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Evaluation of Freezing Capacity of a Conceptual Adaptive Food Preservation System (AFPS) Appliance in the Context of IEC 62552 Standards

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Abstract

Preserving food item individually in an Adaptive Food Preservation System (AFPS) package is a new concept. Before completing a product commercialization process, AFPS packages must be certified against mandatory standards like IEC 62552. This paper evaluates two key aspects of energy efficiency against the IEC standard. Internal volume and storage capacity are evaluated qualitatively. Freezing capacity will be evaluated by experimentation with a simulated AFPS package. The result is verified by an analytical model. Error source and rectifications are identified. The usable storage capacity with AFPS packages is larger than that in a typical refrigerator if both have the same internal volume. Experimentation and theoretical model analysis have demonstrated that the freezing times are 3.18 and 3.32 hours, respectively, which can be considered agreeable. The freezing capacity of the conceptual AFPS package is found to comply with the IEC standard.

Keywords

Adaptive Food Preservation System (AFPS) Appliance; AFPS packages; IEC 62552; Refrigerator freezing capacity; Internal volume; Usable storage capacity

Abbreviations

AEc The annual energy consumption of the model in kWh/year that has been calculated from the test result

AFPS Adaptive Food Preservation System

B_i Biot Number
D Characteristic Distance
d_c Characteristic Distance
D_h Hydraulic Diameter
EEI Energy Efficiency Index
f Friction Factor
FDA Food & Drug Administration
FP I Flow Path I
FP II Flow Path II
h Heat Transfer Coefficient
k Conductivity
k_T Total Conductivity (of more than one layer of materials)
L Length (over which calculation of Nusselt Number is based on)
Nu Nusselt Number
Nu_f Nusselt Number (after considering friction factor)
P Constant (for freezing time calculation)
Pr Prandtl Number
Pk Planck Number
R Constant (for freezing time calculation)
Ra Rayleigh's Number
Re Reynolds Number
SAEc Standard annual energy consumption to which the test result is compared to a reference
Ste Stefan Number
T_f Initial Freezing Temperature
T_m Freezing Medium Temperature
T_{ref} Reference Temperature
t_{RT-18} Cooling Time From Room Temperature to -18°C
USDA United States Department of Agriculture
ΔH_{10} Volumetric Enthalpy Difference (between initial freezing temperature and -10°C)

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Introduction

Energy efficiency of AFPS appliance

Energy efficiency of refrigerators is under constant scrutiny. Legislation and protocols like the Energy Labelling scheme, along with IEC 62552, regulate energy consumption of electrical appliances. While appliance's energy efficiency improves constantly (variable capacity compressor, etc) reducing carbon emission globally becomes a pressing need [1]. The three parts of the standards focusing on the characteristics and test methods of household refrigerating appliance have the following emphasis:

IEC 62552-01 = Part 1: General requirements.

IEC 62552-02 = Part 2: Performance requirements

IEC 62552-03 = Part 3: Energy consumption and volume

Adaptive Food Preservation System (AFPS) Appliance is a novel concept proposed by Tsang & Yung [2,3]. The fundamental principle is a customized food storage in which food item is stored and preserved individually in an AFPS package. As a household refrigerating device, AFPS Appliance is expected to meet IEC 62552 and other mandatory requirements before relevant certification can be granted.

Storing and preserving food item individually in a package over the shelf life has the following major advantages when comparing with storing many food items (with different sizes and characteristics) in the same compartment of a legacy refrigerator. The following are some of the key advantages with customized food storage (with an AFPS package).

1. Each of many AFPS package shields food items from each other so that different temperature operation or other preservation process can take place concurrently. This shielding also minimizes food temperature fluctuation. In addition, the chilling or freezing air supplied to each AFPS package is always "freshly" produced through evaporator. As a result, the temperature of every package can be adjusted independently. In legacy refrigerator, cold air used for freezer compartment may be used to cool the chiller compartment afterward.
2. In a legacy refrigerator, temperature operations like chilling, freezing, defrosting must be applied to the whole compartment inside which all foods are stored. In an AFPS package, two benefits can be realized-temperature operations can be executed inside different packages at the same time, and some packages can function as chillers and some as freezers.
3. In a legacy refrigerator, a separating (insulation) wall between chiller and freezer is necessary. The use of AFPS packages can eliminate this wall. Much less wall materials will be refrigerated and, as a consequence, much less refrigerating capacity and compartment space will be wasted.
4. The temperatures measured inside a package (with a single food item stored) can more accurately represent actual food temperature. Compartment in legacy refrigerator has only a few temperature sensors built along the compartment walls. The temperatures measured, therefore, cannot be representative of food temperatures.
5. Opening and closing of the doors are unavoidable, but the frequency and opening time, can severely impact food quality and energy efficiency due to the induced temperature fluctuation which, in turn, triggers unnecessary compressor cycling [4]. Björk has shown that compressor cyclic loss may account for 5% to 37% of the energy loss [5]. With food items stored inside packages, the package walls serve as the primary thermal insulation. Therefore, opening of compartment door will not cause immediate change to food item temperature.

This is one of a series of papers in exploring the concept of AFPS Appliance such that a more solid technical foundation can be built for future product commercialization. This paper focuses on the applying IEC 62552 standards to AFPS Appliance.

Structural features and operations of an AFPS package

This sub-section facilitates the understanding in how cooling functions are supposed to work in an AFPS package. A conceptual construction and air flow through a package is shown in **(Figure 1.1)**. There are two options in driving the cooling function but both have the same package structures with two different flow paths. Since the AFPS Appliance is still under conceptual design, various options in the driving mechanisms can be considered for different applications and the best cost-effectiveness.

Flow Path I (FP I): Flow Path I is also the space where food item is stored. Cold air is generated and then flows through Flow Path I. There are two options in generating cold air. The first one is through traditional refrigerant compressor and evaporator. This option is readily available and requires tubing installations only for a closed-loop network. Fan motor can generate high speed air but motor generates heat while consumes extra energy. Therefore, a careful balance between costs and benefits must be evaluated. Another option is through vortex tube. Its use is elaborated in detail by Tsang & Yung [2]. The main benefits of using vortex tube are that cold air can be generated much faster than a typical compressor can. In addition, the air can flow at much higher speed. The single most important benefit with vortex tube is that cold air temperature can be much more stable (less cycling). With less temperature cycling, food items can reach the desired temperature much faster. This is why critical applications like refrigeration of vaccine rely more on cooling with vortex tube [6]. Despite the limitations of vortex tube in household application, it is an excellent choice for the test setup fabricated for experimentations of simulated AFPS packages because cold air can be generated quickly and the cold air temperature can be more stable (no cycling). In addition, vortex tube greatly simplifies the test setup.

Flow Path II (FP II): There are also two options to choose in how the Flow Path II is structured and operates. The first one is that this FP II serves as a vacuum insulation only when all the cold air for fast freezing and steady state operations passes through FP I. The advantage is that vacuum can be built and sealed inside FP II such that there is no need to draw air out from time to time (e.g. with a vacuum compressor). However, should the leakage happen, replacement of the whole package will be necessary. Another option is that FP II serves as both passage for cold air in steady state operations and vacuum insulation, as proposed by Michel & Bush [2]. More complicated mechanisms like vacuum compressors, tubings, are involved. The advantage, however, is that cold air for fast freezing (through FP I) and that for steady state operations (through FP II) can be separated to facilitate recycling in different close loops [3].

