Testing Packaging Design Changes in Kiwifruit Packaging for Reefer Container Conditions

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Abstract

Refrigerated transport is widely used for export in the New Zealand horticultural industry, valued to be over NZD $9.5B in 2019, to maintain the quality of perishable produce from farm to consumer. New Zealand's horticultural industry mostly uses refrigerated containers (reefers) to deliver the goods. In which, generally, the precooled produce in stacked boxes will be stored as pallet units, where the refrigeration unit and a fan circulate air into the container. Normally the air inside the reefer is to achieve a homogenous controlled environment around the produce as well as in the container through flow in vertical directions (from bottom to top) towards every corner of container in order to preserve the fruit quality and prolong its shelf life.

Packaging design plays a crucial part in the cooling performance, especially in ventilation (i.e vent size and vent location over the design) with respect to the direction of air flow within the cooling unit. Even though vertical ventilation has its impact on the cooling performance of a design, the modular bulk packaging of polylined kiwifruit has not been equipped with vertical ventilation despite the kiwifruit industry being the largest horticultural sector in New Zealand (worth NZD $ 2.3B in 2019).

To understand the effects of vertical ventilation on a kiwifruit MB box design in a reefer condition, an apparatus was designed and constructed of a single column of MB boxes with similar airflow considerations as a standard reefer. For experimentation purposes artificial kiwifruit simulators were used in place of real kiwifruits. Fruit temperature was used as a variable to understand the cooling efficiency of the box design by using 20℃ or 25℃ as initial temperature and pumping 0℃ reefer condition airflow into the apparatus. In addition to vertical ventilation, the experimental setup also considered polyliner bags and different air flow modes as a design variable and reefer variable respectively.

For single column MB boxes at reefer conditions it was found that 3% vertical ventilation has no significant effect on the cooling profile of the boxes in both economical (40 air renewal/hr) and normal (75 renewal/ hr) air flows. Additionally, removal of polyliner form the design reduced the half-cooling time of the boxes in economical flow ranging from 36-56 %. Where the smallest and largest change was observed in the middle box and the base box. With the addition of vertical ventilation to the polyliner scenario, an added effect of reduction in the half- cooling values ranging 46-52% was observed.

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Nomenclature

Symbol	Description	Units
$\boldsymbol{q}$	Heat Transfer Rate	W
$\boldsymbol{k}$	Conductive Heat Transfer Coefficient	W/m.K
$\boldsymbol{A}$	Surface Area	m^2
$\mathbf{d}\boldsymbol{T}$	Temperature Difference	K
$\mathbf{d}\boldsymbol{x}$	Distance	m
$\boldsymbol{h_C}$	Convective Heat Transfer	W/m^2K
$\boldsymbol{\sigma}$	Stefan-Boltzmann constant	W/m^2K^4
$\boldsymbol{T}$	Absolute Temperature	K
$\boldsymbol{t}$	Thermal Conductivity	W/m.K
$\boldsymbol{\rho}$	Density	kg/m^3
$\boldsymbol{h}$	Height of the point	
$\boldsymbol{t_k}$	Thermal Conductivity for Kiwifruit	W/m.K
$\boldsymbol{t_s}$	Thermal Conductivity for Artificial Simulator	W/m.K
$\boldsymbol{\rho_1}$	Density for Kiwifruit	kg/m^3
$\boldsymbol{\rho_2}$	Density for Artificial Simulator Kiwifruit	kg/m^3
$\boldsymbol{c_k}$	Specific Heat Capacity for Kiwifruit	J/kg.K
$\boldsymbol{c_s}$	Specific Heat Capacity for Artificial Simulator	J/kg.K
$\boldsymbol{A_1}$	Cross-Section Area at Point 1	m^2
$\boldsymbol{A_2}$	Cross-Section Area at Point 2	m^2
$\boldsymbol{v}$	Velocity	m/s
$\boldsymbol{VF}$	volumetric flow rate	m^3/hr
$\boldsymbol{N}$	Number of Renewals	1/hr

