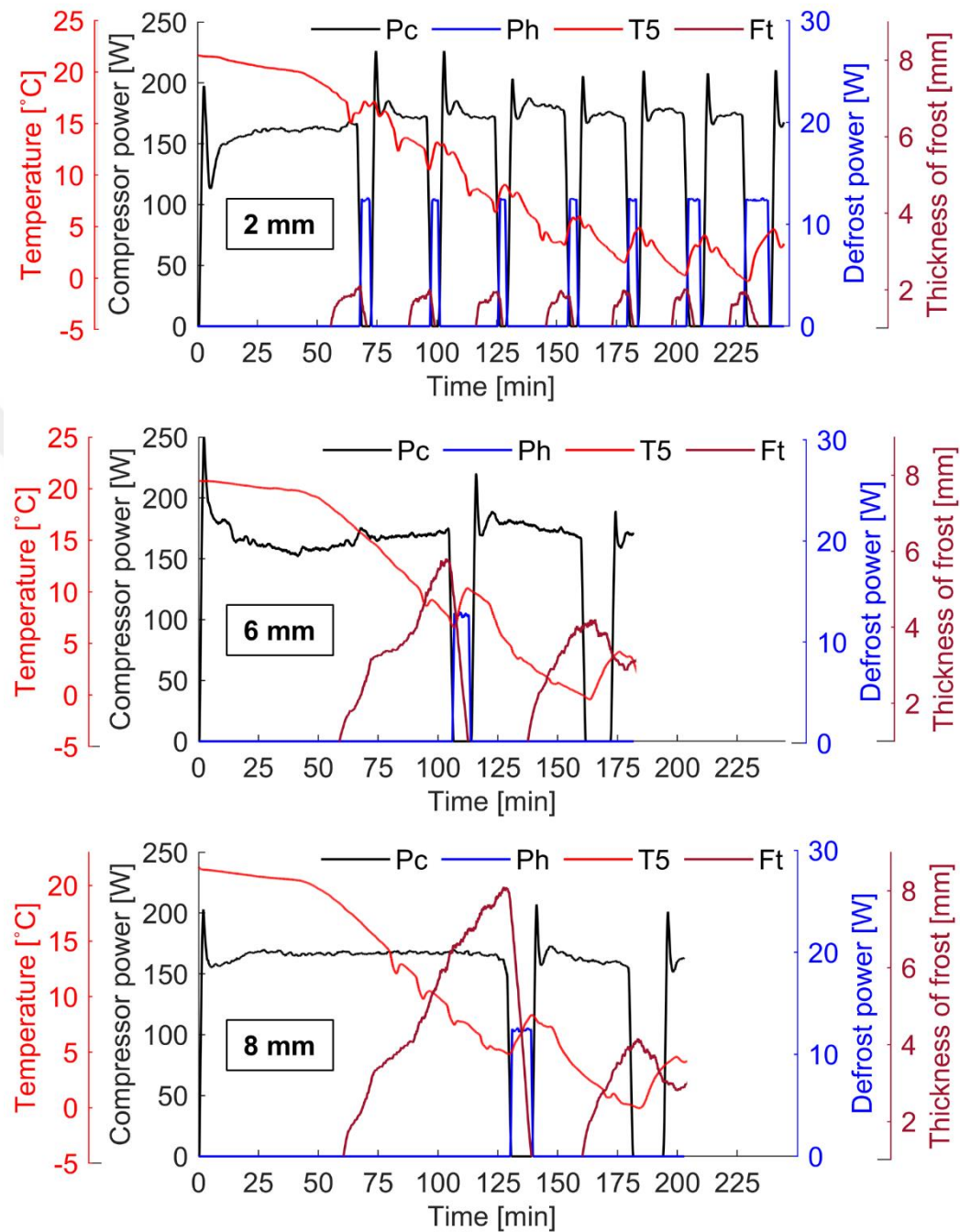


Figure 4.5: The power consumption of the compressor and the defrost heater, the thickness of frost, and cabin temperature during the major cycle of the demand defrost experiments with the defrost threshold of 2 mm, 6 mm, and 8 mm.

The start of the demand defrost experiments remains identical to the PITT case with the initial detection of frost after approximately 60 minutes. However, defrosting is initiated when the frost thickness reaches the respective thresholds of 2 mm, 6 mm, and 8 mm as

illustrated in Figure 4.5. The temperature of the cabin rises during defrosting depending on the duration of the defrost cycle. The compressor restarts after defrosting which causes the frost to reappear on the evaporator. The low defrost threshold of 2 mm causes multiple triggering of defrost cycle however, the higher defrost thresholds of 6 mm and 8 mm required defrosting only once during the major cycle (as shown in Figure 4.5). The compressor is turned off when the target cabin temperature of 0°C is achieved in the 161st minute and 181st minute in the case of 6 mm and 8 mm defrost thresholds, respectively. The system initiates the minor cycles when the cabin temperature rises to 4°C for the 6 mm and 8 mm defrost threshold cases. The target cabin temperature is achieved at 227th minute in the case of the 2 mm defrost threshold. However, at this instance the defrost threshold has also been achieved, and therefore, the system goes into the defrost cycle (as shown in Figure 4.5). The temperature of the cabin rises to 4°C at the end of the defrosting cycle and that causes the system to initiate minor cycles.

The energy consumption of the major cycle for the various defrost thresholds of the demand defrost technique is tabulated in Table 4-3 The 6 mm defrost threshold yields the minimum energy consumption in the major cycle.

The state of the evaporator at the start and end of the defrost cycles for the demand defrost case with defrost threshold of 8 mm is illustrated in Figure 4.6. The frost mostly accumulated on the top of the evaporator and was easily melted away by the hybrid system.

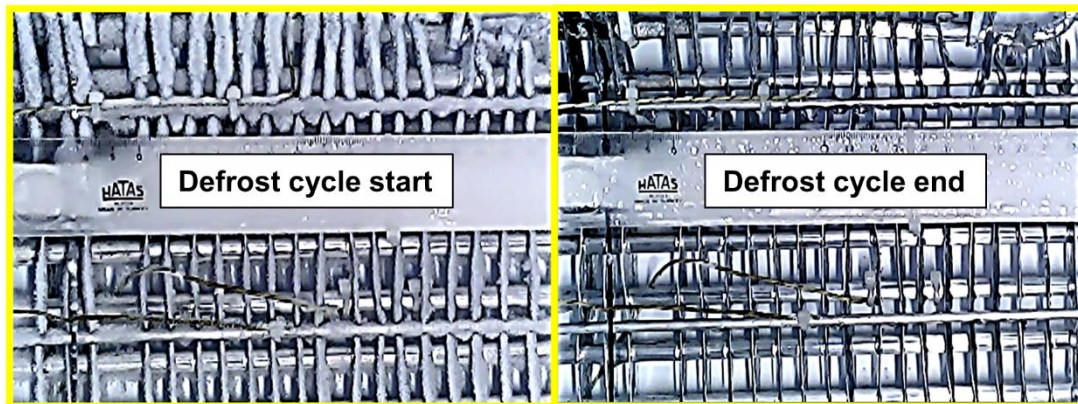


Figure 4.6: Digital images of the evaporator during the demand defrost experiment with a defrost threshold of 8 mm at the start of defrost cycle and the end of defrost cycle.

4.4.2. Minor cycles

The power consumption of the compressor, power consumption of the defrost heater

of the hybrid system, the evolution of the cabin temperature, and the thickness of frost deposited on the evaporator in the minor cycle for the PITT and demand defrost technique with the defrost thresholds of 2 mm, 6 mm, and 8 mm are illustrated in Figure 4.7.