Summary of the two flow path options: In summary, there are two options to structure an AFPS package.

Only refrigerant compressor is used (no vortex tube and its associated components):

1. Flow Path I-Cold air flows through for both fast freezing and steady state operation.
2. Flow Path II-As a vacuum insulation only.

Both, refrigerant compressor and vortex tube are used:

1. Flow Path I-Cold and warm air are generated by vortex tube for fast freezing and defrosting
2. Flow Path II-As both vacuum insulation and cold air passage for steady state operation.

Testing of AFPS packages per IEC 62552 standards

The latest versions of IEC 62552-01, -02, and -03 have been released in 2015. The main purposes are to provide details in how household refrigerators should be evaluated and tested in order to verify the performance of an AFPS Appliance before it can be certified for market release. This paper focuses on evaluating the freezing capacity of the AFPS package in two key aspects of the standards that relates to the internal volume measurement and freezing capacity of AFPS packages. There are three types of volume related to a refrigerating device (Figure 1.2). The main reason that volume and freezing capacity are evaluated together in this paper is that they both are key parameters in calculating the energy efficiency index (%) of a refrigerator [7].

EEI = AEc / SAEc x 100

where the SAEc is calculated based on the storage volume of the different compartments.

Measurement of refrigerator volume and storage capacity: The followings are the different "volumes" related to a refrigerator in decreasing order.

Category #1: External dimensions (Foot print area times height),

Category #2: Internal volume (with odd shapes and unusable volumes taken into account). The way it is measured is defined in the IEC 62552-03 standard).

Category #3: Storage capacity (usable volume),

This paper presents the advantages with using AFPS packages related to the usable storage capacity in storing food when compared with using chiller or freezer compartment in legacy refrigerators. Understanding of how various volumes are measured is critical in refrigerator not only because of the need for as much storage space as possible but also of their impact on energy efficiency measurement as will be elaborated more below.

Freezing capacity test: The purpose of this test is to measure the freezing capacity of freezer compartments by determining the time it takes for the test food load of 3.5 kg per 100 L of compartment volume to be frozen from +25 ºC to -18 ºC. At the same time, the freezer compartment operates at –18 °C. M-package (manufactured by Shenzhen Bonad Instrument Company, China, per IEC 15502 standard) will be used to simulate the food load. The tested compartment can claim a four-star or three-star rating if the time to reach -18 ºC can be achieved in less than 24 hours, otherwise, lower ratings will have to be claimed. If the maximum temperature of the warmest package is less than, or equal to -12 ºC after a 24-hour test, the compartment can claim two-star rating only. If such maximum temperature is less than, or equal to -6 ºC, the compartment can claim one-star only. Other details are documented in Section 8 of the IEC 62552-02 standard.

Cooling capacity test: Section 7 of the IEC 62552-02 standard defines a cooling capacity test. The purpose of this test is to measure the cooling capability of chiller compartments by determining the time for a food load of 4.5 kg per 100 L of volume to be cooled from +25 °C to +10 °C. At the same time, the chiller compartments operate at +4 ºC. The same M-package will be used to simulate the food load. However, since a maximum allowed time from starting to ending temperatures is not defined, cooling capacity test will not be executed in this paper. The relevant test parameters are shown (Table 1) to compare with that in the freezing capacity test as a reference.

Deviations from the IEC standards due to the uniqueness of AFPS packages

The IEC standards are originally developed for refrigerators with chiller, freezer, and other larger size compartments. If the same standards are applied to evaluate AFPS packages, some deviations will be found and may eventually lead to additions or changes in clauses in later version of the standard. Such additions or changes are necessary to accommodate the uniqueness of AFPS packages in an AFPS Appliance. Of course, any change in Standard clause will be possible only after in-depth discussions between prospective manufacturers and the Technical Committee of the standard authority. This section proposes and discusses some of the key deviations identified.

There are two directions that the deviations can move toward-upward and downward. Upward deviations mean that AFPS package can actually facilitate more accurate test results or make the test easier to set up and/or execute than legacy refrigerator can. This implies that an AFPS Appliance can function better that a legacy refrigerator can in the context of the Standard tests. Downward deviations mean that changes in the IEC test protocols are necessary with approval of the standard authority in order to accommodate the uniqueness so that the same accuracy of measurement can be acquired.

1. **Upward Deviations:**

a. Currently, the Annex D of the IEC 62552-02 standard requires that

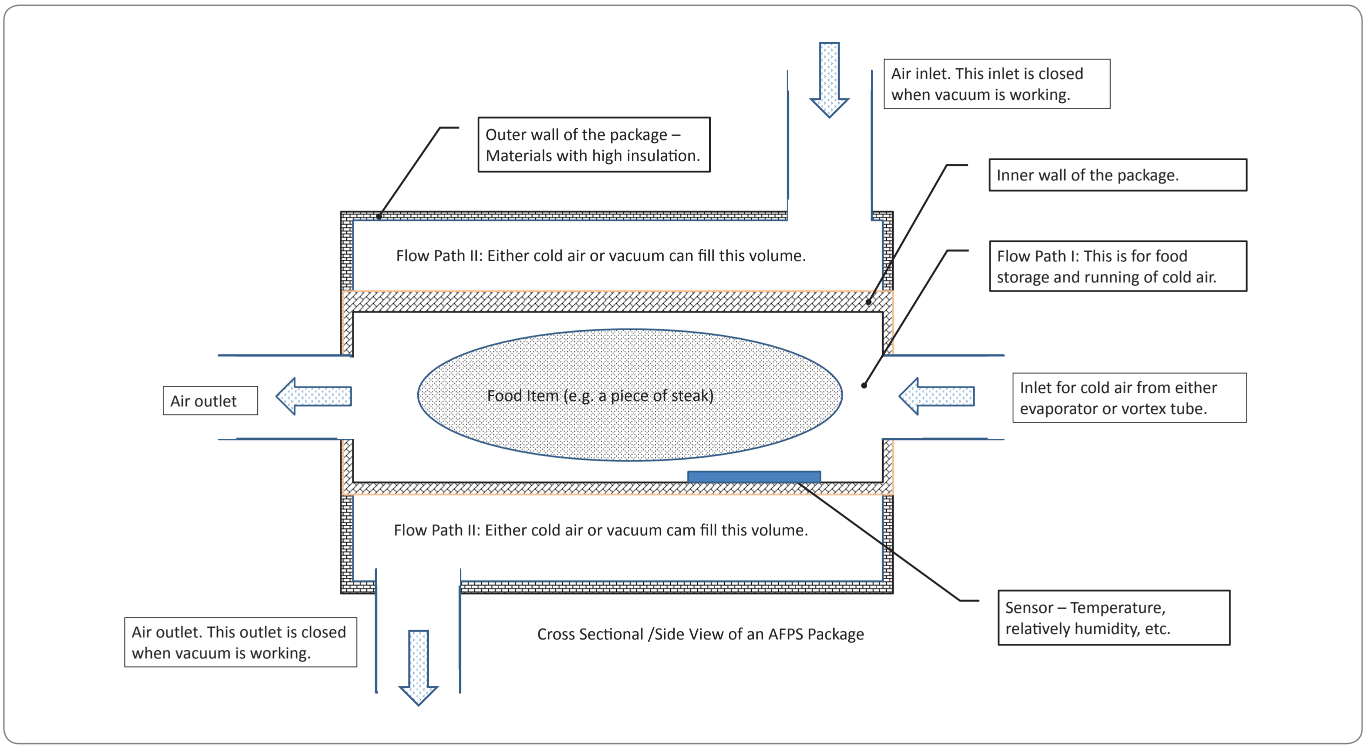

Figure 1.1: Conceptual view of an AFPS package (Adapted and modified from Tsang & Yung [2])