$\boldsymbol{IVS}$	Internal Volumetric Space	m^3
$\boldsymbol{C}$	superficial air velocity	m/s
$\boldsymbol{A_C}$	Cross-Section Area	m^2
$\boldsymbol{Q}$	Heat Energy Stored	W
$\boldsymbol{n_p}$	Number of Simulators	
$\boldsymbol{m}$	Mass of the Simulator	kg
$\boldsymbol{c_p}$	Specific Heat of the Simulator	J/kg.K
$\boldsymbol{\Delta t}$	Difference in the Temperature	K
$\boldsymbol{k}$	Thermal Conductivity	W/mK
$\boldsymbol{Y_{t,n}}$	FUTC of product n	
$\boldsymbol{T_{t,n}}$	Current Temperature of product n	K
$\boldsymbol{T_{i,n}}$	Initial Temperature for product n	k
$\boldsymbol{T_{ref}}$	Reference Temperature	k
$\boldsymbol{\overline{Y}_{X,t}}$	Average FUTC value for the group	
$\boldsymbol{m}$	Total number of products in the group	
$\boldsymbol{P}$	Pressure drop	Pa
$\boldsymbol{V_r}$	Voltage recorded	V
$\boldsymbol{V_i}$	Initial voltage at the start of experiment	V
$\boldsymbol{R}$	Conversion rate	
$\boldsymbol{P_{Max}}$	Maximum Pressure	Pa
$\boldsymbol{P_{Min}}$	Minimum Pressure	Pa
$\boldsymbol{V_{Max}}$	Maximum Voltage	V
$\boldsymbol{V_{Min}}$	Minimum Voltage	V
$\mathbf{V_{Supply}}$	Supply Voltage	V

V_{logger}	Logger Voltage	V
$\boldsymbol{E}$	Error bar	
$\bar{X}$	Mean	
$\boldsymbol{S}$	Standard Deviation	
$\boldsymbol{z}$	Confidence interval co-efficient	
$\boldsymbol{n_o}$	Number of observations	
MB	Modular bulk	
SSC	Soluble Solids Content	
OGR	Orchard Gate Returns	
RH	Relative Humidity	
WCA	Water-Carbohydrate-Air	
PLA	Poly Lactic Acid	
LDA	Laser Doppler Anemometer	
PIV	Particle Image Velocimetry	
TCR	Temperature Controlled Room	
CFD	Computational fluid dynamics	
MBP	Modular Bulk Packaging	
VSD	Variable Speed Drive	
HCP	Half Cooling Point	
SECP	Seven-Eight Cooling Point	
HCT	Half Cooling Time	
TCR	Temperature-Controlled Room	

1 Thesis Introduction

New Zealand earns an impressive amount of earnings from the export industry. According to New Zealand Foreign Affairs and Trade, (2020). New Zealand has a $60.22B export market. The horticultural industry holds about 10 % of total merchandise export income, with kiwifruit making up of $2.3B market share (Fresh Facts, 2019). As New Zealand is an island nation, 99 % of the volume of trade is done through marine transportation.

In marine transportation, bulk reefer ships are being replaced with conventional container carrying ships. Reefer containers have made it possible for transporting a wider variety of cargo through a dedicated supply chain (Arduino et al., 2015). The reefer container is the fastest expanding industry for transporting temperature sensitive products (Gardiner, 2007). In transporting goods from an island nation to a place thousands of kilometers away, the transport time will be in the order of weeks. New Zealand upholds a reputation in transporting high quality fresh produce to the world (Olatunji, 2018), which is partially possible through the advancement and innovation in packaging and refrigeration technology (Carson & East, 2018).

The ventilation designed in packaging influences the air flow structure through a pallet, impacting the cooling rate and cooling heterogeneity inside the packaging (Olatunji, 2018). An organized vertical ventilated packaging can create a good channel of air flow through stacked boxes (Wu et al. 2019). The current kiwifruit modular bulk (MB) pack has no ventilation designed to assist vertical airflow. This thesis investigated the potential of vertical ventilation in the kiwifruit MB pack. This thesis consists of six chapters.

The next chapter presents the current literature regarding the work. Then chapter 3 defines the objectives of the work. Chapter 4 combines the experimental and reefer constraints for designing an experimental apparatus which simulates vertical air flow reefer conditions. Design of the apparatus, apparatus construction and testing of the apparatus are given in detail. Chapter 5 details the packaging design parameters studied, execution of the experiments and consequent data analysis and provides the results and a discussion. Chapter 6 concludes the thesis by summarizing the major outcomes, identifies what has been achieved and learnt and highlights the future scope in the field of studying the vertical flow in reefer transport conditions.

2 Literature Review

2.1 The New Zealand Kiwifruit Industry

New Zealand is the 4th fastest-growing exporter of kiwifruit with an 82.4% increase since 2014. In New Zealand, about 12,747 hectares are utilized by 2,756 kiwifruit orchardists, producing 157 million trays of export fruit in 2019 (Fresh Facts, 2019). There was a 21 % growth in export earnings in 2019 compared to 2018. NZKGI (2018) claims that, by producing about 190 million trays per annum, the kiwifruit industry will become a $4B revenue industry by 2027.

