Journal of Food Technology Research
2017 Vol. 4, No. 1, pp. 16-31
ISSN(e): 2312-3796
ISSN(p): 2312-6426
DOI: 10.18488/journal.58.2017.41.16.31

MANAGEMENT OF FOOD SHELF LIFE AND ENERGY EFFICIENCY WITH ADAPTIVE FOOD PRESERVATION SYSTEM (AFPS) APPLIANCE

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Article History
Received: 7 June 2017
Revised: 18 July 2017
Accepted: 24 July 2017
Published: 27 July 2017

Keywords
Food wastage
Energy efficiency
Adaptive food preservation system (AFPS)
Active thermal insulation
Refrigeration
Food Quality.

ABSTRACT

This paper demonstrates how Adaptive Food Preservation System (AFPS) Appliance reduces the total energy expenditure in food preservation via reduction of food wastage and of thermal gradient between food storage space and the Appliance compartment. It is motivated by the fact that current energy efficiency effort in refrigerators predominantly focuses compressor efficiency, directly or indirectly. However, if foods are wasted before being consumed, the energy consumed along the Cold Chain (manufacturing and logistics) and in household refrigeration will both be wasted. Enhanced by AFPS Packages and Active Thermal Insulation, an AFPS Appliance has two functionalities - Shelf Life Management is responsible for food wastage reduction while Energy Efficiency Management is the responsible for reducing energy consumption through reduction of thermal gradient. The optimal compartment temperature range for the Appliance to reduce thermal gradient is between 10°C and 15°C, which results in a reduction of thermal gradients by 69.6% (between compartment and chiller) and 38.2% (between compartment and freezer), when compared with that of today's refrigerator. Experimentation on simulated compartment and chiller shows a 50.2% reduction. Sources of deviation and the corresponding rectifications are proposed to bring the reduction up close to 69.6%.

Contribution/Originality: The paper's primary contribution is finding that the Appliance's energy efficiency can be reduced with active insulation by reducing the thermal gradient (between foods and compartment space). The paper also contributes the first logical analysis of Shelf Life Management by networking with supermarkets, other AFPS Appliances in the neighborhoods, etc.

Nomenclature

AFPS	Adaptive Food Preservation System
ATI	Active Thermal Insulation
D	Characteristic Distance
DEF	Defrosting
EEM	Energy Efficiency Management
FF	Fast Freezing
h	Heat Transfer Coefficient

ICS	Intelligent Control System
IoT	Internet of Things
K	Conductivity
LTM	Low Temperature Maintenance
Nu	Nusselt Number
Pr	Prandtl Number
Ra	Rayleigh's Number
Re	Reynolds Number
RTD	Ready-To-Drink
SLM	Shelf Life Management
T_{amb}	Ambient Temperature
T_{A0}	Equivalent Surface Temperature of Compartment Box (all five surfaces)
T_{A1}	Temperature of Compartment Box Surface A1 Only
T_{comp}	Compartment Temperature
T_{pack}	Temperature At The Middle of An AFPS Package (including the simulated one)
THA	Thawing

1. INTRODUCTION

Energy efficiency has been pursued relentlessly by home appliance industries, particularly since the introduction of Energy Labelling Scheme. Among all home appliances, refrigerators consume the largest proportion of energy in typical households, primarily because of its continuous operation. A number of existing and emerging technologies help refrigerators to reduce energy consumption, including but not limited to improvement or new design in hardware (e.g. inverter compressor (Bijanzad *et al.*, 2016) hot-wall condenser (Akash *et al.*, 2014) vacuum insulation panel (Dow Corning, 2013) and in firmware and software (Texas Instrument Refrigerator and Freezer Solution Guide, 2016). While these technologies have gained significant merit, their contribution is only as good as the foods that are being refrigerated. Regardless of the energy efficiency rating, the refrigeration effort is still wasted if the compartment space is not loaded, lightly loaded, or loaded with spoiled food. In addition, refrigeration of foods for extended period of time before consumption can also be considered wasteful from energy perspective. In fact, the longer food items stay in refrigerator, the higher chances that they spoil and then become wasted before expiry.

1.1. Significance of Food Wastage

1.1.1. Causes of Food Wastage in Households

The fact that many food items can be stored safely in refrigerators for months has been emphasized out of proportion. In general, good food quality is considered equivalent to long shelf life. However, food suppliers and general consumers do have different emphasis. Food suppliers need to see long shelf life so that food can survive along the supply chain which may cover long distance and inventory time. For consumers, quality and safe foods are their primary wish. Technically, many food items can survive in refrigerators for months (Ronan, 2008) but why would consumers want to stock foods way ahead of their consumption or well beyond their next shopping trip? Stocking food at home for extended period of time means that money are spent too soon and very likely causes "not being used in time" which eventually translates into food wastage. In addition, the energy for refrigeration during the extended period of time is also lost. Such over-stocking causing "food not being used in time" or "foods being forgotten until after expiry" constitutes 48% of all food wastage (Tom and Liam, 2014).

1.1.2. Food Wastage Translates into Energy Wastage

Tremendous amount of energy and resources are used in food production (Banja *et al.*, 2015). As much as 40% of all foods in the United States are wasted in 2012 (Dana Gunders, 2012). Substantial food wastage can also be found in most other developed or developing economies. However, most of the public is not aware of the significance in the induced energy and resource wastages when deciding whether to purchase or throw away foods.

One example is that the energy used along the life cycle of producing and delivering pork, or along the Cold Chain, is about 38.7 MJ/Kg (Foster *et al.*, 2006). If only one Kg of pork spoils in a refrigerator per month due to "not being used in time", totally 464.4 MJ of energy will be wasted annually, and that is 1.65 times of all the energy saved (281 MJ or 78 KWh) by average refrigerator through energy improvement effort from 2004 to 2014 in Europe (Anette *et al.*, 2015). If beef is considered instead, about 44 MJ/Kg (Foster *et al.*, 2006) will be expensed in production and logistics. One Kg of spoilage per month translates into a total of 528 MJ energy wasted on annual basis.

A critical way to see the consequence of food wastage is that if, in average, one Kg of beef is spoiled monthly in a household refrigerator consuming 300 kWh of energy in a year (typical for a 150L refrigerator), 528MJ (equals to 146.7kWh) will be wasted annually. This is 49% of the 300 kWh annual energy consumption of the refrigerator. That means by considering just beef only in wastage, a household with one refrigerator is spending energy as if it operates 1.5 of it (the energy cost will increase accordingly). Note that a larger size refrigerator will suffer from higher energy loss in case of food wastage.