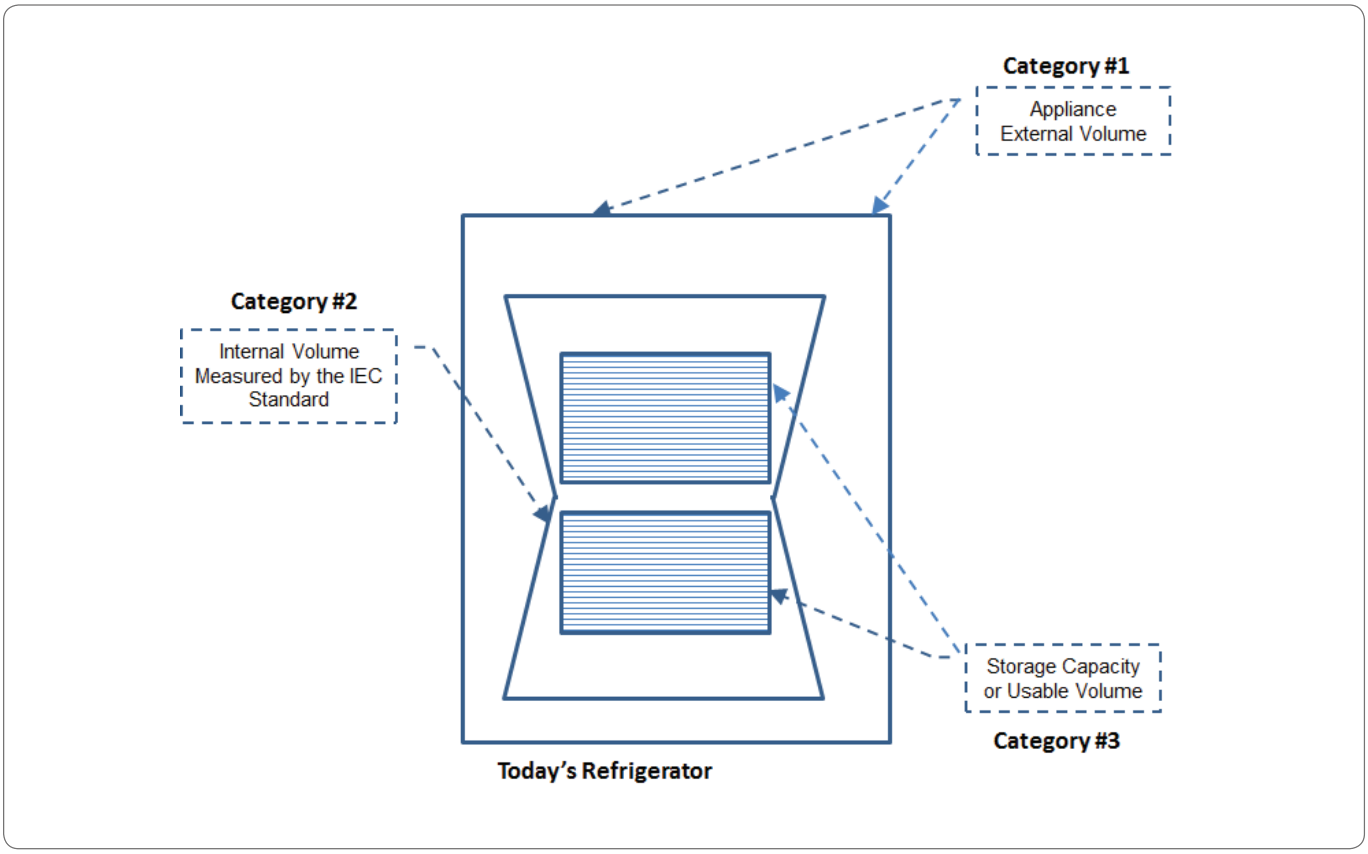

Figure 1.2: Three categories of volume related to a refrigerator device

a number of sensors must be placed in symmetrical order inside a compartment in order to calculate an average temperature by interpolation. However, inside an AFPS package, temperature sensors can be placed in the direct path of air flow. Therefore, the accuracy of temperature measurement is inherently higher. This interpolation is, hence, not necessary or the temperature deviation between sensor readings inside an AFPS package is minimized because of the small head space (after a piece of food item has been placed inside). There is a need to add new options in placement of sensor and test sample locations for testing of AFPS packages.

b. Food temperature can be approximated closely by the package interior temperature. They may even be the same if the temperature probe (or sensor) touches the food surface so that the actual food surface temperature can be detected. In legacy refrigerator, only compartment air temperatures are measured. They neither represent the surface temperature of every food item, nor the surface temperature of foods with various characteristics.

c. In legacy refrigerator, the door must be opened for a defined length of time for placement of test loads. In the case of testing the AFPS packages, it is not be necessary to open all the AFPS packages because each package can function independently.

2. **Downward Deviations:**

a. The mass to volume ratios of test samples for chiller and freezer compartments are 4.5 kg and 3.5 kg per 100L, respectively (per Sections 7 and 8 of IEC 62552-02). However, each AFPS package is supposed to accommodate one piece of food item only. Therefore, there is a need to redefine the number of test samples used at one time and to redefine a test sample size smaller than 500g.

b. Since any AFPS package can function as either chiller or freezer compartment, each package may need to be tested for both cooling and freezing functions (nowadays, a chiller compartment is test for cooling only and a freezer compartment is tested for freezing only). In order to certify the whole Appliance with many packages inside, the Appliance needs to be tested in two modes - all packages function as chillers and all packages function as freezers.

Differences between the conceptual design and an actual product

The following is a typical sequence of any new product commercialization process:

Conceptual model → Simulated setup → Prototype subsystem →Prototype full size product

This paper focuses on design of conceptual model and testing with simulated setup. The proposed AFPS Appliance is still in conceptual design stage with a number of technical research papers already published and being prepared. Simulated setups are fabricated to verify the design conceptual and feasibility. Fabrication and testing of prototype subsystem and full size product are reserved as future work for interested refrigerator manufacturers.

Main goals of the research work

The goals of this research work are to evaluate the AFPS packages, qualitatively and quantitatively, in the context of IEC 62552-01 and IEC 62552-02 (2015) in the following two aspects.