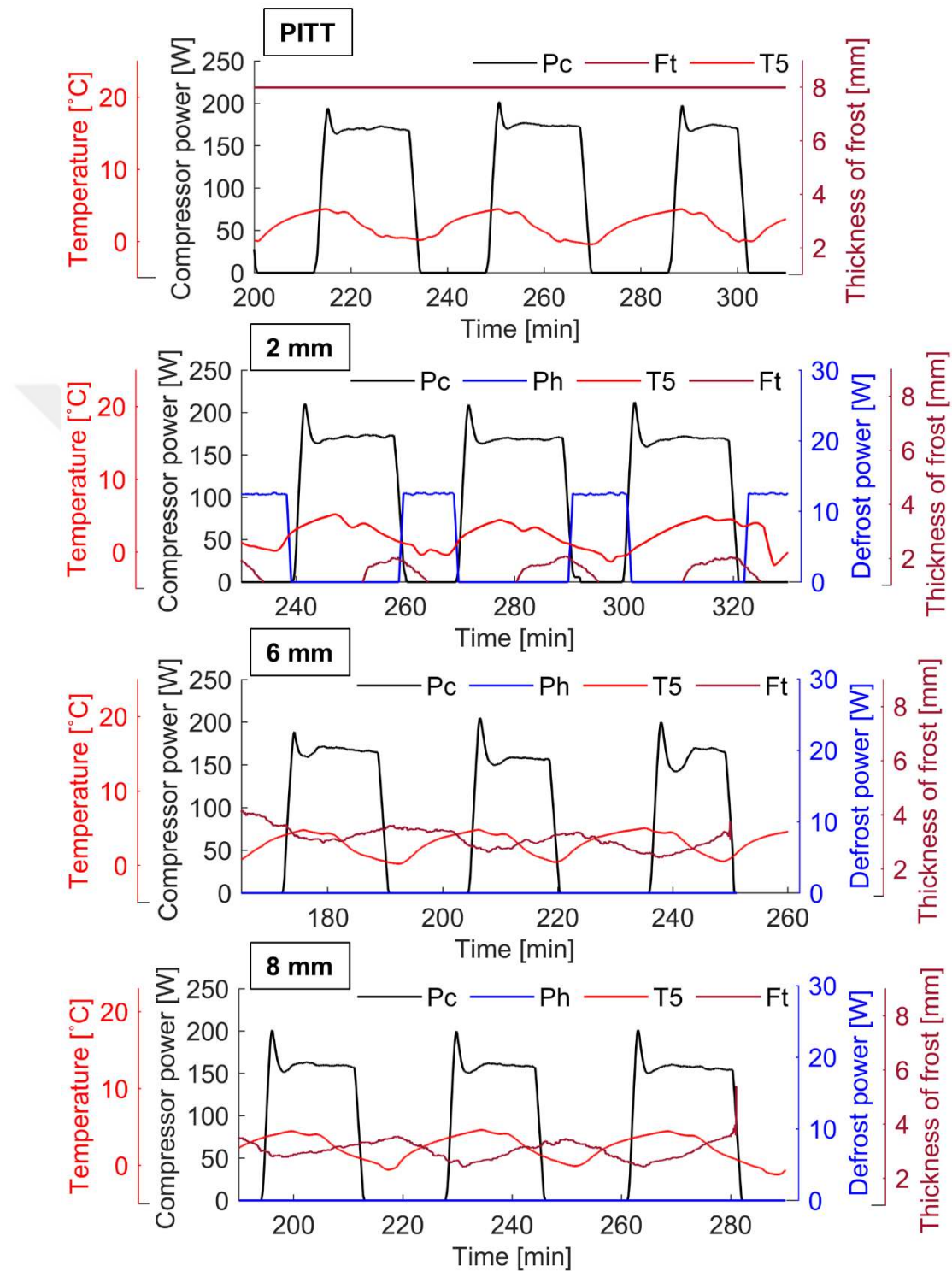


Figure 4.7: The power consumption of the compressor and the defrost heater, the thickness of frost and cabin temperature during the first three minor cycles of the periodically initiated temperature terminated (PITT) experiment, and the demand defrost experiments with the defrost threshold of 2 mm, 6 mm, and 8 mm.

The first minor cycle starts when the cabin temperature rises above the cut-in temperature. The temperature is maintained by the interrupted operation of the compressor which causes the thickness of frost carried forward from the major cycles to oscillate (as shown in Figure 4.7). These oscillations are visible in cases of demand defrost with 2 mm, 6 mm, and 8 mm defrost thresholds however, it remains beyond the measuring range of the hybrid system in the case of the PITT experiment. The thickness of frost remains below the defrost threshold in the minor cycles of demand defrost cases except for the 2 mm case (Figure 4.7). Therefore, if the evaporator is defrosted tactfully in the major cycle, then the level of frost remains below the critical threshold during the minor cycles. The total energy consumption of the minor cycles for the PITT case and the various defrost thresholds of the demand defrost technique are tabulated in Table 4-3.

Table 4-3: The summary of the average energy consumption during the major and minor cycles for the default PITT case and demand defrost case with various defrost thresholds.

Defrost control Strategy		Major cycle			Minor cycle				Total energy in 24 h [Wh]
		Energy [Wh]	Time [h]	No. of defrost cycles	Energy [Wh]	Time [h]	No. of cycles	No. of defrost cycles	
PITT		590	3.30	0	44.7	20.66	36	1	2156
Demand defrost	2	509	3.75	6	61.5	20.35	36	35	2711
	3	474	3.22	4	42.6	20.78	43	0	2280
	4	454	2.93	2	37.2	21.07	44	0	2077
	5	448	3.03	2	35.9	20.97	44	0	1975
	6	443	2.83	1	35.3	21.17	42	0	1933
	7	457	2.95	1	35.5	21.05	42	0	1949
	8	490	3.12	1	40.7	20.88	40	0	2119

4.4.3. Optimal defrost threshold

The effect of the defrost threshold on energy consumption is illustrated in Figure 4.8. The low defrost threshold of 2 mm adversely affects energy consumption as the system goes into the defrost cycle frequently. The frequent triggering of the defrost cycles increases the defrost energy which in turn increases the total energy consumption. The defrost threshold of 3 mm reduces the number of defrost cycles causing the energy consumption to reduce

significantly. Increasing the defrost threshold to 4 mm, 5 mm, and 6 mm further reduces energy consumption. The defrost threshold of 6 mm yields the minimum energy consumption with only 1 defrosts cycle in 24 hours. However, the defrost threshold of 7 mm and 8 mm causes energy consumption to increase even though the defrost cycle was triggered only once. The higher defrost thresholds allow the thickness of frost to increase before defrosting is triggered which leads to inefficient heat exchange. Furthermore, the higher thickness of frost also disrupts the airflow which increases the inefficiency of heat transfer. The same has been observed in the PITT case where the major cycle consumed higher energy due to the accumulation of frost beyond 8 mm. The difference in the energy consumption of the various demand defrost cases reinforces the importance of adaptation of the thickness of frost as the defrost threshold.

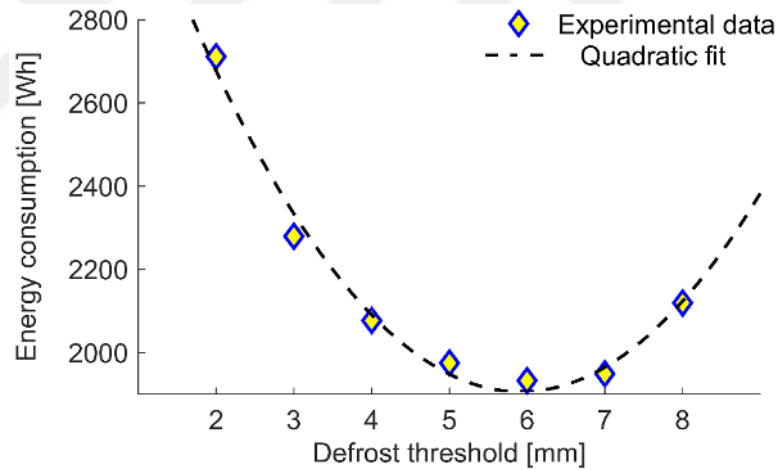


Figure 4.8: The effect of the defrost thresholds on the energy consumption of the refrigerator.

The correlation between energy consumption and the defrost threshold appears to be quadratic and can be approximated by Equation 1, with a coefficient of determination $R^2 = 0.98$.

$$E = 50.23D^2 - 600.75D + 3665 \quad (4.1)$$

The optimal defrost threshold can be estimated by the minimization of Equation (4.1) which turns out to be 5.97 mm and therefore, the 6 mm demand defrost case is considered optimal. The optimal defrost threshold based on the thickness of frost can now be utilized to implement the demand defrost technique to yield maximum energy conservation.

4.4.4. Comparison of the two defrost control methods

A total of 36 minor cycles were recorded on average during 24 hours in addition to an initial major cycle for the PITT experiments as illustrated in Figure 4.9. The system triggered the defrost cycle in the PITT experiment after 24 hours which lasted for 30 minutes on average, therefore increasing the total duration of the experiment to 24.5 hours. The average total energy consumption of the PITT experiment is 2211 Wh including the major cycle, minor cycles, and the energy spent on defrosting. The normalized energy consumption for 24 hours is therefore 2156 Wh.

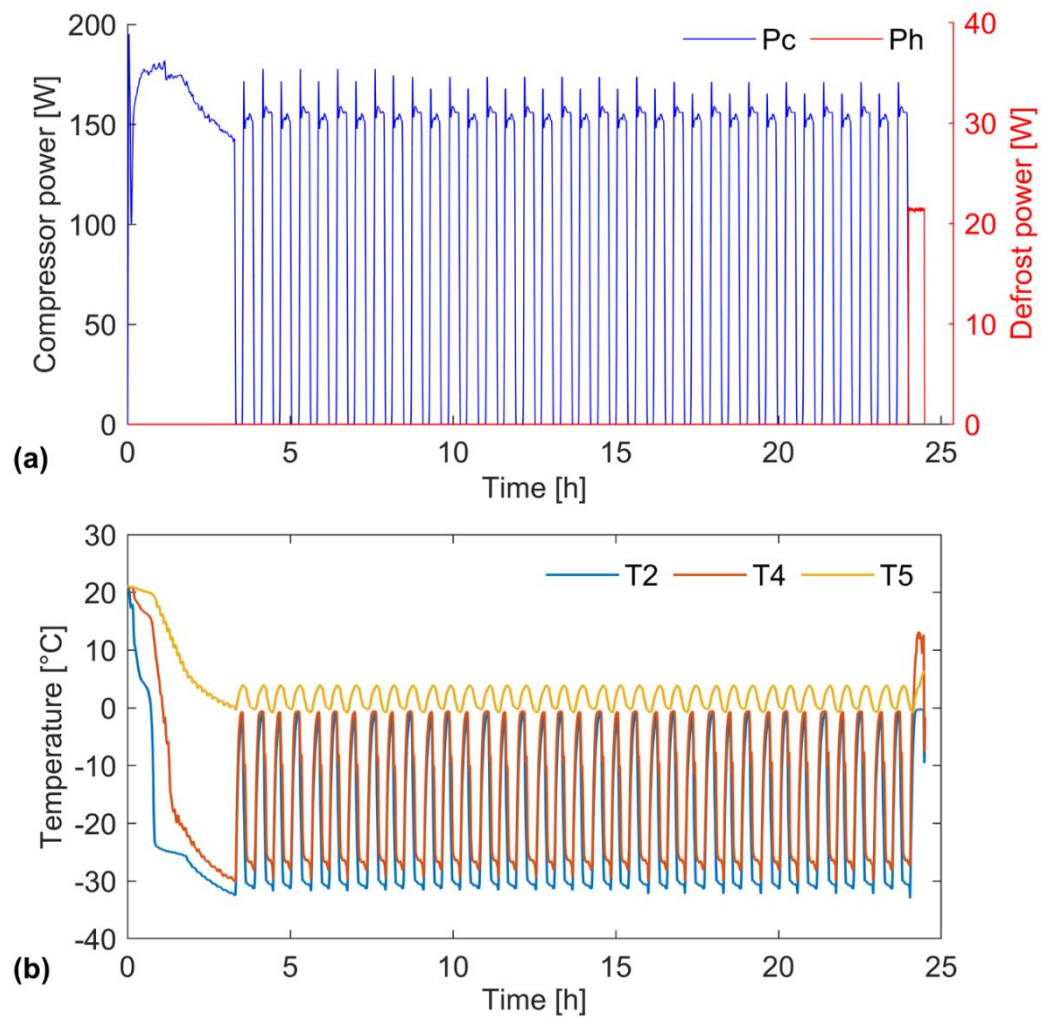


Figure 4.9: (a) The power consumption of the compressor (Pc) and the default defrost heater (Ph) along with the (b) evolution of the temperature of the evaporator (T2), default defrost heater (T4), and the cabin (T5) for the complete periodically initiated temperature terminated experiment.