Meats, in general like poultry and fishes combined, account for 41% of all foods wasted while vegetables and diary account for 17% and 14% respectively (Jean and Jeffrey, 2012). That means at least 72% of all foods wasted need refrigerated storage. It is clear now that improvement in food wastage can make significant contribution to energy efficiency, or to a larger scope, the total energy expenditure in food preservation.

1.2. Thermal Gradient Translates into Energy Wastage

Another aspect of energy efficiency improvement is the high thermal gradient between foods and their ambient. Typical structure of today's refrigerator is that there is only one set of insulation system (made up of compartment wall and door seal) between foods and the ambient. Therefore, the compartment space itself is not considered as insulation because its primary function is to chill or freeze the foods being accommodated.

32°C and 16°C are the maximum and minimum ambient temperatures defined in IEC 62552 standard for energy efficiency testing, and therefore are used for theoretical calculation and result comparison in subsequent sections. If the ambient temperature is high, the thermal gradient between the ambient and the compartment will be correspondingly high. Higher gradient naturally drives up heat influx into the compartment through the wall and the door seal. It, in turn, lengthens compressor run time. Heat generated by running compressor is another source of heat influx into the compartments. Energy wastage is then resulted.

1.3. Comprehensive Approach

Total energy expenditure in food preservation can be defined as the energy expensed along the food Cold Chain (from farm all the way up to arriving at refrigerator) and when foods are being refrigerated before being consumed. Qualitative analysis has just been presented to demonstrate that reducing total energy expenditure requires us to look beyond the energy efficiency of just the refrigerator's hardware (e.g. compressor).

A more comprehensive approach must be adopted to ensure that the energy expensed are used productively - Energy are not productively used if the refrigerated foods are thrown away before consumption. Figure 1-1 shows that typical hardware and software improvement of refrigerator technologies focusing on achieving an X% reduction in energy consumption in refrigeration. However, if foods are wasted for any reason before consumption, the bulk 1-X% portion expensed during refrigeration and the energy consumed along the Cold Chain will both be in vain. "Reduction of both food wastage and energy consumption to reduce total energy expenditure" becomes the comprehensive approach.

Future refrigerators should, therefore, help users, to reduce food wastage, in addition to improve hardware energy efficiency if total energy expenditure is our concern. AFPS Appliance (Andrew and Yung, 2017a) offers this opportunity because of its customized food storage (AFPS) packages. One unique feature of the AFPS Appliance is the Active Thermal Insulation (ATI) which is made up of both compartment wall and the compartment space. The cold air temperature in compartment space can be adjusted dynamically to maintain a smallest possible thermal gradient between foods in the AFPS packages and their immediately environment (compartment in this case). Note that the cold air is used the second time after fast freezing inside the packages.

It is important to understand the difference between the immediate environment of the foods in today's refrigerator and that in an AFPS Appliance. In the former, the ambient is the immediate environment while in the latter, the compartment space is. This is main advantage of ATI because the ambient temperature is not controllable (or cannot be controlled without additional operating cost, e.g. with use of air-conditioning); however, the ATI or compartment space temperature can be controlled with much lower operating cost and more effectively, as will be explained further below. As a result, the thermal gradient between food and its immediate environment in the Appliance is inherently lower than that in today's refrigerator.

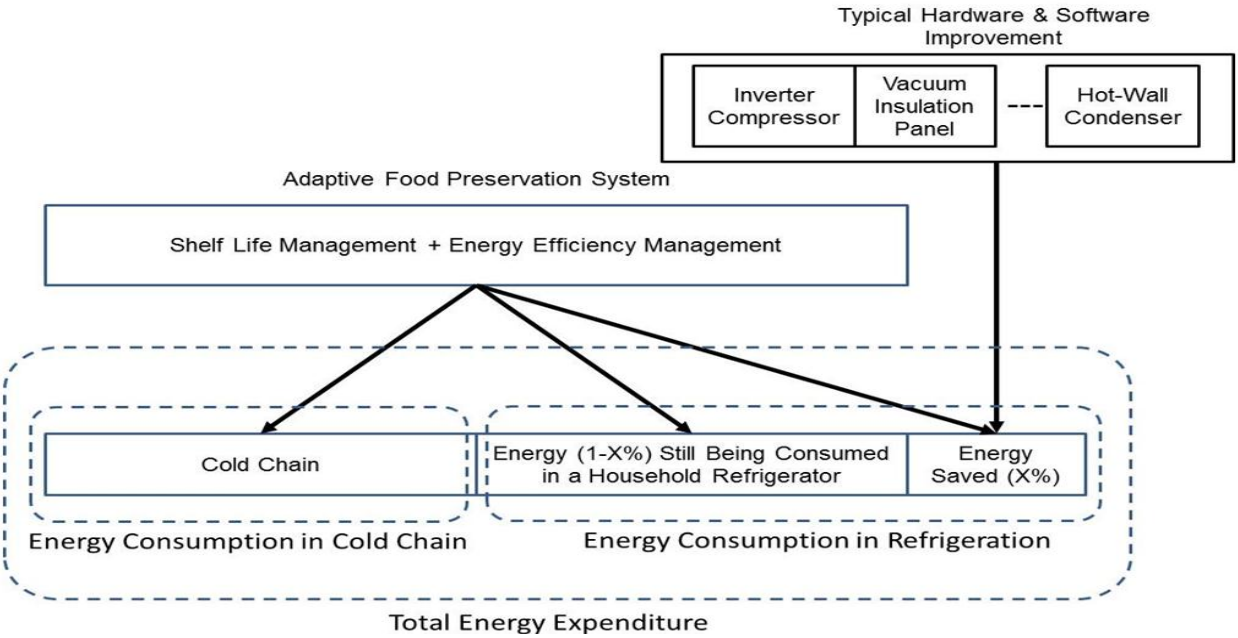


Figure-1.1. Contribution of refrigerator technologies to various types of energy consumption.
Source: This figure originates from this paper and is not referenced from other paper.

1.4. Main Goals

The main goals of this paper are to demonstrate how AFPS Appliance can realize the comprehensive approach (Section 2) in reduction of total energy expenditure by exercising the following functionalities.

1. Shelf Life Management (SLM) – Provide conceptual design and operational principles of SLM, and architectural concepts of the relevant information technology. Section 3 will address these topics.
2. Energy Efficiency Management (EEM) – Execute experimentation to demonstrate that ATI can reduce thermal gradient between food storage package and its immediate environment (compartment in case of AFPS Appliance) when compared with refrigerator without ATI. This is the focus in Section 4.