(a) Qualitative evaluation of the advantages with AFPS packages in improving usable storage capacity and relevant aspects with AFPS packages. This topic is addressed in Section 2.

(b) Evaluation of freezing capacity. This topic is addressed in Section 3.

Advantages of AFPS packages in improvement of usable storage capacity

There are two approaches to analyse these advantages based on the context of the standard and the practical aspects in how consumers can make the best use of a compartment. The first one presents the fact that the usable storage capacity of an AFPS Appliance can exceed that of the compartments of a legacy refrigerator. The second one presents the advantage of AFPS packages in calculation of refrigerator internal volume and storage capacity per the specified IEC protocols when compared with that of legacy refrigerator. Both approaches assume that the Appliance and the refrigerator have the same refrigerator internal volume.

Efficiency of storage Capacity in a single refrigerator compartment

Issues with stacking up of foods: It is common for food items to stack up on each other in a compartment. However, they must be stored in vessels before stacking up since most food items originally come in odd shape (non-rectangular or non-uniform), like a whole piece of frozen chicken, sandwiches, vegetables, etc, unless they are inside rectangular packages when purchased. After all, different food types should not have direct contact with each other, especially when some of them are raw. However, these vessels themselves may have odd shapes and certainly be rigid (due to plastics or glass materials). Paper packaging material is more flexible, but once the package is open, they may lose the structural rigidity and will not be good for stacking up anymore. Food items on plates or in bowls are certainly not stackable. Comparison between rectangular AFPS packages and odd shape vessels in top and side views are shown in **Figure 2.1**.

AFPS packages as the solution: As a solution to the issues mentioned, AFPS packages provides three key advantages related to stacking up:

1. It can be seen that stacking up of odd shape vessels will leave air gap between the vessels, hence wasting compartment space. In case of legacy refrigerator, some air gaps are necessary for cold air flow. However, for AFPS packages, cold air flow takes place inside the packages such that stacking up of AFPS packages will not interfere or block flow path of cold air (full contact between packages is feasible).

2. AFPS packages can come in a number of standard sizes. Different combinations of package sizes can be accommodated in the same Appliance for different family demographics and occasions. In addition to those that come alongside with an AFPS Appliance, consumers can buy additional packages as purchasable spare parts. This flexibility allows users to expand their choices and to change the sizes of packages to fit various food types.

3. A consequential benefit of cold air flowing inside AFPS packages is that non-uniform temperature distribution within the compartment of a legacy refrigerator will not be a problem any longer (inside an AFPS package, temperature distribution is much more uniform due to the comparatively smaller internal space). This also means that the location of a specific AFPS package inside the Appliance does not affect the food item temperature and its stability because all cooling and freezing are inside the package. On contrary, food temperature is affected by where the foods are located inside a legacy refrigerator.

In this paper, all AFPS packages are assumed to have the same size in order to facilitate calculations. The wall thickness of a package depends on the requirement for being a vacuum insulation only or a combination of both vacuum insulation and air flow duct, as mentioned in Section 1. Calculations relevant to the wall thickness with vacuum function have been performed by Tsang & Yung [2].

Calculation of refrigerator internal volume

Issues with calculated internal volume: Section 4.8 of the IEC 62552-03 standard provides uniform means of determining refrigerator size. Understanding that compartment space is not a clean rectangular hollow space but filled with various special features and/or functional components with odd shape (e.g. ice makers, air duct, shelves, baskets), the standard provides methods in taking them into account in the calculation. When measuring the

IEC Standards	Performance Measured	Ambient Temp (C)	Sample Start Temp (C)	Sample End Temp (C)	Compartmet Temp (C)	Mass / Volume Ratio	Test Sample	Measured Paramters	Test Samples Exposed to Air	Defrost Cycles	Door is Open before Test	AFPS Package Volume in L	Test Subject Mass (g)
62552-02	Freezing Capacity	25	25	-18	-18	3.5 Kg / 100 L	M-Package	Time & Temperature	Yes	Yes	No	0.29	1.0
(Section 8)						3.5 g/L							
62552-02	Cooling Capacity	25	25	10	4	4.5 Kg / 100 L	M-Package	Time & Temperature	Yes	Yes	No	0.29	1.3
(Section 7)						4.5 g/L							

Table 1: A summary of the requirements and parameters specified in various IEC 62552 standards

compartment internal volume, the exact shapes of the walls including all depressions or projections will be considered. The same standard does not provide means to measure neither the food storage capacity nor usable volume.

AFPS packages as the solution: To elaborate more from Section 1.3.1, there are three categories of sizes or volumes inherent to a refrigerating appliance. They are as follows in decreasing order.

1. External volume (Category #1)-The external dimension, made up of footprint area and the height, are critical in that consumers need to consider how a refrigerator will fit into a kitchen.
2. Internal volume (Category #2)-This is the internal space, or generally known as "compartment" (typically in Litre), that the IEC standard mentioned measures and refrigerator manufacturers report and promote to consumers. A number of energy efficiency performances of a refrigerator are calculated based on this information. Analysis of a total of 35 models of refrigerator models from four major brands from the United States, Japan, Korea, and Germany has shown that the ratio of internal volume to external volume are between 41% and 54%. Note that the raw data in sizes are available from the website of the corresponding company.
3. Storage capacity and usable space (Category #3)-Manufacturers may choose not to report this information to consumers, neither the IEC standards require such measurement. However, consumers may have the most interests in this information.

Figure 2.2 depicts conceptually the difference between refrigerator and AFPS Appliance in usable storage space. The left side of Figure 2.2 shows that, in a typical refrigerator, the usable storage space is "compressed" due to the odd shapes or presence of various compartment internal features. However, in case of AFPS Appliances, much less internal features are needed because all temperature operations take place inside AFPS packages. Compression of usable storage space can be minimized or eliminated, allowing more AFPS packages to fit in.