The energy consumption of the demand defrost experiments with the optimal defrost

threshold of 6 mm yielded average energy consumption of 1933 Wh in 24 hours that includes the energy consumption of one major cycle, 42 minor cycles, and one defrosts cycle as illustrated in Figure 4.10.

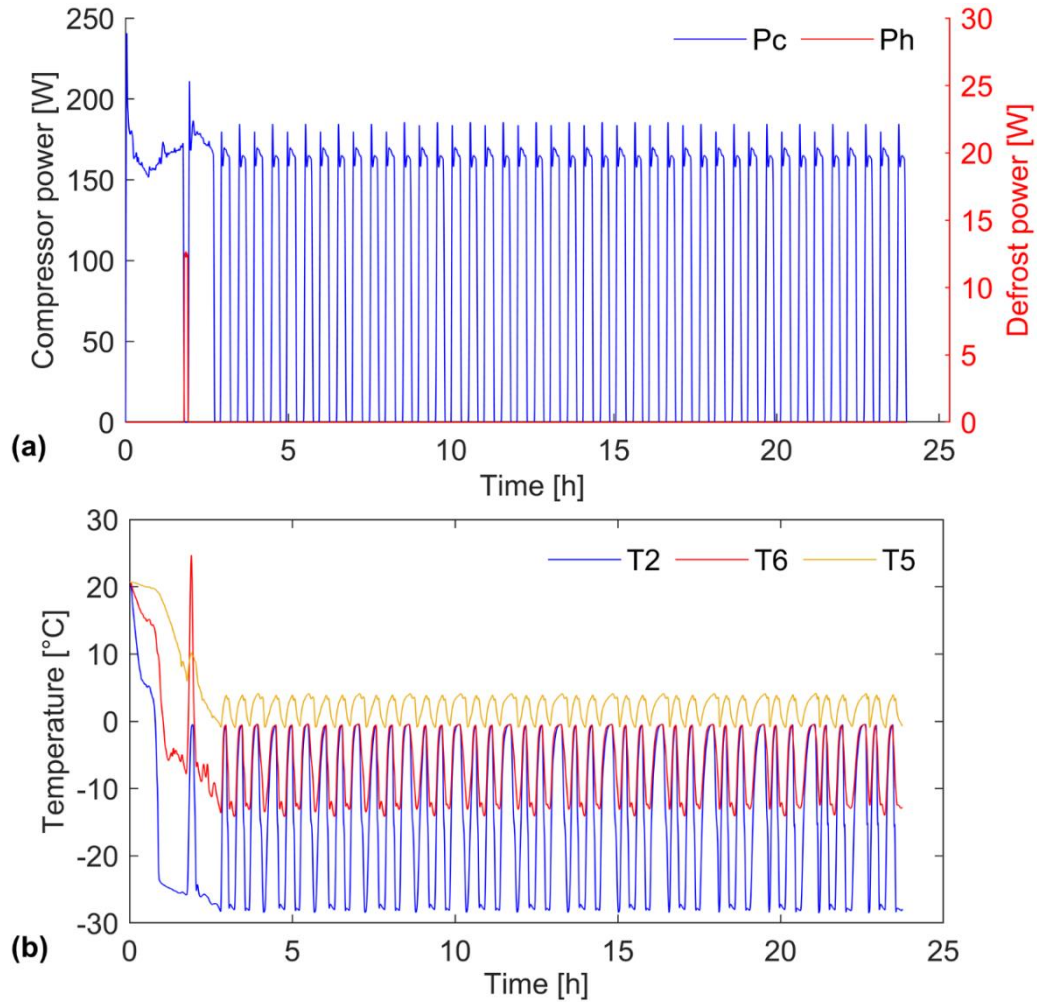


Figure 4.10: (a) The power consumption of the compressor (Pc) and the hybrid system heater (Ph) along with the (b) evolution of the temperature of the evaporator (T2), the cabin (T5), and hybrid system heater (T6), for the complete, demand defrost experiment with the optimal defrost threshold of 6 mm.

The frost grew unrestricted on the evaporator for the PITT case, on the other hand, the evaporator was defrosted as soon as the thickness of frost reached 6 mm, in the case of the demand defrost experiments with the optimal defrost threshold. Virtuous to the early detection of frost and quick defrosting using the hybrid system, the cabin temperature was achieved with a significantly lower expense of energy. Furthermore, the average thickness of frost on the evaporator during the minor cycles of the PITT case is significantly higher than

that of the demand defrost case. This additional thickness of frost leads to higher energy consumption on the minor cycles in the PITT case. It can be concluded that most of the frosting occurs in the major cycle due to the continuous operation of the compressor, which if not detected early and removed, will lead to a detrimental loss of energy until the next scheduled defrost.

The adaptation of the thickness of the frost-based demand defrost technique using the optimal defrost threshold of 6 mm yields a 10% reduction in the energy consumption as compared to the default PITT defrost strategy. The optimal defrost threshold ensures that the system takes advantage of the initial layer of frost and defrosts the evaporator only when the thickness of the frost layer causes thermal losses. Moreover, tackling the frost at a thickness of 6 mm significantly reduces the duration of the defrost cycle which in turn reduces the energy spent on defrosting.

4.4.5. The relation of frost with the operation of the compressor

The continuous operation of the compressor in the major cycle leads to a continuous increase in the thickness of frost. On the other hand, the intermittent operation of the compressor in the minor cycles causes the frost on the evaporator to melt partially during the compressor off-time. However, the frost starts to reappear during the compressor on time, and therefore, its thickness on the evaporator oscillates around the thickness carried forward from the major cycle. The frost stays below the optimal defrost threshold during the minor cycles in the demand defrost experiments for the test conditions. However, the door of a typical domestic refrigerator is opened several times throughout the day to store and retrieve items. The frequent opening of the cabin door during the minor cycles may increase the compressor on time which in turn causes the thickness of frost to increase. The effect of the opening of the cabin door on a partially frosted evaporator during minor cycles is studied by opening the door for 30 seconds after every 30 minutes. The ambient conditions remain the same as defined in section 4.3.3. Demand defrost was not employed in these experiments to demonstrate the extent to which frost may accumulate.

The effect of the door opening on the cabin temperature and thickness of frost is illustrated in Figure 4.11. Points A, B, C, and D represent the effects of the opening of the cabin door after every 30 minutes. The opening of the door for the first time causes the hot and humid air of the test room to enter inside the cabin which creates a sharp rise in the cabin

temperature and therefore, the compressor turns on. The thickness of frost increases as the compressor operates to reduce the cabin temperature. The subsequent door opening does not allow the target temperature to be achieved and therefore, the compressor must operate continuously, contrary to the intermittent operation expected in the minor cycles. The continuous operation of the compressor causes the thickness of frost to keep increasing which demonstrates its influence on frost. The thickness of frost can increase beyond the optimal defrost threshold during the minor cycles in real-life applications; therefore, the evaporator must be defrosted to revive the performance of the refrigerator. The application of real-time quantification of the thickness of frost-based demand defrost ensures that the effect of frosting stays manageable and does not deteriorate the performance of the refrigerator in both the major and minor cycles.

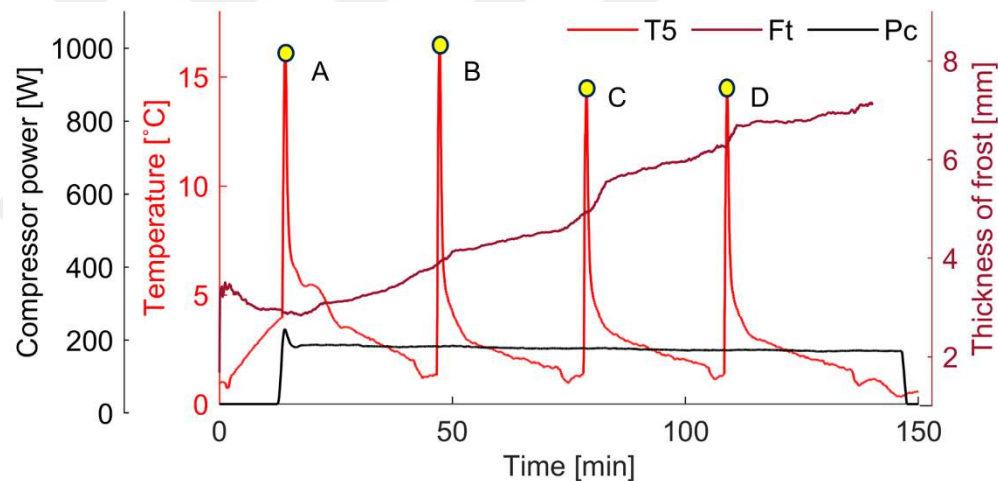


Figure 4.11: The evolution of temperature and the thickness of frost along with the power consumption of the compressor during the door opening experiment.