2. REALIZATION OF THE COMPREHENSIVE APPROACH

AFPS Appliance is the enabling technology to reduce both food wastage and energy consumption. Inside AFPS Appliance, each of many AFPS packages provide customized storage condition for a single (or small bundle of) food item(s). The most critical elements are the AFPS packages and ATI. Coordinating the operations of the AFPS packages and ATI is the main task of an Intelligent Control System (ICS) inside the AFPS Appliance. The ICS informs users of real-time food conditions, remaining shelf life, and food inventory information so that wise decisions can be made during shopping, handling, and food item selection for consumption. Functions of the ICS are made possible by the sensors built inside each package.

To realize the Comprehensive Approach, AFPS packages and ATI execute two main functionalities – SLM and EEM. The primary objective of SLM is to assure that users will consume or dispose of food items properly before expiry arrives. Aided by ATI, stored foods in AFPS packages are well insulated from each other, the ambient, and Appliance's devices, hence minimizing the thermal gradient that cause high storage temperature and temperature fluctuation. On the other hand, customized temperature operations in AFPS packages reduce compressor run time because refrigeration is provided only to those food items in need – no more and no less. Table 2-1 summarizes how the AFPS packages and ATI contribute to SLM and EEM.

2.1. AFPS Packages

1. To execute Shelf Life Management, the packages (with built-in sensors) perform fast freezing (FF), low temperature maintenance (LTM), defrosting (DEF), and thawing (THA) at the temperature ranges and rates pre-defined for each food type. This customized approach assures that the food spoilage process is the slowest possible when compared with that of typical refrigerator with no such customized storage afforded. Regular communication with users is available to ensure that timely consumption and proper disposal is made.
2. Energy Efficiency Management is realized with the following means (Andrew and Yung, 2017b):

a. Fast freezing (FF) - It is found to be more efficient than with that of typical freezer

b. Defrosting (DEF) and thawing (THA) - when compared with traditional refrigerators, AFPS packages consume less energy because these processes are directed to toward those food items in need only, instead of affecting the whole compartment. In addition, hot/warm air is drawn from the hot side of vortex tubes. No extra energy input is needed because the cold air is exiting out of AFPS packages anyway (cold air recycling).

2.2. Active Thermal Insulation - Compartment Wall & Space with Recycled Cold Air

1. To execute Shelf Life Management, the ATI reduces thermal gradient between the ambient and the compartment space. This, in turn, reduces food temperature and its fluctuation inside AFPS packages, especially when the door is open and/or ambient temperature is high (approaches or exceeds 30°C). The lower and more stable temperature, in general, helps food to maintain quality.
2. To execute Energy Efficiency Management, the thermal gradient mentioned above is reduced so that the foods stored inside the package experiences less temperature fluctuation, hence, reducing the demand of refrigeration.

Table-2.1. Key elements that support the functionalities of managing of shelf life and energy efficiency

Functionalities	**Key Elements in an AFPS Appliance**	
	AFPS Packages	**Active Thermal Insulation (Compartment wall & space, including door and door seal)**
Shelf Life Management	(1) Customized temperature operations (FF, LTM, DEF, and THA) are executed to fit the specific needs of a food item. (2) Regular update to users on food quality or spoilage status so that proper consumption or disposal can be made before expiry.	Thermal gradient reduction - mininizes food temperature fluctuation.
Energy Efficiency Management	Customized temperature operations (FF, LTM, DEF, and THA) are executed to specific food item on need basis.	Thermal gradient reduction - mininizes heat influx into food storage packages.

Source: This table originates from this paper and is not referenced from other source.

Existing and other emerging technologies, however, are not exclusive of AFPS Appliance. Instead, they are fully compatible with the approaches proposed in this paper. For example, inverter compressor, vacuum insulation panel, etc, can be installed in an AFPS Appliance.

3. SHELF LIFE MANAGEMENT WITH INTELLIGENT CONTROL SYSTEM (ICS)

User habits play a central role in food wastage. Therefore, future refrigerator should assist consumers to minimize food wastage which translates into energy wastage, even though no law has existed yet in demanding consumers to exercise food saving, at least in developed or highly-populated countries. Refrigerator complying with Energy Labelling scheme is only the theoretical best. Minimization of food wastage, hence energy wastage, is possible only if consumers are fully informed of food storage conditions and shelf life information so that more intelligent decision can be made on handling, shopping, and consumption.

Emerging technologies, like smart refrigerators (Prapulla *et al.*, 2015) has many new functions. Tracking of food item spoilage process, technologies for supporting proper handling, and timely consumption are not available. This is basically due to the absence of real-time food spoilage and quality information in current and emerging technologies. As different food items or categories are stored in the same compartment during storage, it is not possible to provide dedicated storage conditions. Sensors can be used, but in order to be effective, each food item must be physically segregated from each other. Modified atmosphere technologies do contribute to better storage conditions; however, different food categories need different types of atmosphere over different phases of shelf life. Therefore, complete physical segregation is a necessary condition to enhance food quality beyond what current refrigerators can achieve. This is why AFPS packages are so essential.

The main tasks of this ICS are to control and optimize the storage conditions dedicated for each food item or category over the storage period and to help users to achieve economy by reducing food wastage and making the best shopping decision (by networking to supermarkets and the immediate neighbourhood). In addition, increased use of mobile devices and network capability, allows users to control and monitor refrigerator when away from home without difficulty. Users can easily use mobile devices to connect to the cloud to "see" in real time information of food items in the Appliance. Figure 3-1 shows the architecture tying up all the networking elements mentioned above.