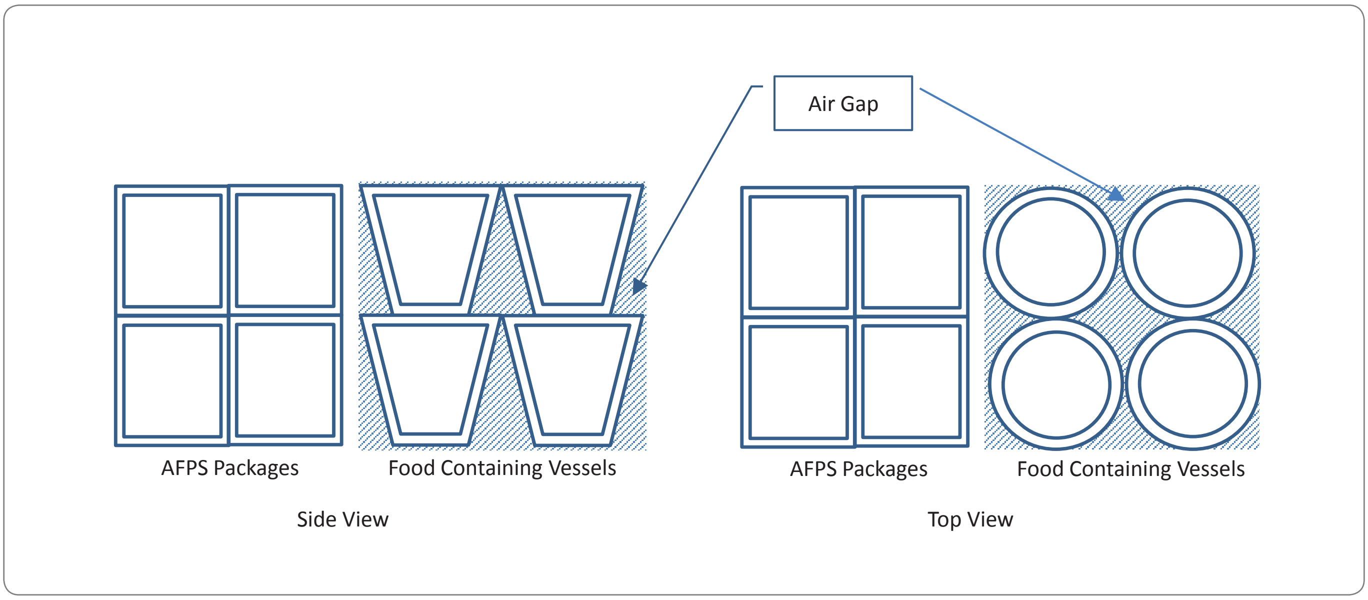

Figure 2.1: Both sides and top views show that odd shape vessels, waste usable storage space in a compartment. The rectangular shape of AFPS packages allows full contact and minimize the air gap

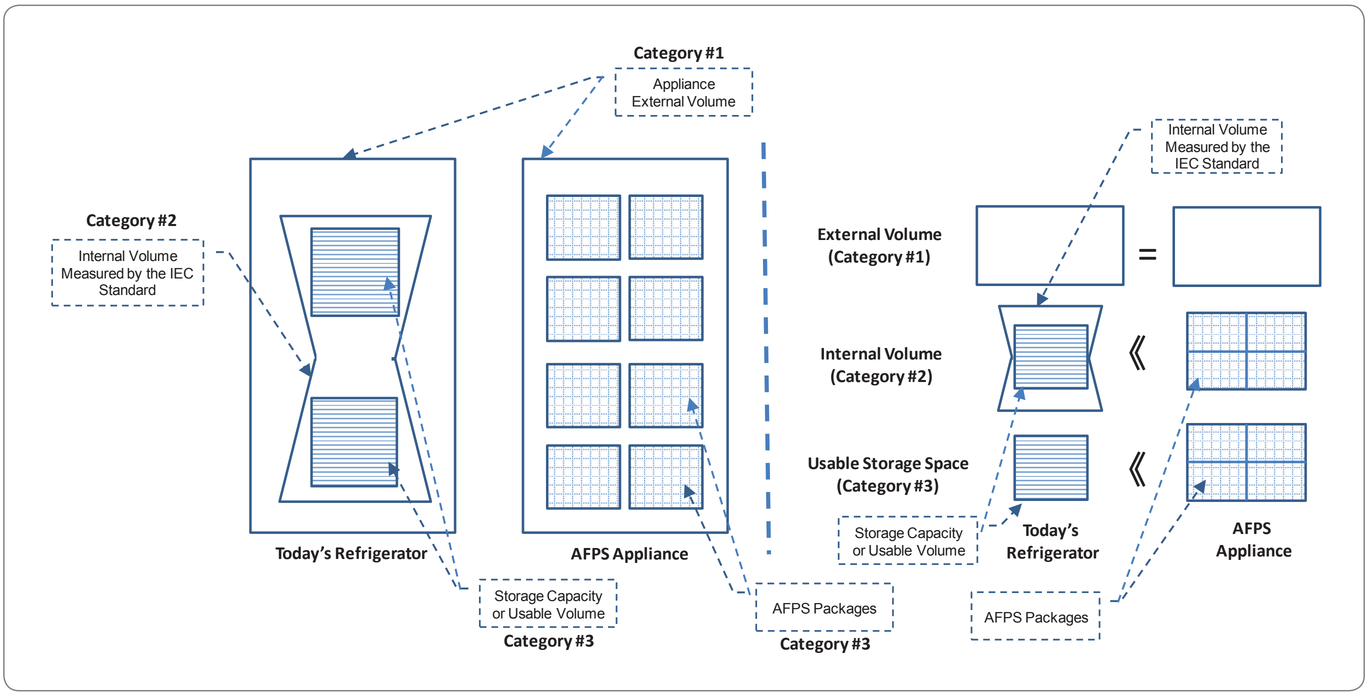

Figure 2.2: Comparison of storage capacity or usage space between legacy refrigerator and AFPS Appliance with the same external volume

The right side of Figure 2.2 indicates that with the same dimensions in the external volume (first category), the internal volume (second category) of a refrigerator compresses the usable storage space (third category) due to the odd shapes and features. In an AFPS Appliance, no such compression happens because the internal volume (second category) is the same as the usable storage space (third category). In the IEC standard, compartment is identified as the space where food storage and thermal processing take place. Therefore, in an AFPS Appliance, the term "compartment" is the same as the storage space of the AFPS packages. In the other words, the internal volume or compartment (second category) is exactly the same as the storage capacity or usable space (third category).

A direct benefit of the equivalency between the second and third categories in an AFPS Appliance is that the calculation of compartment food storage capacity inside the package is strict forward and accurate mainly because of the rectangular shape and of the absence of odd feature. Another key benefit is that energy consumption and efficiency performance related calculations like the EEI can be more accurate if AFPS package space are calculated [8].

Materials & Methods

Preparation of the experimentation

Experimental setup: The test hardware is made up of such custom-made fixture and standard measurement equipment - Test Setup #1 with simulated AFPS package with a Vortex Tube of Model 3215 from Exair (Figure 3). Note again that vortex tube is a key component for the test setup but is an option for an actual AFPS package. The accuracy values of the2-channel digital thermometer is ±0.1%+0.5 °C.

Temperature range: The standard required starting and ending temperatures for freezing capacity test are 25 ºC and -18 ºC (or a temperature drop of 51 ºC), respectively. Since the actual laboratory ambient temperature is less than 25 ºC, the test sample will be first heated up artificially to 25.5 °C before the test is executed. The standard allows a ±1 ºC deviation from the mean of 25 ºC.

Test sample: The defined mass to volume ratios for the freezing tests is 3.5 kg per 100 L. Yet, due to the small size (0.29 L) of the simulated AFPS package, the mass of test sample is only 1 g for the freezing tests. Note that the standard does not define a minimum compartment volume nor a minimum mass of test sample. However, in order to use a test sample that is more representative of an actual food item and make better use of the space inside the simulated AFPS package, a larger test sample of 20 g will be used. Note that this larger sample has exceeded the standard requirement, and therefore, can be considered as the worst-case analysis.