The manufactures of domestic refrigerators have carried exhaustive research and development to minimize energy consumption however, the energy conservation demonstrated by the thickness of the frost-based demand defrost technique in this study reflects room for improvement. The application of the demand defrost technique using the additively manufacturable hybrid system can bring a paradigm shift in the refrigeration industry enabling domestic refrigerators to smartly control the amount of frost on the evaporator to improve the energy rating.

4.5. Summary

In this chapter, the energy conservation of a domestic refrigerator is presented by the

implementation of a novel real-time thickness of frost-based demand defrost technique. The successful implementation of the demand defrost technique is owed to the accurate quantification of frost and the low-powered heater of the hybrid system. The following are the main conclusions drawn from the study.

- The growth of frost on the evaporator is highly influenced by the compressor's operation time.
- The periodically initiated and temperature terminated (PITT) defrost strategy leads to the uncontrolled growth of frost between consecutive defrost cycles resulting in inefficiencies.
- Defrosting the evaporator before the optimal defrost threshold of 6 mm leads to frequent defrost cycles which increases energy consumption. However, the thickness of frost beyond the optimal defrost threshold significantly deteriorates the performance of the test refrigerator.
- The difference in the energy consumption of the various defrost thresholds demonstrates the importance of the real-time quantification of the thickness of frost on the evaporator.
- The early detection and quantification of frost minimize the required defrost energy which allows the low-powered additively manufactured heater to successfully defrost the evaporator.
- The application of the novel, real-time thickness of frost-based demand defrost technique with the optimal defrost threshold yields energy conservation of 10% for the test refrigerator as compared to the default blind and periodic defrost control strategy.

The proposed method to implement the real-time thickness of the frost-based demand defrost technique can be applied to any domestic refrigerator owing to the adaptability of the hybrid system due to its additive manufacturability.

Chapter 5 : A FROST FEEDBACK BASED DISTRIBUTED DEFROSTING APPROACH TO IMPROVE THE ENERGY CONSERVATION OF REFRIGERATION SYSTEMS

5.1. Overview

The frosting is an inevitable phenomenon that bottlenecks the energy efficiency of domestic refrigerators. The commonly adopted defrost technique employs a single defrost heater with a blind, temperature-based termination criterion which may lead to incomplete defrosting. The incorporation of a frost feedback system can ensure complete defrosting of the evaporator. Furthermore, the uneven distribution of frost leads to early defrosting in certain regions of the evaporator and therefore, creates desynchronization in defrosting. In this chapter, a novel, frost feedback-based distributed defrosting approach to minimize desynchronization is proposed. The evaporator is divided into three regions based on the frost distribution pattern. Each of these regions was equipped with an additively manufactured low-powered defrost heater controlled by an optical frost feedback sensor. The frost feedback-based distributed approach proved to be effective in eliminating the defrosting desynchronization. The frost feedback enables the system to terminate defrosting as soon as the frost in the discretized region melts, which reduced the defrost energy significantly. The distributed approach minimizes the rise in the cabin temperature during defrosting and therefore, leads to the reduction of energy spent in the subsequent recovery cycle. The results of the frost feedback-based distributed approach were compared to the default temperature-based strategy using a single defrost heater. The frost feedback-based operation of the three distributed defrost heaters at 6 W each demonstrated maximum overall energy conservation of 18.9% as compared to the default temperature-based strategy.

5.2. Experimental setup and procedure

The experimental setup was comprised of five main components which include, optical frost detection sensors, additively manufactured defrost heaters, a domestic refrigerator, the data acquisition system, and the refrigerator control unit.

5.2.1. The optical frost detection sensor

The optical frost detection sensor was comprised of a 940 nm infrared (IR) transmitter and a receiver. The working principle of the optical frost detection sensor is based on the

change in the intensity of the IR radiations on the receiver end, in response to the change in the opacity of the frost when it melts. The amount of current flow in the receiver circuit is directly proportional to the varying intensity of the IR radiations on the receiver end. The melting of frost reduces the intensity of the IR radiations which decreases the current flowing through the receiver circuit. This change in the current changes the voltage response of the system as represented by Equation 5.1.

$$V_r = V_{cc} - I_r R_r \quad (5.1)$$

Where, V_r is the output voltage of the system, V_{cc} is the supply voltage, I_r represents the flow of current through the receiver and R_r is the total resistance in the receiver circuit. The transmitter and receiver were installed on the same plane directed towards the evaporator. Figure 5.1 illustrates the working principle of the optical sensor.

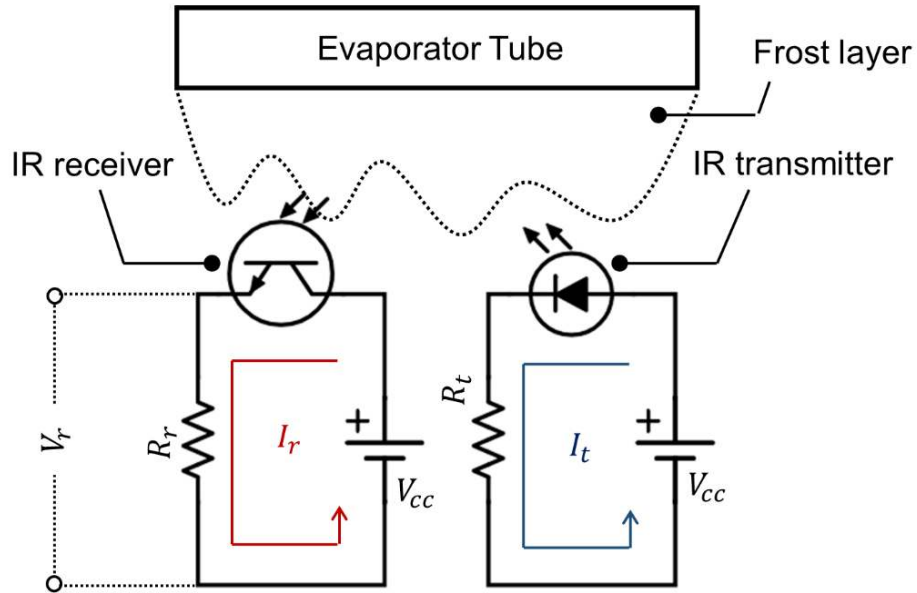


Figure 5.1: The schematic of the optical frost detection sensor.

The transition in the output voltage of the receiver circuit with respect to time during the presence of frost (~ 0.4 V), defrosting, and after complete defrosting (~ 4.0 V) is illustrated in Figure 5.2. The detection of complete defrosting by the optical sensor is used as the defrost termination criterion in this study.

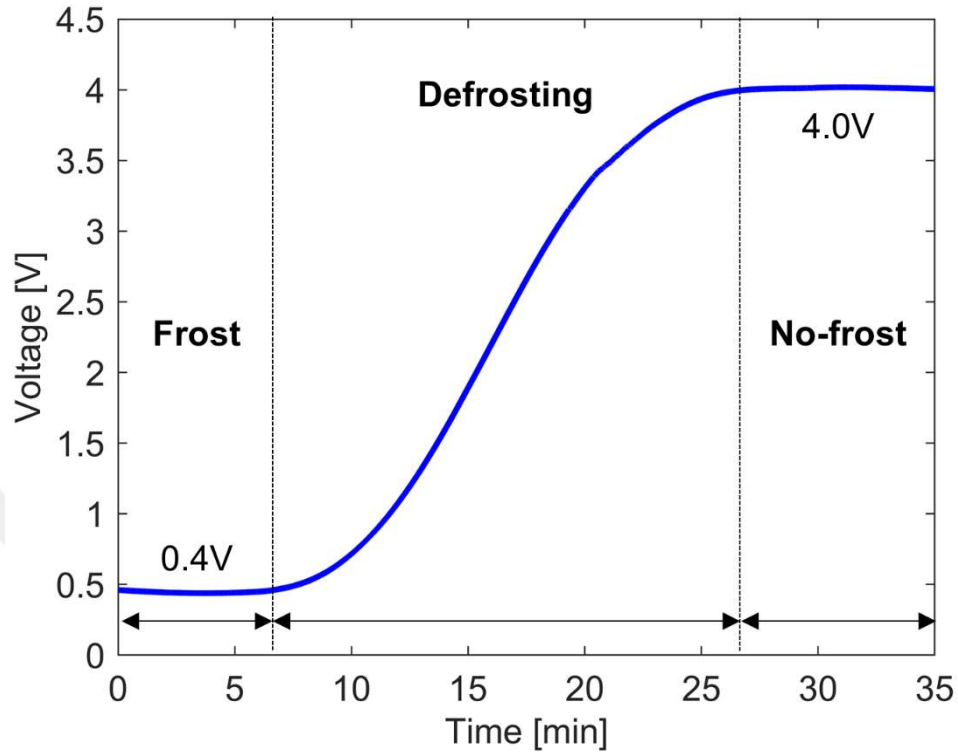


Figure 5.2: The output voltage response of the optical frost detection sensor in the presence of frost, during defrosting, and no-frost conditions

5.2.2. Additively manufactured defrost heater

The development of the defrost heater using a multi-material additive manufacturing setup is already described in Chapter 3, section 3.2.2. The heat produced by the additively manufactured heater is described by Equation 2.

$$H = V I t \quad (5.2)$$

where H is the heat produced, V is the input voltage applied, and I is the current drawn in time t . The power consumption by the additively manufactured heaters can be controlled by varying the input voltage.