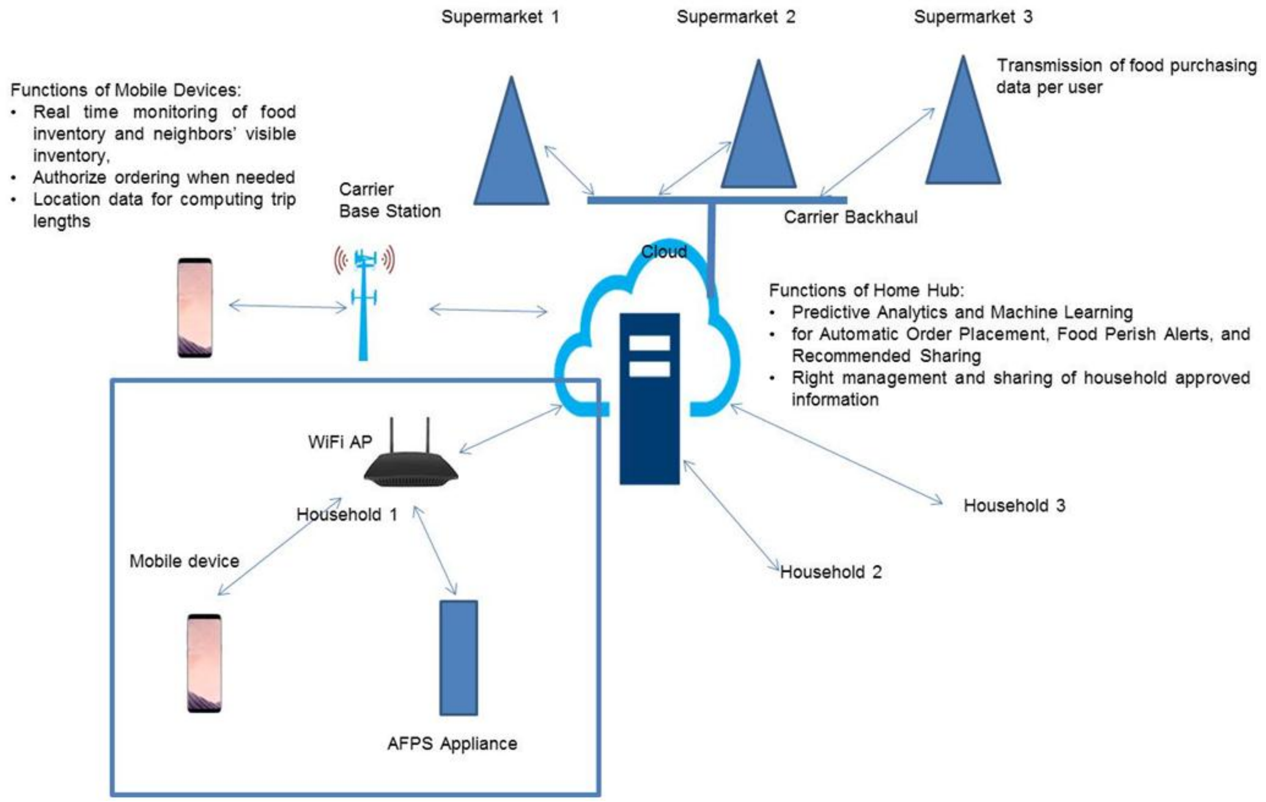


Figure-3.1. Architecture tying up the key members of the network with the ICS of an AFPS Appliance being at the center.
Source: This figure originates from this paper and is not referenced from other source.

3.1. ICS Networking with Supermarkets

This section explains how food quality information is being handled and transferred to enable customized food storage in AFPS packages, which, in turn, facilitate food quality enhancement and eventually, food wastage reduction. After payment is made in a checkout counter when shopping, mobile device, with proper hardware and software installed, can record and relay the history of a home-returning trip that the purchased foods endure along the way (e.g. the time spent between checkout counter and storage at home, and the environmental conditions). Once checkout and payment transaction has been completed, the food data will be downloaded from the supermarket network into the Appliance's ICS via the user's mobile device (e.g. with Wi-Fi technology). It is obvious that food data input into the ICS enjoys a high level of automation (the checkout counter initiates the data flow).

Once a user has returned home and placed the foods in the AFPS packages, the trip data will be downloaded into the ICS memory (Now that the mobile device is close to the Appliance, another Wi-Fi connection is readily available). Combining the food type info, quantity and trip data, the ICS will calculate the best storage conditions for each item and then commands the corresponding AFPS packages to start execution immediately after the packages are closed. Figure 3-2 depicts the concept of data flow from supermarket checkout counter to mobile devices and then to the Appliance.

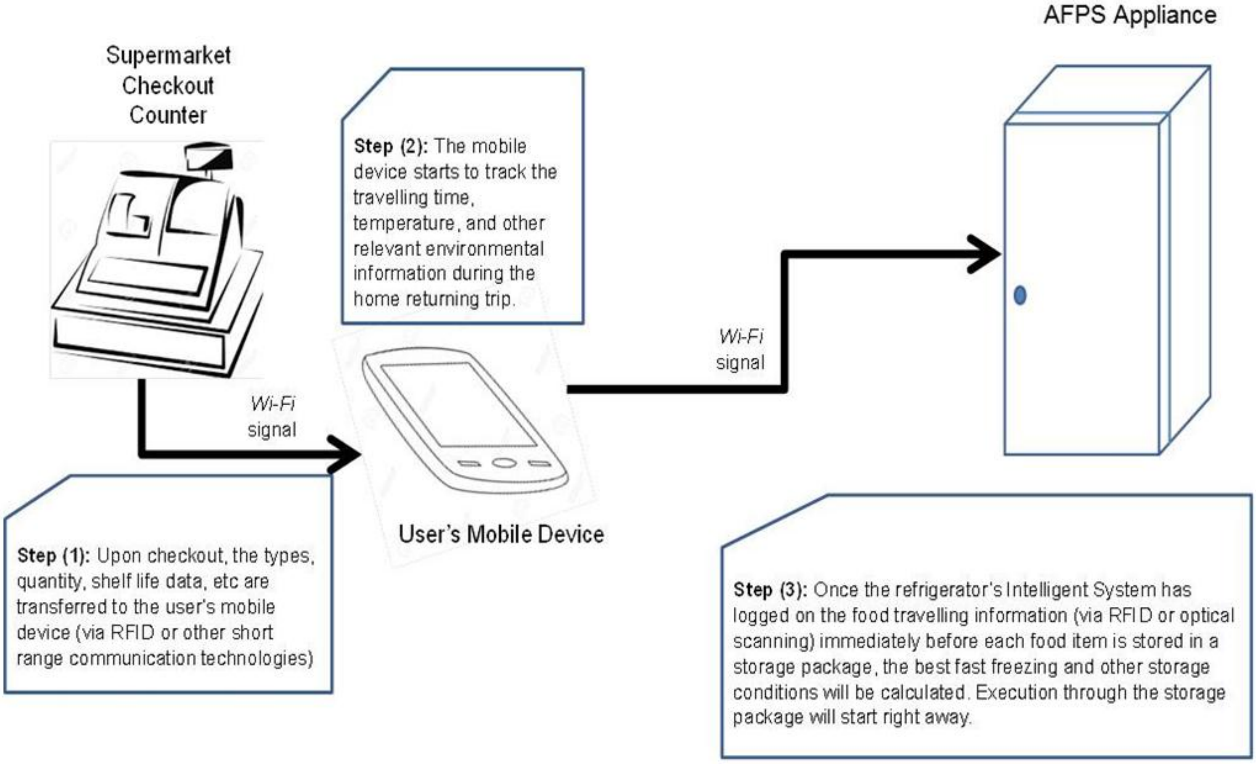


Figure-3.2. Relay of food travelling information between supermarket counter checkout to the time that food data are logged in to the Appliance.
Source: This figure originates from this Paper and is not referenced from other source.