The test sample (20 g) used is the same as the M-package (also shown in (Figure 3)) required by the standard except that the sample is cut out from the M-package which originally weighs 500 g. Since the sample material has a property approaching that of lean beef. The thermal property of lean beef will be used for thermal transfer calculations in later section [9].

Freezing capacity test of the simulated AFPS package

The purpose of this test is to measure the freezing capability of the simulated AFPS package when it functions as a freezer compartment. **Table 2.1** shows the key parameters used in the test. **Table 2.2** indicates that it takes 3.18 hours for the test sample temperature to drop from 25.5 ºC to -17.3 ºC.

Defrosting and recovery, ice-maker, anti-condensation heaters and other auxiliary devices are ignored in the analysis of this paper. In addition, defrost and recovery cycles are not considered in the following experimentations and model analysis.

Analysis of the experimental results

Test Sample temperature in freezing: The fact that this lowest temperature (test sample) of -17.3 ºC did not reach -18 ºC does not affect the validity of the tests or the testability of the test setup due to the following two reasons:

1. The first reason is that once the sample temperature (measured at the thermal centre) has dropped to and below -17 ºC, the mean difference between the sample temperature and the freezing air (as the driver) temperature is 2.9 ºC (with a standard deviation of 0.3 ºC or 12% which is acceptably insignificant). In other words, the sample temperature is maintained at around 3 ºC above the driving temperature once the freezing process has become stabilized (80% of the freezing time span has passed). The limiting factor is actually the driving temperature which, if can become lower than that achieved in this test, will have no problem in driving down the sample temperature to -18 ºC or even lower. For example, freezing air temperature at -21 ºC can drive down sample temperature to -18 ºC. More powerful vortex tube can acquire a lower driving temperature easily.
2. Another reason is that the thermal insulation (ABS material) of the simulated AFPS package is not an ideal insulation material. If the insulation can be improved such that less heat is gained by the test sample when ambient heat moves in, the test sample temperature will be able to approach -18 ºC without difficulty.

Simulated AFPS Package		
a (Width) (m)	a	73.0000
b (Height) (m)	b	49.0000
L (Length) (m)	L	80.0000
Volume (m3)	Total Vol	0.00000
Volume (L)		0.00
Test Sample		
Simulated food item	Ice	M-Pacakge Materials (Similatr to Lean Beef)
Mass (Kg)	N/A	0.02
# of surfaces receiving refrigeration	6	5
Refrigerating Capacities:		
Ambient temperatures (deg C)	0	22.8
Initial freezing temperature (deg C)	0	-1.7
Refrigerating air flow speed (m•s-1)	1	5.3

Table 2.1: Key parameters related to the simulated AFPS package and test sample

Cooling Test					Freezing Test				
Total Hr	T Comp	T Food Ctr	Temp Diff (Comp & FC)	% Time	Freezing Time Span (Hr)	Temp (Driving Air or Package Space)	Temp (Test Sample Thermal Center	Temp Difference Between Driving Air & Thermal Center)	% Time Span from Starting
0.00	0.0	0.0	0.0	0%	0.00	22.5	23.8	1.3	0%
0.00	11.5	24.3	12.8	0%	0.47	-10.5	-1.1	9.4	13%
0.01	9.4	23.3	13.9	2%	0.50	-11.0	-1.0	10.0	14%
0.02	7.6	21.4	13.8	3%	0.57	-11.7	-2.1	9.6	16%
0.03	6.3	19.0	12.7	5%	0.61	-12.3	-2.6	9.7	17%
0.03	6.1	18.3	12.2	6%	0.63	-13.0	-2.8	10.2	18%
0.03	5.7	17.4	11.7	7%	0.73	-14.7	-6.7	8.0	21%
0.04	5.2	15.8	10.6	8%	0.73	-12.2	-6.9	5.3	21%
0.05	4.8	14.2	9.4	10%	0.75	-13.3	-7.4	5.9	21%
0.06	4.4	12.6	8.2	12%	0.80	-13.0	-8.5	4.5	23%
0.07	4.3	11.7	7.4	13%	0.80	-13.5	-8.6	4.9	23%
0.08	4.1	10.7	6.6	15%	0.82	-13.4	-9.1	4.3	23%
0.08	3.9	9.7	5.8	17%	0.86	-12.1	-9.9	2.2	25%
0.09	4.0	8.9	4.9	18%	0.87	-13.5	-10.0	3.5	25%
0.10	3.8	8.1	4.3	20%	0.91	-13.2	-10.4	2.8	26%
0.11	3.8	7.5	3.7	22%	0.96	-12.8	-10.8	2.0	27%
0.12	3.9	7.0	3.1	23%	1.07	-12.7	-11.1	1.6	30%
0.13	4.0	6.1	2.1	27%	1.14	-13.1	-11.3	1.8	33%
0.14	4.0	5.7	1.7	29%	1.41	-12.1	-11.3	0.8	40%
0.15	3.9	5.4	1.5	30%	1.54	-15.7	-12.0	3.7	44%
0.16	4.0	5.1	1.1	32%	1.68	-20.6	-12.0	8.6	48%
0.18	3.9	4.6	0.7	35%	1.87	-20.5	-12.4	8.1	53%
0.18	3.9	4.5	0.6	37%	2.01	-18.0	-12.6	5.4	57%
0.19	4.0	4.3	0.3	38%	2.02	-19.1	-12.4	6.7	58%
0.20	4.0	4.2	0.2	40%	2.03	-19.8	-13.0	6.8	58%
0.21	4.0	4.0	0.0	42%	2.07	-19.6	-13.5	6.1	59%
0.22	4.0	3.9	-0.1	43%	2.11	-20.0	-14.2	5.8	60%
0.23	4.0	3.8	-0.2	45%	2.16	-20.0	-15.1	4.9	62%
0.23	4.0	3.7	-0.3	47%	2.27	-20.1	-16.2	3.9	65%
0.24	4.0	3.7	-0.3	49%	2.67	-20.3	-16.5	3.8	76%
0.25	3.9	3.6	-0.3	50%	2.68	-20.5	-16.7	3.8	77%
0.27	4.0	3.5	-0.5	54%	2.77	-19.9	-16.8	3.1	79%
0.34	4.0	3.3	-0.7	68%	2.79	-20.2	-16.9	3.3	80%
0.38	4.0	3.2	-0.8	77%	2.85	-20.4	-17	3.4	81%
0.43	4.0	3.2	-0.8	85%	2.89	-20	-17.1	2.9	82%
0.47	4.0	3.2	-0.8	93%	3.13	-19.9	-17	2.9	89%
0.49	4.0	3.1	-0.9	99%	3.17	-20	-17.2	2.8	91%
0.50	4.0	3.2	-0.8	100%	3.18	-19.8	-17.3	2.5	91%
					3.37	-20.3	-17.1	3.2	96%
					3.50	-19.6	-17.1	2.5	100%
					Temp Difference Between Driving Air & Thermal Center			2.9	(When thermal center temp stabilizes)
					Standard Deviation			0.3	
					% Standard Deviation			12%	