5.2.3. Experimental apparatus

The test refrigerator was a double door-type domestic refrigerator installed in a room with controlled ambient conditions. The fresh food cabin (FFC) and the freezer cabin (FC) were comprised of a tube fin type dual evaporator along with a dedicated fan to generate a constant airflow for heat transfer through forced convection mode. The refrigerator employed an HC-R600a refrigerant with a variable speed compressor. The experiments were carried out inside the emptied fresh food cabin of the refrigerator whereas the freezer cabin remained

undisturbed throughout the experiments. The detailed specifications of the test refrigerator are already provided in Chapter 4, section 4.3.1, Table 4-1. The main controller of the refrigerator was bypassed with an external controller to control the speed and the operation of the compressor. A 12V DC fan, interfaced with the external controller was installed inside the refrigerator cabin to accelerate the heat transfer. A humidifier with an inbuilt humidity controller was installed inside the refrigerator cabin to maintain the desired humidity level to accelerate the frost accumulation throughout the experiment.

The temperature of the refrigerator cabin and the evaporator along with the wet and dry bulb temperatures inside the cabin were monitored using several J-type thermocouples. The humidity sensor was installed inside the refrigerator cabin to record the humidity changes during the experiment. The power consumption by the compressor, the additively manufactured distributed defrost heaters and the refrigerator's default defrost heater was monitored using hall-effect-based current sensors. The status of frost on the surface of the evaporator was visually monitored using a high-resolution digital camera. The detailed specifications of the measurement instrumentation used in the experiments are tabulated in Table 5-1. A customized graphical user interface was designed to display the output responses of the optical sensors, thermocouples, humidity and current sensors, the frosting and defrosting status of the evaporator, and the states of the defrost heaters. The data was acquired at the sampling rate of 0.2 samples/second and stored in a comma-separated value file for subsequent analysis.

Table 5-1: Specifications of the measuring instruments used in this study.

Item	Model	Quantity	Range	Uncertainty
Thermocouple	J-type	10	-60.0 to 400 °C	± 0.40 °C
Current sensor	ACS712	5	-5.0 to 5.0 A	± 0.0750 A
Humidity sensor	AM2301	2	0 to 99 %RH	± 3.0 %RH
Humidifier	WHC752	1	-	-
Digital camera	V-52	1	-	-

The evaporator in the refrigerator cabin of the test refrigerator had 12 tubes and a fins pitch of 10 mm. A single 20 W defrost heater was attached by default to the evaporator of the test refrigerator. Three additively manufactured heaters were installed on the top, middle, and bottom of the evaporator along with the three optical frost detection sensors, respectively. The melted frost for each defrosts cycle was collected in an external water container attached

at the exit of the refrigerator cabin's water drain pipe. The collected defrost water was weighed on a precise electronic weighing scale for subsequent analysis. The fresh food cabin of the test refrigerator, the data acquisition system, the default 20 W heater of the refrigerator, and the zoomed view of the evaporator highlighting the installation of optical frost detection sensors, additively manufactured distributed defrost heaters, and thermocouples are illustrated in Figure 5.3.

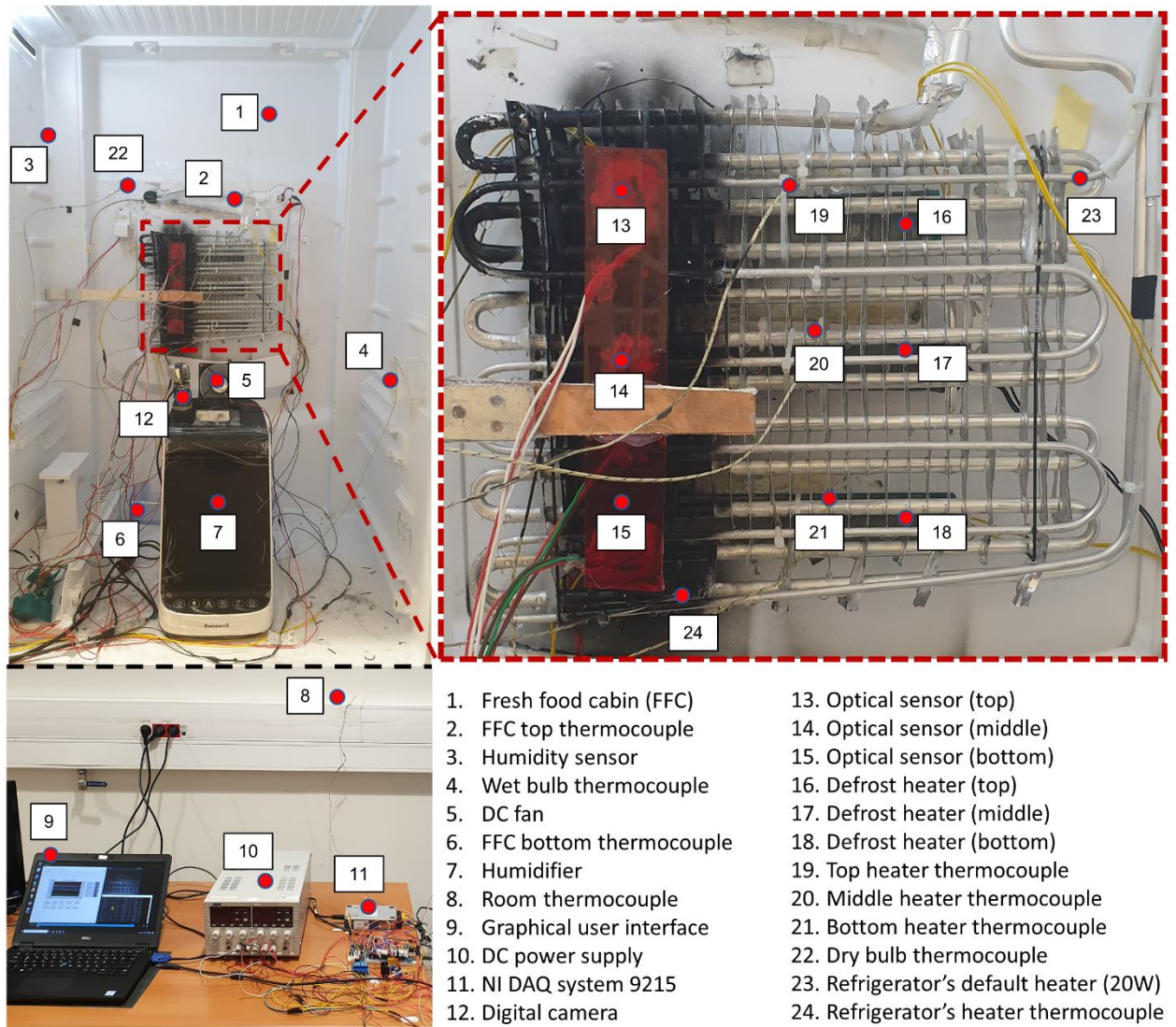


Figure 5.3: The experimental setup including the fresh food cabin (FFC) of the test refrigerator, the humidifier, the data acquisition system, the zoomed view of the evaporator with additively manufactured distributed defrost heaters, and optical sensors, and the location of the thermocouples.

5.2.4. *Determination of sensor and heater location*

The placement of the additively manufactured defrost heaters and the frost detection sensors on the evaporator should be determined tactfully so that the energy can be conserved during defrosting of unevenly distributed frost. The location of the additively manufactured heaters and the frost detection sensors is mainly dependent upon the frost distribution pattern on the surface of the evaporator. Typically, in the refrigerator cabin of the domestic refrigerators, the refrigerant enters the evaporator from the first tube (inlet), passes through the middle of the evaporator, and exits from the last tube (outlet) of the evaporator. There exists a temperature gradient between the inlet and the outlet of the evaporator tubing. This gradient in temperature can be attributed to the superheating of the refrigerant inside the evaporator tubing. The temperature near the inlet tubing drops down to -30°C quite earlier as compared to the outlet tubing. Therefore, frost starts to deposit near the inlet tubing and gradually reaches the middle. By the time frost reaches the outlet tubing of the evaporator, the amount of frost deposited earlier near the inlet tubing of the evaporator increases many folds. This uneven frost distribution pattern is also reported by [89].

Several experiments were performed to carefully observe the frost distribution pattern visually using a digital camera. Experiments were comprised of continuously running a compressor at a maximum speed for 2.5 hours while maintaining the 90 %RH humidity inside the refrigerator cabin to accelerate frost deposition. The accumulation of frost initiated from the top of the evaporator in every experiment and gradually moved down the vertical axis of the evaporator. There was a significant difference in the accumulation of frost in the top, middle, and bottom of the evaporator along the vertical axis whereas the variation in the accumulation of frost along the horizontal axis of the evaporator was negligible. The frost deposition starting from the top row of the evaporator varies in decreasing order along the vertical axis of the evaporator. The variation in the frost deposition along the vertical and horizontal axis of the evaporator is illustrated in Figure 5.4 (a). Based on these findings, the evaporator was divided into three distinct regions comprising of four tubes each. Three additively manufactured defrost heaters and three optical frost detection sensors were installed on the evaporator such that each distinct region contained one defrost heater and one optical frost detection sensor. The additively manufactured defrost heaters were installed and aligned in the middle of each region whereas the optical frost detection sensors were

installed on the left side of the evaporator. The heaters were attached to the fins of the evaporator to transfer heat mainly through conduction. The distance of 20 mm was kept between the plane carrying optical sensors and the evaporator to attain the maximum sensitivity. Figure 5.4 (b) illustrates the location of the additively manufactured defrost heaters (H1, H2, and H3) and the optical frost detection sensors (S1, S2, and S3) on the evaporator.