With the advent of the smart supermarket such as Amazon Go Deborah and Kiril (2016) all the shopping data and patterns are already captured and analysed. Such data can be made available to a home hub like the Amazon Echo. The Appliance can be the main device in the home connected to the home hub, thereby creating a seamless flow between the supermarkets, cloud based database and analytics, the home hub, and devices such as the Appliance and the user's mobile devices. Alternatively, the Appliance can be the home hub and integrated with Amazon services:

3.2. ICS Networking within an Appliance and its Users

The ICS starts tracking food storage status (both quality an in/out record) once a food item is placed inside an AFPS package. Since there are many packages inside an Appliance, intensive internal networking takes place to coordinate all temperature operations (e.g. fast freezing, chilling). When the shelf life is approaching expiry or food quality has reached a predetermined level (users can choose a specific time to consume before the printed expiry date), users will be notified so that the food items in question will be prioritized in meal consumption accordingly based on a schedule like which day the users will dine at home in the near future, types of dinner preferred, etc.

The complexity of making an optimized shopping decision is easily seen when one considers the variability of food's susceptibility to the environmental impact during a delivery or home-returning trip. For example, diary or frozen foods are the most susceptible while Ready-to-drink (RTD) beverage products (e.g. soft drink, beer) are the least.

RTD beverage products that do not need refrigerated storage for preservation (except immediately before consumption for chilling purpose) post a special problem in energy efficiency. It is common that they are refrigerated for days before consumption. Users accept this just to make sure that cold drinks are ready at any time. However, this readiness has a very high cost because if, for example, a can of beer is refrigerated for 48 hours before consumption, yet, it actually needs only around two hours to be cooled from room temperature to around +5°C. This translates into an energy wastage of 95.8%, or =(48-2)/48. Percentage-wise, such wastage is tremendous but it is simply not obvious to users. In addition, there is no option anyway. If the wastage is multiplied over a long period of time (since this practice repeats indefinitely) and over the population, the total wastage will certainly more eye-catching. Therefore, another main task of the ICS is to advise user on when to refrigerate less perishable foods before consumption so that unnecessary refrigeration can be avoided.

The ICS processes real-time quality information of foods as follows:

1. Synchronize with the user's calendar so that on which day a meal will be spent at home and the size of the dining party will be known. User's habit and preference are also an important input to the ICS in customizing food storage conditions.
2. Learn technical rules in maintaining food quality (the temperature, relative humidity, atmospheric conditions, freezing and thawing rates, the best defrosting time and cycles, etc) from a third-party database through the network (so that user input is not necessary).
3. Execute the rules by maintaining necessary storage conditions in the storage packages.
4. Process data based on continuous feedback through sensors built inside the packages. Project food acceptability based on pre-defined technical rules and regulatory requirements;
5. Advise users on options for food disposal if immediate consumption is not possible. A shopping list can be generated so that users can decide whether to shop in person or to let the refrigerators to place orders to supermarkets automatically.

3.3. ICS Networking within the Neighbourhood

Appliances in the neighbourhood can communicate with each other through networks without human intervention. If any food item is approaching expiry, the ICS can propose alternatives to users like sharing food with neighbours or donation to charity organization or persons in need, etc, if the original package is still intact or not damaged, or the food quality is still acceptable. In addition to raw food, cooked dishes can also be shared. There are already many platforms sharing home cooked dishes. However, human intervention is significant. Having Appliances in the neighbourhood talking to each other greatly facilitates food sharing. The potential of neighbourhood sharing of food items in refrigerators has not been explored before but will significantly help to reduce food wastage and consequently to save energy. The ICS performs all data processing and communication work. The only involvement of the user is to make a "go / no go" or "share / not share" decision and to physically move the food items.

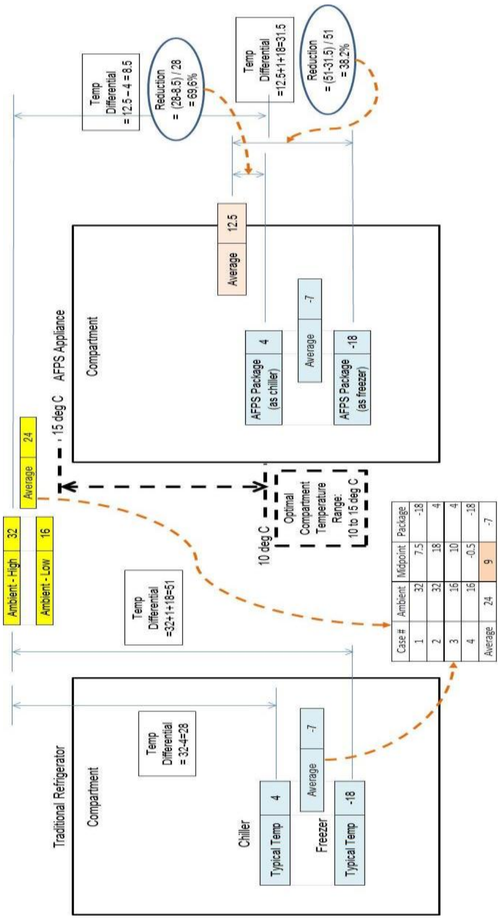
One major consequential benefit of the above is that sharing food stock data among a neighbourhood helps users to acquire food in group and negotiates for better discounts with supermarkets. These stock level projection, negotiations, and order placement activities can be handled with proper software with the user preference predefined. Social network has already re-defined contemporary lifestyle. This neighbourhood-based shopping is just an extension of the social network and delivers tangible economic benefits to the social group. Delivery to the same neighbourhood helps supermarkets and users to lower per unit transportation costs and energy consumption.

4. ENERGY EFFICIENCY MANAGEMENT

As mentioned in Section 2, compartment wall and space together forms the Active Thermal Insulation (ATI) responsible for reducing the thermal gradient between food items and their immediate environment (Compartment space is the immediate environment in case of AFPS Appliance while the ambient is the one in case of today's refrigerator). This reduction is a comparison with traditional refrigerators without ATI such that there is only one set of "passive" insulation system between food items and the ambient. Reducing such gradient is essential for energy efficiency and food temperature stability. Since thermal gradient is directly proportional to temperature differential between food and its environment, minimizing the temperature differential is equivalent to minimizing the mentioned thermal gradient. Therefore, this section will focus on demonstrating that a significant reduction of temperature differential can be achieved by ATI of an AFPS Appliance. Deviation between the experimental and calculated temperature differentials (based on an optimal temperature range) will be explained. Rectification of the sources of deviation will also be discussed.