2.1.1 Kiwifruit

The (green) Hayward (Actinidia deliciosa) variety is the foundation cultivar for the New Zealand kiwifruit industry partially due to its high resistance to diseases (FreshFacts, 2013) and hence is more suitable for long-term refrigerated storage and transport (Manolopoulou & Papadopoulou, 1998). Low temperature sensitivity/response to kiwifruit is closely linked to variations in the low temperature storage capacity of the cultivars and how the fruit matures on the vine early or late. (Asiche et al., 2017).

The harvest index for ‘Hayward' kiwifruit has long been based on the fruit's soluble solids content (SSC). In 1980, a harvest index of 6.2 % SSC was defined for 'Hayward' kiwifruit grown in New Zealand that would be harvested for storage and exportation (Harman, 1981). This precise SSC value was chosen on the basis that, once achieved, the rate of aggregation of soluble solids would have risen due to a shift in the fruit's starch breakdown. As such, a distinct physiological state of the fruit was assumed to mark it.

In recent times, the initial concept of 6.2 % SSC harvest index has undergone certain modifications, where Kiwifruit post-harvest performance can be affected with different starch metabolism even the fruits have the same SSC. For immediate use, a relatively early harvested chilling-sensitive fruit can be suitable given that it can be matured to an acceptable food condition and is not preserved for too long. Similarly, after a degree of chilling resistance has grown, a fruit for long storage must be harvested later, but when the fruit has not softened excessively it will shorten the lifespan of storage. The post-harvest kiwifruit performance was positively predicted by the rate of soluble solids accumulation than by the absolute SSC value (Burdon et al., 2013). By the end of the 17th week of storage at 0 °C, relative to the other green varieties, the Hayward kiwifruit had exhibited high levels of soluble solids, sugars and most importantly firmness (Papadopoulou & Manolopoulou, 1988).

With the introduction of commercialization in the kiwifruit industry, a new cultivator variety of ‘Hort16A’ was produced by HortResearch (now The New Zealand Institute for Plant & Food Research Limited) and is traded as ZESPRI ® GOLD Kiwifruit, which has been the most popular of these so far with the launch and promotion of new cultivars in the kiwifruit industry (Burdon & Lallu, 2011). New Zealand kiwifruit industry had shown Orchard Gate Returns (OGR) of $146k per hectare with an increase of 28% for gold kiwifruit whereas the Hayward only produced OGR of $63k per hectare with an increase of 6% when compared to last year sales (Fresh Facts, 2019).

Kiwifruit in New Zealand has a short harvest time from March to early June (NZKGI, 2018), so this fruit needs to be stored in such a way that fruit is available throughout the year. With the use of efficient cooling, refrigerated storage and transportation technology, the New Zealand kiwifruit industry ships fruit across the globe while sustaining the product quality (NZKGI, 2018), the largest importer of kiwifruit from New Zealand are Asian countries ($1.53B in 2019), where Japan ($590m) and China ($510m) are the leading importer of kiwifruit from New Zealand’s market (Fresh Facts, 2019).

2.1.2 Environmental Factors Influencing Kiwifruit Deterioration

In the process to sustain the quality of the kiwifruit in post-harvest management, temperature and relative humidity plays a pivotal role specifically during transportation.

Temperature is a predominant factor in regulating the metabolism of a fruit (Asiche et al., 2017; Seager, 1993). Low temperatures also inhibit the growth of pathogens, spore germination and other microbial activity that damages the quality and eliminates market value of fruit (Hasey, 1994). The optimum storage temperature of kiwifruit is from -0.6 ℃ to 1℃, while freezing occurs on average at -1.5 °C. When compared to different cultivators such as ‘Sanuki Gold’(A.chinensis) and ‘Rainbow Red'(A. chinensis), the hayward’s are more resistant to low temperatures (Asiche et al., 2017). On the verge of the freezing point, kiwifruit can suffer chilling injuries as another form of product loss. The vulnerability of 'Hayward' to chilling injury is more closely related to the shift in the color of the seed coat, and finally to the cessation of growth (Burdon et al., 2016). Lallu (1997) demonstrated that the frequency of chilling injury was greatly decreased by the precooling of 'Hayward' kiwifruit to 7.5 ℃ before progressive cooling to 0 ℃. Low temperature cooling has also been shown to minimize chilling injury and increase antioxidant activities by keeping 'Hayward' kiwifruit for 3 d at 12 °C before storage (Yang et al., 2013). Burdon et al. (2017) found that keeping 'Hayward' at 16 °C for 4-6 d after harvest was effective during subsequent storage at 0 ℃ to preserve firmness. Original storage at 0 ℃ and later moving to 2 ℃ was helpful in extending the storage life and reducing the occurrence of 'Hayward' chilling injury (Gwanpua et al., 2018). Thus, temperature plays a vital role in avoiding chilling injuries in the kiwifruit and storing the product for a longer time. The slight variation in temperature readings of the fruit during the storage and transportation time may alter the composition of the fruit and might damage the quality of the product, which will be a disadvantage for commercial trade purposes. Thus, maintaining temperature through the cold chain process plays a major role in conserving the quality of the kiwifruit.