Table 2.2: Results of the freezing capacity test

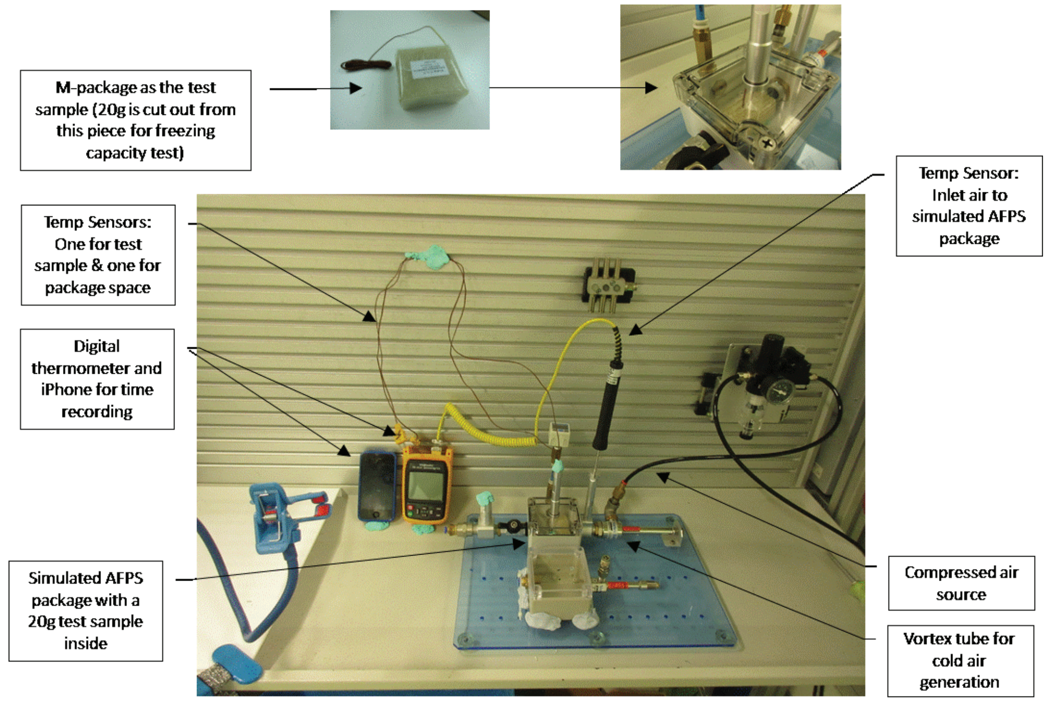

Figure 3: Test setup for cooling and freezing tests

In this test, the sample mass is 20 g only and occupies 30% of the package internal space which is 0.29 L. In case of a pre-production type of AFPS Appliance, the package size, food item size, and the delivery rate of cold air generated will be all proportionally raised to a practicable level.

The simulated AFPS package can claim a four-star rating. Of course, it is more desirable to rate a pre-production AFPS Appliance once it is in product commercialization process.

Effect of sample size on freezing times: If half of the thickness of a piece of lean beef (no bone) equals to the closest distance between the beef surface and the thermal centre (this is normally the case), another beef sample with many times less mass than this piece of lean beef, but with the same thickness can have the same freezing time.

In this test, the 20 g sample is lighter than the Standard-defined 500 g sample by 25 times. However, the freezing time of the thermal centre of a piece of material is directly proportional to the closest distance between the food material surface to the thermal centre (also called thermal distance). Such distances for the 500g and 20g samples are 25 mm and 8 mm, respectively, being 3.12 times different. Therefore, the freezing time of the 500g test sample is 3.12 times, not 25 times, longer than that of the 20 g sample. As a result, a smaller size sample can represent food load effectively in the freezing time evaluation defined by the Standard as long as the factor of thermal distance is properly considered.

Theoretical model analysis of cooling and freezing capacities:

This section presents theoretical model analysis in freezing capacity of the simulated AFPS package that has been tested in Section 3.2. The results will be compared with the experimental ones as validity check. Sources of error and proposal for rectification will be identified to explain the deviations between the experimental and analytical results.

Key assumptions of the analysis: The followings are key qualitative and quantitative assumptions for the analysis.

1. The Standard requires that refrigerator compartment has reached a stable low temperature (4 °C or -18 °C) before test commences. This stable temperature assumes that the refrigerator has been operating for many hours already. In the test, the simulated AFPS package generates cold air only when the test starts (no pre-cooling or pre-freezing).
2. In the Standard, the final or stable test sample thermal centre temperature should be equal to the driving air temperature which is responsible for pulling down the test sample temperature. However, the analytical model used in this section does not allow the driving air temperature (-18 °C) to be equal to the final test sample temperature (-18 °C) because otherwise the freezing time will be infinitely long. Therefore, the driving temperature is selected as -19 °C which can pull down the sample thermal centre temperature within reasonable time.
3. The following factors are not considered - Radiation heat transfer and heat influx through the door seal; Expansion in size when water is frozen; Evaporative loss of mass and energy; Heat transfer through edges and corners between walls in AFPS package.
4. All outside surfaces of the simulated package, except the bottom one which is assumed to be adiabatic, receive the same ambient heat influx, and are of the same temperature.

Methodologies for calculations of cooling and freezing times:

The freezing time from 25 ºC to -18 °C can be calculated using Cleland & Earle's method [10], or Formula (1). Correction factor must be considered because the food thermal centre (or test sample in this case) is at -18°C (lower than the typical -10°C reference temperature from the method). To calculate the freezing time from room temperature, or RT, to ending temperature, or ET, is the following.

$$t_{RT-18} = \frac{\Delta H_{10}}{T_f - T_m}\left(\frac{PD}{h} + \frac{RD^2}{k_T}\right)\left[1 - \frac{1.65Ste}{k_T} L_n\left(\frac{T_f - T_m}{T_{ref} - T_m}\right)\right] \quad (1)$$

Freezing time calculations & analysis of results Calculations: Cooling of a food item inside an AFPS package is realized by passing cold air through FP I. The heat transfer coefficient is calculated considering both friction factor and the resulted Nusselt Number using Sieder & Tate formulation per Formula (2) [11].

$$Nu = 1.86 \cdot [Re \cdot Pr / (L/D_h)]^{1/3} \cdot (\mu / \mu_s)^{0.14} = 23.202 \qquad (2)$$

Friction factor (f) of the cold air flow over the package wall internal surface is now evaluated per Formula (3) below [11].

$$f = 1 / [1.82 \cdot Log_{10}Re - 1.64]^2 = 0.0272 \qquad (3)$$

Nusselt Number (N_{uf}) considering the Friction Factor (f) per Formula (4) is found to be 1.98 times higher than the original Nu per Formula (2) [12].

$$Nu_f = (f/8) \cdot (Re - 1000) \cdot Pr / [1+ 12.7 \cdot (f / 8)^{0.5} \cdot (Pr^{2/3} - 1)] = 46.02 \qquad (4)$$

The resulted heat transfer coefficient is found as 75.90 $Wm^{-2}K^{-1}$. The Biot Number becomes 1.56.

Various parameters in Formula (1) can be calculated with the thermodynamic variables found above. The resulting freezing times can then be calculated with Formula (1) and are shown in Table 2.3.