4.1. Derivation of an Optimal Compartment Temperature Range

Reduction of the temperature differential is made possible by an optimal compartment space temperature range. It is optimized when a balance is achieved between two extremes - High compartment temperature minimizes ambient heat influx (through wall and door seal) but is negative for the food items inside the packages. Low compartment temperature is good for food but results in higher ambient heat influx. Less heat influx consequently means less need to lower compartment temperature and then less compartment heat influx into food storage package. Again, the Appliance's compartment space is cooled by recycled air from the package. Hence, no extra energy is needed. Figure 4-1 shows that an optimal compartment space (or ATI) temperature range is between 10°C and 15°C for the AFPS Appliance. Note that this range is not exactly in the middle (e.g. 9°C+/-2.5°C) between the ambient average and chiller-freezer average but tilts toward the chiller-freezer average temperature. The ICS of the Appliance dynamically adjusts the compartment temperature between 10°C and 15°C by controlling cold air recycling depending on factors like the number of packages functioning as freezers and/or chillers, the best setting for energy efficiency, and other pre-defined conditions. Figure 4-1 also shows that if the maximum/minimum temperatures of the ambient, the compartment, and the package, are 32°C/16°C, 15°C/10°C, and 4°C/-18°C respectively, the reductions in temperature differentials between the package space and its immediate environment (the compartment space) are 69.6% (package as a chiller) and 38.2% (package as a freezer).



Case #	Ambient	Midpoint	Package
1	32	7.5	-18
2	32	18	4
3	16	10	4
4	16	-0.5	-18
Average	24	9	-7

Figure-4.1. Evaluation of the temperature range for compartment space as the ATI
Source: This figure is originated from this paper and is not referenced from any other source.

4.2. Experimentations & Result Analysis

4.2.1. Measurement of the Temperature Operations

The purpose of the experiment is to determine the temperature differentials between package space and the compartment space with the test setup described below and to compare the percent reduction in temperature differential with the theoretically calculated optimized percent reduction (69.6%) for the ambient at 32°C, compartment at 12.5°C, and chiller at 4°C, or 32-12.5-4 setting.

The operation of the experiment is such that hot air is directed toward one outside surface (identified as Surface A1) of the simulated compartment box at constant speed and temperature. Once the compartment box and AFPS package #B temperatures have raised and reached steady state, cold air from AFPS package #A (this one has vortex tube attached) is injected into the compartment box for cooling until the raised temperatures have dropped to a new steady state. Temperature differentials and the associated percent reductions will then be calculated.

4.2.2. Experimentation Setup

To simplify the test setup, instead of having both AFPS packages to generate cold air, only one of them (#A) produces cold air with vortex tube and package #B is simply an empty box with thermocouple inserted. The three temperatures of 32-12.5-4 setting are raised up so that the package #B can stay close to room temperature. We take advantage of the fact that generating hot air at high speed (for instance with hair dryer) is much easier than that for cold air. That means temperature differentials are calculated with all temperatures “elevated”. After all, it is the temperature differentials and the percent reduction that are of primary interests, not the absolute temperatures themselves.

The hardware is made up of such custom-made fixture and standard measurement equipment as mentioned below. There is only one simulated package inside the simulated compartment box. The simulated AFPS package that generates recycled cold air is located outside of the compartment box but they are connected with tubing.

1. Test Setup #1 (Figure 4-2) is made up of the following key elements. Basic dimensional data, parameters, and quantifiable assumptions of the experimentation are shown in Table 4-2.

(a) Simulated compartment box – It functions as the Appliance compartment. The wall material is of ABS material instead of typical refrigerator wall materials.

(b) Simulated AFPS package #A – With vortex tube, it provides recycled cooling air into the compartment box. Cooling air temperature and air speed are measured and shown in Table 4-1. Setting of the compressed air into the vortex tube is 6 bar and 0.4 kPa.

(c) Simulated AFPS package #B – Thermocouple is inserted into the package so that the center temperature can be measured for calculation of thermal gradient.

(d) Hair dryer – It functions as the concentrated heat source. Air temperature and speed are measured and shown in Table 4-1. The nozzle of the dryer is positioned at 10 cm away from the heated compartment box surface.

2. Accuracy values of measurement equipment –

(a) Digital thermometer (2-channel) - ±0.1%+0.5°C

(b) Digital air pressure gauge - ±2%Full Scale±1digit

(c) Digital temperature data logger - ±1°C Full range

(d) Hot-wire aneomometer - ±(5%+0.1ms-1)