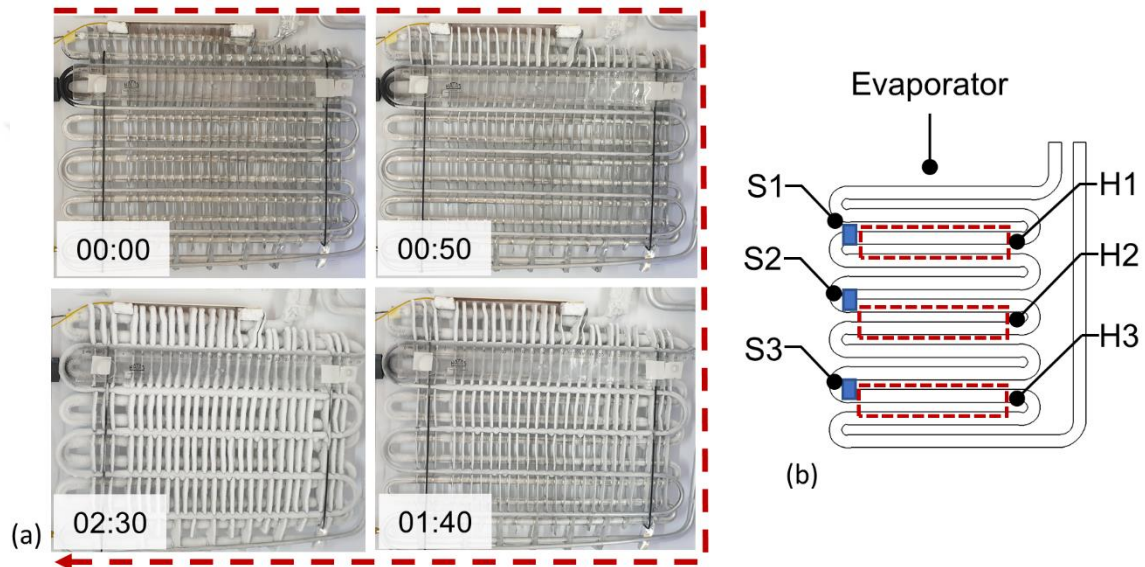


Figure 5.4: (a) The distribution of frost along the horizontal and vertical axis of the evaporator in time [HH: MM]. (b) The placement of additively manufactured defrost heaters top (H1), middle (H2), and bottom (H3) along with the optical frost detection sensors top (S1), middle (S2), and bottom (S3) on the evaporator.

5.2.5. Experimental procedure

To analyze the defrosting performance of the additively manufactured distributed defrost heaters with frost feedback, several experiments were conducted. The experiments were divided into two types. Type 1 dealt with the defrosting performance of the default defrost strategy that uses the single heater with a temperature-based (7°C) defrost termination criterion. Type 2 dealt with the additively manufactured distributed heaters with frost feedback as the defrost termination criterion.

The experiments were carried out under controlled ambient conditions where the room temperature was maintained at $20 \pm 4^{\circ}\text{C}$ and the relative humidity at $60 \pm 5\% \text{RH}$. The door of the refrigerator cabin was left open for 8 hours, before the start of every experiment to remove any residual melted frost water from the evaporator and to maintain an equilibrium

with the ambient conditions. The experiment was started by triggering the compressor of the refrigerator to run at a constant speed of 4200 RPM. The humidifier was set to maintain a relative humidity of 90 %RH inside the cabin. The door of the refrigerator cabin remained closed throughout the experiment. The compressor was kept running until the cabin temperature dropped down from ambient temperature to a predefined threshold value of $2 \pm 0.5^{\circ}\text{C}$. The high humidity level inside the cabin resulted in the substantial deposition of frost. The defrosting was initiated at this moment and the cabin fan remained off during defrosting.

The termination criteria of defrosting for type 1 experiments were based on the output of the thermocouple that was mounted above the left corner of the evaporator. Defrosting was terminated when the output of the thermocouple exceeded 7°C . The termination criterion of defrosting for type 2 experiments was based on the output of the optical frost detection sensors. Defrosting was terminated when the output voltage of the optical frost feedback sensor rose to 4 V. A dwell period of two minutes was inserted in the control algorithm after the defrost termination, to drain any residual melted frost from the evaporator. The compressor was then triggered back along with the cabin fan to execute the recovery cycle. The experiment was completed when the cabin temperature dropped back to the predefined threshold value of $2 \pm 0.5^{\circ}\text{C}$.

Virtuous to the resistive nature of the additively manufactured defrost heaters, the power consumption of the distributed heaters can be controlled by varying the input voltage. The heat generated by the heaters per unit time varies in direct proportion to the input power. Therefore, the type 2 experiment was divided into five subcategories based on different input power levels to evaluate the optimum defrosting performance with minimum energy consumption. The details of different input power levels and the average of the maximum attainable temperature for additively manufactured distributed defrost heaters are tabulated in Table 5-2.

Table 5-2: Input power and the average maximum attainable temperature of the additively manufactured distributed defrost heaters.

Type 2	Power [W]	Temperature [°C]
A	12	55.5 ± 1.6
B	10	47.3 ± 1.8
C	8	37.9 ± 2.1
D	6	30.6 ± 2.3
E	4	19.7 ± 1.9

5.3. Results and Discussion

The average mass of the frost melted during type 1 and type 2 experiments was 122 ± 4 g. The amount of frost deposited in all the experiments is assumed to be equal owing to the consistency in the experimental conditions and the low variation in the mass of the melted frost.

5.3.1. Defrosting synchronism

The defrosting synchronization of type 1 and type 2 experiments was investigated using the digital camera as well as the optical frost feedback system. The rise in the cabin temperature, the power consumption of the defrost heater, and the evolution of the temperature of the heater and various regions of the evaporator along with the digital images of the evaporator during defrosting of the type 1 experiment are presented in Figure 5.5.

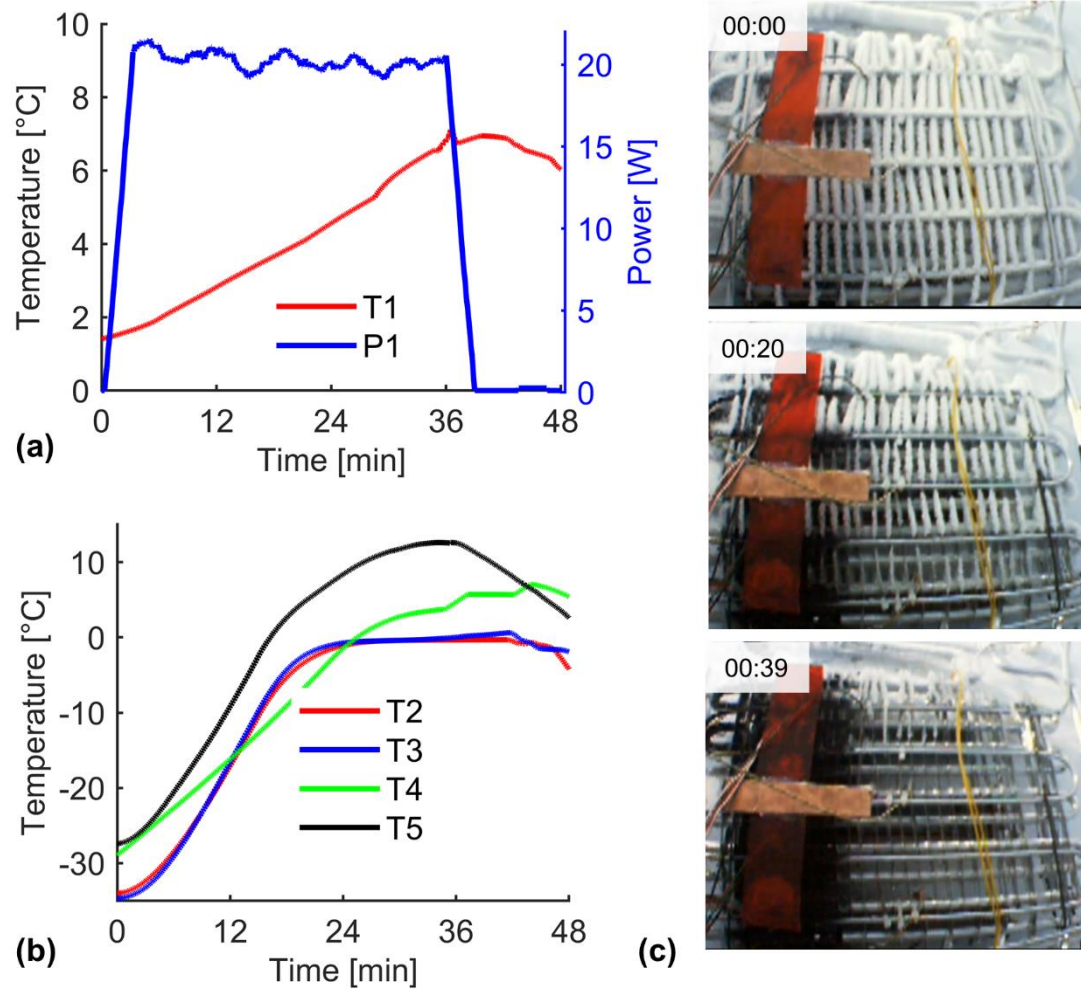


Figure 5.5: Test results of the defrost cycle of type 1 experiments. (a) The evolution of cabin temperature (T1) and the power consumed by the default defrost heater. (b) The evolution of the temperature of the evaporator (T2 – top, T3 – middle, T4 – bottom) and the defrost heater (T5). (c) Digital images of the status of the evaporator at various intervals.