In the experimentation, the test sample starting and ending temperatures are 25.5 °C and -17.3 °C respectively. The theoretical model analysis in this section will calculate the analytical freezing times in order to compare with experimental freezing times. One point to note is that, the freezing air supplied to the simulated AFPS package that drives the thermal centre temperature of the test sample is not fixed at -19.8 °C throughout the freezing time span. Instead, this driving temperature drops from 22.8 °C to -19.8 °C over the test time span (Of course, it drops much faster than the test sample temperature). However, Formula (1) makes an assumption that the driver freezing air has a constant temperature. Therefore, an adjustment must be made to improve the accuracy of the model analysis. There are four steps to adjust.

1. Two average driving freezing air temperatures are calculated. The first one is the average driving temperature (-12.8 °C) when temperatures drops from 22.8 °C to -15.7 °C over a time span of 1.54 hr. Another is the average driving temperature (-19.9 °C) when temperatures drop from -15.7 °C to -19.8 °C, over a time span of 1.64 hr (= 3.18 hr-1.54 hr). The standard deviations of these two average driving temperatures are 9% and 3%, respectively, and are acceptably small.
2. Calculate the time span within which the test sample thermal centre temperature drops from 25.5°C to -12.0 °C when the average driving temperature is -12.8°C. From Table 2.3, it is 2.35 hours.
3. Calculate the time span from -12.0°C to -17.3°C when the average driving temperature is -19.9°C. From Table 2.3, it is found as 0.97 hour (=2.06 hours-1.09 hours).
4. Simply add up 2.35 hours and 0.97 hour to gain a total of 3.32 hours which can be identified as the analytical freezing time with driver temperature adjustment.

Result and error analysis

Comparisons between various freezing times are summarized in Table 2.4.

Column A is the IEC standard requirement while the driving air temperature is at -19 °C (This deviates from -18 ºC as explained in Section 3.4.1). 24 hours are the maximum allowed limit for being rated as four-star.

Column B shows that the freezing time calculated by using the same analytical model on the IEC standard requirement. It is 2.86 hours (much less than 24 hour).

Column C shows that the experimental freezing time to -17.3 °C is 3.18 hours (Table 2.2). This is longer than the 2.86 hours (Column B) by 11.1% due to two main reasons: (1) Low thermal insulation of the package wall; and (2) the driving air temperature starts at 22.8 °C and gradually drops to -19.8 °C over the 3.18 hour time span. The fact that the ending temperature (measured at test sample thermal centre) is -17.3 °C and not -18 °C (per the Standard) does not affect the testability or analysis. The reason is that the simulated package itself is not the limiting factor. Should the vortex tube become more powerful, the simulated package will have no problem in reaching -18 °C. 11.1% deviation is considered acceptably small.

Column D shows that the analytical freezing time is 2.1 hours through theoretical model analysis when the driving air temperature is fixed at -19.8 °C. This is 51.4% shorter than the 3.18 hours (Column C). The single driving air temperature needs adjustment to reflect a more accurate freezing time.

Column E shows that the adjusted analytical freezing time is 3.32 hours which is longer than the 3.18 hours by -4% only. It demonstrates that the adjusted analytical freezing time is agreeable with the experimental freezing time. The primary source of error for the -4.2% deviation is that the actual air flow inside the package may not be uniform over all surfaces of the test sample, resulting in cold air flow leaving the package prematurely (or before it can carry out its mission of freezing the test sample). This reduces the efficiency of heat removal.

Due to the agreeable experimental and analytical freezing times, it can be concluded that the AFPS package is testable against the specified IEC standard in freezing capacity.

Conclusions and Future Work

Qualitative analysis was performed to analyse the advantages of using customized packages in storing and preserving foods as far as usable storage space is concerned. The specified IEC standard provides means to measure internal volume but odd features and parts inside a compartment often compressed the usable storage space. Yet, calculation of usable storage capacity is not provided by the standard. Using customized AFPS packages in an AFPS Appliance can minimize those odd shapes, hence allowing more room to fit in AFPS packages for food storage. In addition, when AFPS packages are used, the internal volume and total usable storage capacity are equal,

Three Cases of Temperature Drop	Starting Temp (C)	Ending Temp (C)	Average Driver Temp (C)	Ending Temp (C)	Average Driver Temp (C)	Time (hr)
Case #1: From 25.5C to -17.3C if the driver temp	25.5			-17.3	-19.9	2.06
Case #2: From 25.5C to -12C if the driver temp	25.5	0.0			-19.9	1.09
Case #3: From 25.5C to -12C if the driver temp	25.5	0.0	-12.8			2.35
Freezing Time = Case #1 - Case#2 + Case#3						3.32

Table 2.3: Results of adjustment of freezing times due to two driver freezing air temperatures

	A	B	C	D	E
Measured Parameters	Based on the IEC Standard		Experimental Results	Results per Theoretical Model Analysis	
	Required Temp & Time	Analytical Results		Fixed Driver Temp	Two Driver Temp
Room Temperature (Starting)	25.0	25.0	25.5	25.5	25.5
Final Thermal Center Temperature (Ending)	-18.0	-18.0	-17.3	-17.3	-17.3
Freezing Air Temperature (As the Driver)	-19.0	-19.0	-19.9	19.8	-12.8 & -19.9
Note: Driving temperature is not specified in the standard.					
Freezing Times (Measured or Calculated)	24.00	2.86	3.18	2.10	3.32
Maximum Allowed For 4-Star Rating					
Deviation Between Column B & C =			-11.1%		
Deviation Between Column B & D =				26.6%	
Deviation Between Column C & D =				51.4%	
Deviation Between Column C & E =					-4.2%

Table 2.4: Summary of freezing time comparisons between the IEC standard requirement, experimental results, and the analytical work

hence allowing an accurate calculation of usable storage capacity. Energy performance metric (e.g. EEI) can also be calculated more accurately. Due to some uniqueness in structure and operations of AFPS packages (and the AFPS Appliance in general), modifications of the IEC standards on key clauses are necessary so that the standard can be used to certify the Appliance in its product commercialization process. Some of the proposed modifications are identified.

Experimentations and theoretical model analysis have demonstrated that the freezing times are 3.18 and 3.32 hours, respectively, from a starting temperature of 25.5 ºC to a stable ending temperature of -17.3 ºC. The 4.2% deviation between these two freezing times indicates that both results are agreeable. The fact that the stable ending temperature is not at or below -18 ºC does not affect the performance of the simulated AFPS package because it has been shown that the ending temperature stabilises at around 3 ºC above the driving air temperature which is the only limiting factor. In addition, since the mass to volume ratio in this test is 20 times larger than the required 3.5 kg per 100 L, the freezing times will be much shorter if the Standard-required ratio is followed.

Testing with the simulated setup of AFPS package leads to the conclusion that the conceptual AFPS package design complies with the freezing capacity test specified by the mentioned IEC standard.

Future work should be carried out to continue the testability evaluation of the AFPS packages by focusing on energy consumption and efficiency test as defined in Section 6 of the IEC 62552-03 Standard. Effect on energy consumption and efficiency of the defrosting and recovery functions will be also be studied in this future work.

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