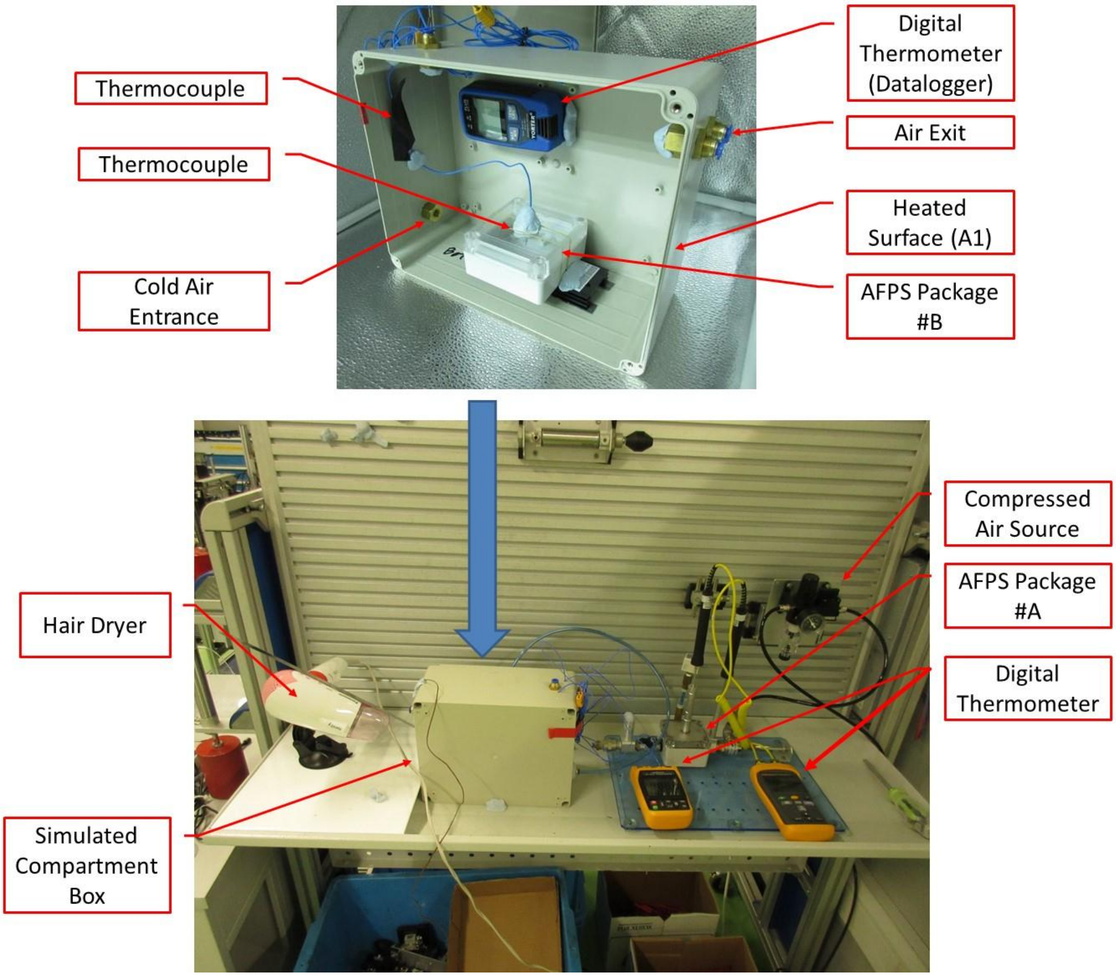


Figure-4.2. Test setup with inside view of the simulated compartment box.

Table-4.1. Key dimensions and parameters used in the experiment.

	Max	**Min**	**Average**		**Hot Air Information (Concentrated Heating)**					**Cooling Air**	**Enter**	**Exit**
Temp (Amb)	23.4	22.2	22.8		Air speed =		16.5	m/s		Temp (C)	7.2	24.6
					Temp (Heated Surface)		105.4	deg C		Speed (m/S)	17.3	13.8
						Width	Height	Length	(m)	Volume	(m3)	
Simulated AFPS Appliance Compartment (External Dimension) =						0.250	0.220	0.130		0.0072		
Simulated AFPS Appliance Compartment (Internal Dimension) =						0.247	0.197	0.128		0.0062		
Simulated AFPS Package (External Dimension) =						0.080	0.057	0.080		0.0004		
Simulated AFPS Package (Internal Dimension) =						0.073	0.049	0.073		0.0003		
Orientations of the Surfaces					Front	Back	Left	Right	Top	All		
Surface Area Exposing to the Ambient =					0.0550	0.0550	0.0286	0.0286	0.0325	0.1997	(m2)	
Surface (A1) Area Receiving Blowing Hot Air =							0.0215	which is	10.7 %	of the total surface area		
Note: All temperatures are in degree C												

4.2.3. Calculation of the Equivalent Surface Temperature of Compartment Box

Since only Surface A1 is subject to hot air flow, this analysis calculates the equivalent surface temperature of the whole compartment box as if all five surfaces are subject to hot air in natural convection, instead of forced convection. This equivalent surface temperature will be used as the new ambient temperature for the compartment box in calculating the temperature differentials. Radiation heat transfer is ignored in the following calculation.

Based on the formulation from Yunus (1997) the Nusselt Number of the hot air impinging on one of the compartment box surface (or Surface A1) is calculated as follows.

$$Nu = 0.102 \text{ X } Re^{0.675} \text{ X } Pr^{1/3} \qquad (1)$$

With the Reynolds and Prantl Numbers calculated as 168,062 and 0.688, respectively, the Nusselt Number becomes 302.89.

With the following relationship, the heat transfer coefficient (h) of the impinging hot air becomes

$$h = Nu \text{ X } K / D = 43.98 \text{ W•m-2•K-1 } (2)$$

Where K is the thermal conductivity of air at T_{A1} or 105.4°C and D is the height of the compartment box.

With h calculated, the energy delivery rate of the impinging hot air becomes

$$Q = h \text{ X } A_1 \text{ X } (T_{A1} - T_{amb}) = 77.92 \text{ W} \qquad (3)$$

If the same energy delivery rate is distributed evenly over all five surfaces, the new energy delivery rate becomes 8.37 W.

Surface A1 faces forced convective air flow from the concentrated heat source. When the heat delivery rate is distributed evenly over all five surfaces, it is assumed that the surrounding air has natural convection only (without forced air flow). Therefore, formulation in Rathore *et al.* (2011) is used to calculate the equivalent surface temperature (same for all five surfaces) in which Rayleighs Number is involved.

Several iterations are to be made in the calculation, the film temperature is calculated based on the ambient temperature of 22.8°C and first trial of the new surface temperature, 50°C. After several iterations, the Rayleighs Number is calculated as 44,540,734. Formula (4) below generates the new Nu which, in turn, yields a new h per Formula (5).

$$Nu = 0.59 \text{ X } Ra^{0.25} = 48.20 \qquad (4)$$

$$h = Nu \text{ X } K / D = 1.05 \text{ W•m-2•K-1} \qquad (5)$$

The equivalent surface temperature, T_{A0}, is found to be 62.9°C which becomes the new ambient temperature of the compartment box for calculation of a new temperature differential.

4.2.4. Analysis of Experimental Results

The average ambient temperature is originally at 22.8°C which is assumed to be the same around the five surfaces of the simulated compartment box (except the table-contacting bottom surface which is assumed to be adiabatic). When hot air (from the concentrated heat source) is blown directly at one of the surfaces, the average surface temperature at the affected zone is recorded as 105.4°C. It is assumed that other four surfaces remain at 22.8°C during the heating period. Calculation is then made to determine the equivalent average ambient temperature while the thermal energy delivered by the concentrated heating source is now evenly distributed over all five surfaces.

The % reduction of temperature differential can be calculated by (T_{amb} - T_{comp}) / (T_{amb} - T_{pack}). In order to have a high % reduction, the T_{comp} must be small when compared with T_{amb}, but also need to be higher than T_{pack}. Mathematically speaking, the T_{pack} must be as close to T_{amb} as possible, but it is not practical because, by definition, T_{amb} and T_{pack} is far apart and is separated by T_{comp} in between. In the other words, T_{amb} is a given condition and T_{pack} is the desired target and cannot be adjusted neither. The only adjustable variable is T_{comp} which should then be as close to T_{pack} as possible in order to achieve a high % reduction. Table 4-2 summarizes the experimentation results.