The response of the optical frost feedback system, the total power consumed by the distributed defrost heaters, the evolution of the temperature of the evaporator, distributed defrost heaters, and the cabin temperature along with the digital images of the evaporator during the defrost cycle of the type 2 experiment are illustrated in Figure 5.6. The points X, Y, and Z in Figure 5.6 (a) represent the termination of the bottom, middle, and top defrost heaters, respectively.

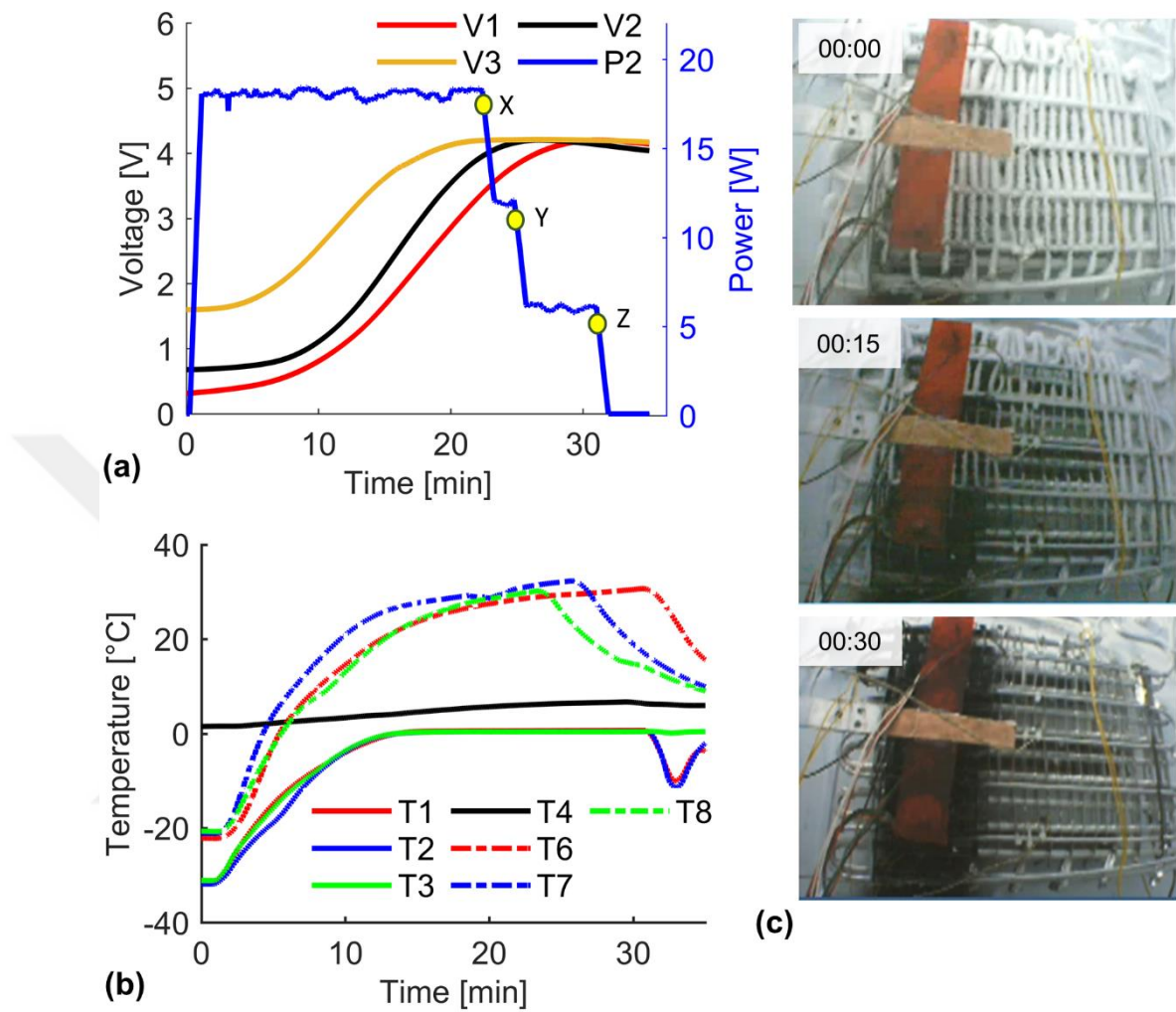


Figure 5.6: The results of the defrost cycle of a typical type 2 experiment with three distributed defrost heaters operating at 6W each. (a) The response of the frost feedback system (V1 – top, V2 – middle, V3 – bottom) and the total power consumed by the distributed defrost heaters (P2). (b) The evolution of the temperature of the fresh food cabin (T1), evaporator (T2 – top, T3 – middle, T4 – bottom), and the distributed defrost heaters (T6 – top, T7 – middle, T8 – bottom). (c) Digital images of the status of the evaporator at various intervals.

The uneven distribution of frost results in early defrosting of some regions of the evaporator in both types of experiments. However, the type 1 experiment is impervious to the state of the evaporator and relies solely on the cabin temperature to terminate defrosting. Therefore, the default heater of the evaporator remained on for approximately 39.6 minutes during which the temperature of the cabin rose to 7°C. However, the images in Figure 5.5 (c) indicate that a significant amount of frost remains on top of the evaporator at the end of the

defrosting cycle. Therefore, it may be concluded that the cabin temperature is an inept criterion for the termination of defrosting, as it cannot guarantee the complete defrosting of the evaporator. The defrost desynchronization can be observed in the digital images in Figure 5.5 (c). Furthermore, the region-based synchronization of frost cannot be achieved using a single continuous heater, and therefore, heat loss to the cabin increases in regions where the frost has melted earlier. On the other hand, the distributed defrost heating approach in typical type 2 experiments detected the region-wise melting of frost and terminated the respective heater accordingly, and therefore, the total defrost power decreases. The defrost cycle duration, of a typical type 2 experiment with three distributed defrost heaters operating at 6 W each, was 31 minutes however, the bottom region was defrosted in 23 minutes whereas, the middle region took 26 minutes. Therefore, the synchronization of the distributed defrost heaters was achieved with their respective regions based on frost feedback. Furthermore, the digital images in Figure 5.6 (c) reflect the complete defrosting of the evaporator in the type 2 experiments which demonstrate the effectiveness of the frost feedback as the criterion of defrosting termination.

The defrosting synchronization of distributed regions minimizes the heat loss to the cabin and therefore, the complete defrosting of the evaporators was achieved at temperatures lower than 7°C. A typical type 2 experiment with three distributed defrost heaters operating at 6 W each demonstrated a 1.75°C reduction in the cabin temperature at the end of the defrosting cycle. This decrease in the cabin temperature at the end of the defrost cycle was attributed to the decrease in the total energy supplied to the system due to the early termination of defrosting in certain regions of the evaporator.

5.3.2. *Energy consumption in the recovery cycle*

The evolution of cabin temperature and the power consumed by the compressor during the recovery cycles for the type 1 experiment and a typical type 2 experiment with three distributed defrost heaters operating at 6 W each are illustrated in Figure 5.7. The total energy spent during the recovery cycle of a type 1 experiment was 92Wh whereas a typical type 2 experiment spent 77 Wh of energy. The significant reduction in the energy expenditure in the recovery cycle of the type 2 experiment was owed to its low cabin temperature at the end of the defrost cycle.

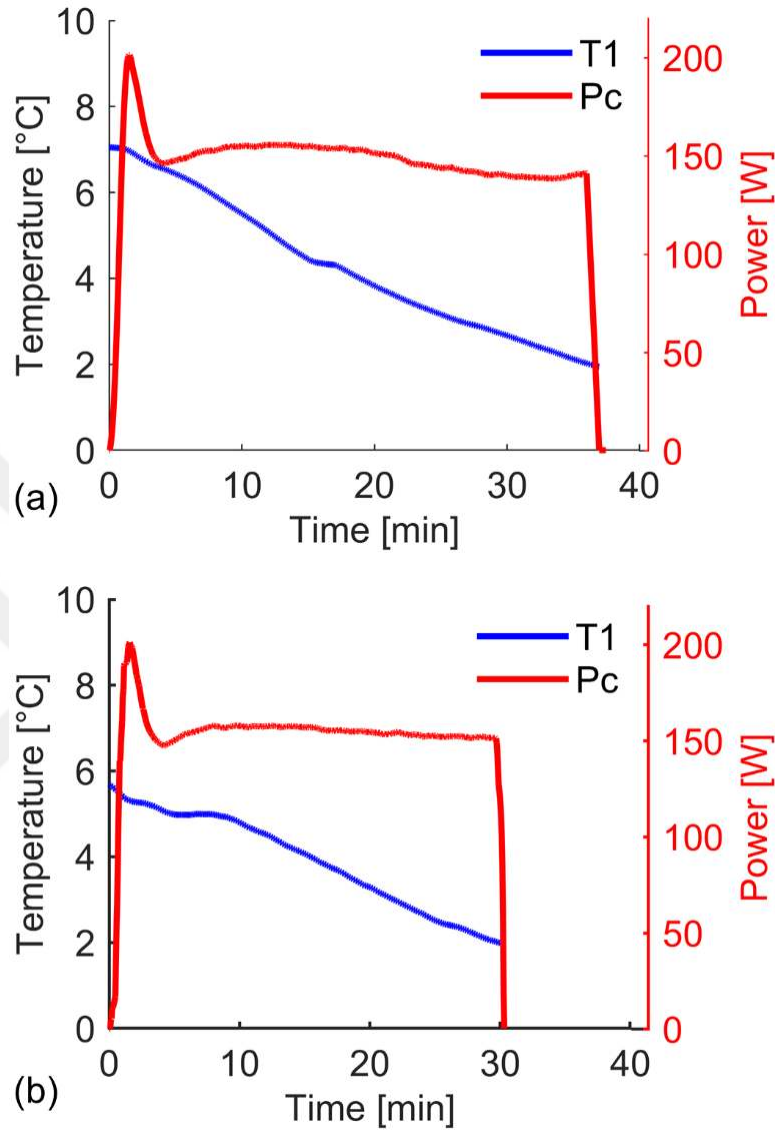


Figure 5.7: The evolution of the temperature of the fresh food cabin (T1) and the power consumption by the compressor (Pc) in the recovery cycles of (a) type 1 experiment and (b) a typical type 2 experiment with three distributed defrost heaters operating at 6 W each.