Table-4-2. Key results from the experiments – the temperature differentials and the % reduction.

Note: All temperatures are in degrees C.		**Average Compartment Temp**		**Average Ambient Temp**		**Temperature Differentials**		
	AFPS Package Temp	Compartment Temp	Compartment Wall Temp (Inside)	Compartment Wall Temp (Outside) (Heated Zone)	Ambient Temp	Ambient (Heat) to Compartment	Compartment to AFPS Package	Ambient to AFPS Package
32-12.5-4 Setting (Basis of comparison)								
Temperature Setting	4	12.5	12.5	32	32	19.5	8.5	28.0
% Reduction of Temp Differentials		69.6%						69.6%
Heating Starts.	23.9	34.5	74	105.4	22.8			
Heat Continues & Cooling Starts	31.4	39.9	55.4	105.4	22.8			
Heating & Cooling at Steady State	22.6	29.9	55.4	105.4	22.8			
Steady State Average Temperatures	22.6	42.7		62.9		20.2	20.1	40.3
% Reduction of Temp Differentials		50.2%						50.2%
Artificial Temperature Depression to Meet the 32-12.5-4 Setting	31	31.0			31.0			
Temperature After Depression	-8.4	11.7			-31.0			

Source: This Table originates from this Paper and is not referenced from any other source.

When the resulting compartment and package temperatures have reached steady state (both hot and cold air are steadily supplied to the simulated compartment box), a percent reduction of 50.2% in temperature differential can be achieved. Recalling that the main reason of raising the temperatures from 32-12.5-4 setting in this experiment is that, raising air temperature is easier that lowering air temperature as far as test equipment and test time are concerned. Therefore, another way to interpret the experimental result is that, if the "elevated" steady state ambient-compartment-package temperatures (or 62.9-42.7-22.6) are all subtracted by 31°C, the new ambient-compartment-package temperatures become 31.9-11.7-(-8.4). 31.9°C and 11.7°C are just below 32°C and 12.5°C, respectively. -8.4°C is much lower than 4°C and, therefore, indicates a positive result because it means that the package temperature will not exceed 4°C. In short, any package temperature equals or lower than 4°C is a positive result.

4.3. Deviation Analysis and Rectifications

The above experimentation is run in conditions under which the resulted percent reduction of 50.2% is less than the theoretically calculated 69.6% due to the following sources of deviation.

1. The simulated compartment box is made of ABS material which has high thermal conductivity when compared with the materials of typical refrigerator wall. Heat influx from the ambient, therefore, moves across the compartment wall to neutralize part of the cooling air. Rectification in an actual Appliance is simply by using typical wall insulation materials.
2. The tubing (0.3m long) for cold air delivery from the simulated AFPS package and the simulated compartment box is not well insulated such that the cold air picks up heat along the tubing (temperature is raised from -6.4°C (Andrew and Yung, 2017c) to 7.2°C). This tubing is not necessary in case of an actual AFPS Appliance because all packages are inside the Appliance such that cold air exiting out of any package will enter the Appliance compartment space immediately.
3. In order to achieve the same % reduction as in the 32-12.5-4 setting, or 69.6%, T_{comp} should be reduced to no higher than 31°C. However, the cooling capacity is limited by the temperature of the recycled air which

is at 7.2°C. Therefore, the lowest achievable temperature is 42.7°C. Rectification is similar to the second source of deviation above because, once all AFPS packages are positioned in the Appliance, the cold air temperature will not be warned up by the ambient like the experimental setup faces. A lower cold air temperature will certainly bring down T_{comp} close to 31°C as desired.

Even though the above three factors adversely impacted the percent reduction in temperature differentials, hence the thermal gradient, this percent reduction can still be considered significant. The reason is that even with a single digit percent reduction in energy usage, if being multiplied over long term considering that the Appliance operates non-stop, significant total saving in energy expenditure can still be realized. Referring back to [10] again on the improvement in energy efficiency by the effort of complying with Energy Labelling Scheme, the average annual saving in refrigerator energy consumption from 2004 to 2014 is only 7.8 KWh or 2.5%.

5. CONCLUSIONS

This paper presents that fact energy wastage in food preservation is a direct result of food wastage. Despite its significance, food wastage reduction is not the focus of improvement in today's refrigerator. To achieve saving in total energy expenditure, we must look beyond refrigerators' operating efficiency and expand the focus to cover the energy consumption in the Cold Chain. AFPS Appliance meets such needs, by reducing food wastage and by minimizing the thermal gradient between foods and their immediate environment, as part of its overall effort to reduce total energy expenditure. The responsible functionalities are Shelf Life Management and Energy Efficiency Management. The key elements of AFPS Appliance are AFPS packages with built-in sensors. Such sensors detect real-time food quality information and make it possible for the Intelligent Control System to work with supermarkets, users, and neighbourhood in food wastage reduction. Another key element is the Active Thermal Insulation with which the thermal gradient between foods and their immediate environment is reduced in such a way that the food temperature and its fluctuation is minimized. Both food quality and energy efficiency are benefitted as a result. Despite the rapid advances (e.g. IoT) in information and networking technologies while more cost-effective hardware and software solutions appear constantly, AFPS packages with built-in sensors detecting, processing and reporting quality status of individual food item are the fundamental in enabling all the new functions mentioned in this paper, including but not limited to communication between Appliances in a neighbourhood for food sharing, communication with supermarkets for more cost-effective shopping, and helping users to monitor and handle food items on individual basis. Other new functions are only limited by ones' imagination. Experimentation is executed to determine the effectiveness of ATI in reducing thermal gradients. The optimal temperature range of the ATI is found to be between 10°C and 15°C. The best percent reduction in temperature differential, hence the thermal gradient, is found to be 69.6% (between compartment and chiller) in 32-12.5-4 setting. Experimentation has resulted in 50.2% which is less than 69.6% but is still considered significant. In addition, rectifications are available in case of a real AFPS Appliance to bring the percent reduction up closer to the ideal case. This research paper and Andrew and Yung (2017a) (a) from Tsang & Yung have together laid a foundation of the conceptual design and operational characteristics of AFPS Appliance. Further research in this topic will be directed toward providing more data in energy efficiency and food quality improvement with the use of this technology. Engineering design and product industrialization will be reserved for interested home appliance manufacturers.

Funding: This study received no specific financial support.
Competing Interests: The authors declare that they have no competing interests.
Contributors/Acknowledgement: Both authors contributed equally to the conception and design of the study.

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