5.3.3. Effect on the overall defrost energy consumption

The overall defrost energy consumption of the distributed defrost heater approach in type 2 experiments remains lower than that of type 1 experiments. The lower energy expenditure is owed to the early termination of the defrost heater in certain regions of the evaporator. The energy conserved in the recovery cycle also plays a vital role in reducing the overall defrost energy consumption. A typical type 2 experiment with three distributed defrost heaters operating at 6 W each consumed 85.1 Wh of overall defrost energy, whereas

the type 1 experiment consumed 104.95 Wh.

The power input to the distributed defrost heaters plays a crucial role in the overall defrost energy consumption. The overall energy consumptions of type 1 and type 2 experiments with various power inputs as discussed in section 5.2.5 are tabulated in Table 5-3. Operating the distributed defrost heaters at a power above 6 W reduces the defrost duration at the cost of higher defrost energy expenditure, however, the high temperature of the heaters facilitates the heat loss to the cabin which also increases the energy consumption in the recovery cycle. On the other hand, operating the distributed defrost heaters at powers lower than 6 W reduces the energy spent on defrosting, consequently the defrost duration increases which increases the cabin temperature at the end of the defrost cycle. Therefore, the energy spent in the recovery cycle increases. The operation of the distributed defrost heaters at 6 W each yielded the maximum reduction of 18.9% in the overall energy consumption as compared to the default temperature-based strategy adopted in the type 1 experiment.

Table 5-3: Region wise (T = top, M = middle, and B = bottom) defrosting performance comparison between different types of experiments.

	Parameter	Type 1	Type 2														
			A			B			C			D			E		
Defrosting	Region	-	T	M	B	T	M	B	T	M	B	T	M	B	T	M	B
	Power [W]	20	12	12	12	10	10	10	8	8	8	6	6	6	4	4	4
	Duration [minute]	39.6	24.3	21.5	19.9	27.8	23.9	20.4	29.1	24.8	21.6	31.2	25.9	23.7	35.7	29.6	27
	Energy [Wh]	13.2	4.6	4.3	3.9	4.6	3.9	3.4	3.8	3.3	2.8	3.1	2.6	2.4	2.8	2	1.8
	Temperature rise [°C]	7.05		6.5			6.2			5.8			5.3			5.9	
Recovery	Duration [minute]	36.7		34.2			33.1			31.9			30.8			32.3	
	Energy [Wh]	91.75		85.5			82.7			79.7			77.1			80.7	
Overall energy [Wh]		104.95		99.1			94.7			89.8			85.1			86.9	

5.3.4. Efficacy of the distributed defrost heaters with frost feedback

The results indicate that the complete melting of frost can be achieved at cabin temperatures lower than 7°C. Therefore, the blind heating of the system in temperature-based defrost termination strategies lead to an increase in the energy spent on defrosting as well as the energy consumed by the subsequent recovery cycle. Furthermore, the difference in the termination time of the distributed heater reinforces the different heat requirements of various regions of the evaporator due to the uneven distribution of frost. The distributed defrost system virtuous to its region-based frost feedback enables the system to conserve defrost energy along with a significant reduction in the energy consumed in the recovery cycle. The proposed distributed defrosting approach can be scaled up for industrial refrigeration applications.

5.4. Summary

In summary, this chapter proposed a novel approach to combat the desynchronization of defrosting caused by the uneven distribution of frost on the evaporator. The evaporator was discretized into three regions with each region having its independent additively manufactured defrost heater and a frost feedback sensor. The transition from the commonly adopted temperature-based defrost termination criterion to the frost feedback-based criterion eliminated the defrosting desynchronization. The defrosting synchronization reduces the defrost energy consumption. The distributed approach reduces the rise in the cabin temperature during defrosting which leads to significant energy conservation in the recovery cycle. The proposed defrosting approach using distributed heaters, operating at 6W each, resulted in overall energy conservation of 18.9% as compared to a temperature-based counterpart. The proposed approach is simple and easily adoptable owing to the low cost of the components and the additive manufacturability of the system.

Chapter 6 : CONCLUSION

Frosting on the surface of the evaporator of the refrigeration systems is proven to be the most detrimental phenomenon. Frost deposits on the surface of the evaporator when the water vapors present in the refrigerator cabin interact with the cold surface of the evaporator. The very initial frost layer improves the heat transfer as it results in increasing the surface of the evaporator. However, as the frost layer gets thicker, the heat transfer decreases because frost acts as a thermal resistance between the cold surface of the evaporator and the surrounding air inside the refrigerator. Furthermore, the deposition frost blocks the air passage through the evaporator, which is required for convective heat transfer. Consequently, the refrigerator takes more time to maintain the cabin temperature and the compressor starts consuming excessive power. Therefore, a smart defrosting system is mandatory for refrigeration systems to maintain the rated performance coefficient.

In this research, a novel hybrid frost detection and defrost system (HFDDS) for refrigeration systems have been developed using a combination of photoelectric sensing, capacitive sensing, and resistive heating techniques. The frost detection module is comprised of an infrared (IR) based optical couple and a capacitive sensing module (CSM). The evaporator of the refrigerator and an additively manufactured cathode (AMC) were used as a parallel plate capacitor for capacitive sensing. The AMC was manufactured using a graphite-based polymer composite with a moderate electrical conductivity which enables the use of AMC as a resistive heater for defrosting. The frost detection range of the HFDDS is from 1 mm to 8 mm with a 5% margin of error. The HFDDS triggers defrosting when a critical thickness of frost is reached. This critical threshold can be adjusted based on the application. The developed HFDDS is flexible, allowing the use of application-specific geometries of photoelectric and capacitive sensing modules. Additionally, results show that the additively manufactured graphite-based heating elements could potentially be used as a low-power defrosting system for commercial refrigeration systems.

The successful development and validation of a hybrid frost detection and defrost enabled us to study further about improving the energy conservation of the refrigeration systems. Therefore, the developed hybrid system was employed to investigate the energy

conservation of a domestic refrigerator by implementing a novel real-time thickness of frost-based demand defrost technique. The successful implementation of the demand defrost technique was owed to the accurate quantification of frost and the low-powered heater of the hybrid system.

The growth of frost on the evaporator is highly influenced by the compressor's operation time. The periodically initiated and temperature terminated (PITT) defrost strategy leads to the uncontrolled growth of frost between consecutive defrost cycles resulting in inefficiencies. Defrosting the evaporator before the optimal defrost threshold of 6 mm leads to frequent defrost cycles which increases energy consumption. However, the thickness of frost beyond the optimal defrost threshold significantly deteriorates the performance of the test refrigerator. The difference in the energy consumption of the various defrost thresholds demonstrates the importance of the real-time quantification of the thickness of frost on the evaporator. The early detection and quantification of frost minimize the required defrost energy which allows the low-powered additively manufactured heater to successfully defrost the evaporator. The application of the novel, real-time thickness of frost-based demand defrost technique with the optimal defrost threshold yields energy conservation of 10% for the test refrigerator as compared to the default blind and periodic defrost control strategy. The proposed method to implement the real-time thickness of the frost-based demand defrost technique can be applied to any domestic refrigerator owing to the adaptability of the hybrid system due to its additive manufacturability.

The frosting is a dynamic process as it depends on several varying parameters. Therefore, the deposition of frost on the surface of the evaporator is not uniform. This non-uniform deposition of the frost results in desynchronization during the defrost process. Modern frost-free refrigeration systems employ a single high-powered electric heater to defrost the evaporator. However, due to uneven frosting, the single electric heater may end up removing the frost from some regions of the evaporator earlier as compared to other regions. Therefore, it may result in increasing the refrigerator cabin temperature and excessive energy consumption during defrosting and in the subsequent recovery cycle. Considering this uneven frosting problem, we proposed a novel approach to combat the desynchronization of defrosting caused by the uneven distribution of frost on the evaporator. The evaporator was discretized into three regions with each region having its independent

additively manufactured defrost heater and a frost feedback sensor. The transition from the commonly adopted temperature-based defrost termination criterion to the frost feedback-based criterion eliminated the defrosting desynchronization. The defrosting synchronization reduces the defrost energy consumption. The distributed approach reduces the rise in the cabin temperature during defrosting which leads to significant energy conservation in the recovery cycle. The proposed defrosting approach using distributed heaters, operating at 6W each, resulted in overall energy conservation of 18.9% as compared to a temperature-based counterpart. The proposed approach is simple and easily adaptable owing to the low cost of the components and the additive manufacturability of the system.

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