Relative humidity (RH) is a description of water vapor content in air at a given temperature. RH is expressed in percentages with the ratio of amount of moisture in the air to the maximum amount of moisture that the air can hold at the given temperature. The relative humidity has a significant influence on maintaining the moisture content of the kiwifruit during storage. Diffusion phenomenon causes water molecules to travel from high concentration surfaces (e.g. the fruit surface) to the surrounding (relatively dry) air. Fresh fruit lose their water content due to this diffusion often also referred to as transpiration. If the lost water leads to a weight loss of 3-4% in kiwifruit, shriveling of the fruits' skin may occur leading to product rejection (McDonald, 1990). Shrivel in the fruit is a commercial risk and this also affects the firmness of the fruit which can lead to reduction in the shelf life of the product (Burdon et al., 2015).

Even though kiwifruit is stored at 0℃, significant moisture loss has been observed from the fruit due to the relative humidity of the surroundings. The optimum relative humidity for storing the kiwifruit is considered 95%. Kiwifruit which has been stored over 95 % RH has greater firmness than the fruit stored in 85-90% RH or 90-95%. RH (Harman & McDonald, 1982; Harris, S., & Reid, M. S 1982). In order to avoid the frequent chilling destruction, soft rot, and mildew, and also to minimize and enhance the change of the chemical profile and bioactivity properties of kiwifruit during storage, the effective method and technology for the storage and preservation of kiwifruit during pre-harvest and post-harvest remains to be explored (He et al., 2019).

2.2 Cold Chain for Horticultural Products

In the horticultural industry, the cold chain supply system mainly consists of three major processes: precooling, refrigerated transport and cool storage. After removing the fruit from the farm, the field heat from the fruit must be removed to get the fruit to its ideal temperature conditions. Pre-cooling methods can facilitate this. In the horticultural industry, forced air cooling which uses horizontal air flow rates of 0.2 to 1 L $s^{-1}kg^{-1}$ (Brosnan & Sun, 2001; Thompson, 2004; Thompson, et al., 2008). Forced air cooling is one of the most commonly used pre-cooling techniques which was adopted in 1978 into the cold chain (McDonald, 1990).

Storage is applying optimal conditions in a stationary location in order to maximize the shelf life of the product. Cold storage usually has horizontal air flow conditions with a lower flow rate of around 0.002 L $s^{-1}kg^{-1}$ to maintain the required conditions around the fruit (Wu et al., 2019).

Refrigeration transport is used to maintain the temperature of the fruit in the desired low temperature during its time of transport. A nearly constant energy supply in order to maintain cooling is needed in order to avoid wastage of temperature-sensitive produce during transportation (Fitzgerald et al., 2011; Wilmsmeier et al., 2014). In order to extend the shelf life of the product, refrigeration transport (containers) are often employed which are equipped with vertical air flow conditions with a flow rate of 0.02 to 0.06 L $s^{-1}kg^{-1}$ (Defraeye et al., 2015). Refrigeration containers have similar features as controlled atmospheric containers for controlling the ethylene, temperature, and relative humidity of the environment (Yahia, 2009).

Product temperature rises can be observed in refrigeration containers or cold stores during defrosting cycles or failure of cooling systems. Therefore, within the cool chain, together with the initial precooling, there is occasionally a need for partial re-cooling. Rapid and uniform (re)cooling of the fruit at various locations in each cargo pallet is crucial to reduce the loss of quality (Wu et al., 2019).

In contrast to the other cold chain processes, refrigeration transport has gotten less formal research attention. In reality, refrigeration transport is a complex interactive system with different working conditions than cold storage (James et al., 2006).

The majority of refrigeration transport system works in a harsh environment and the cooling efficiency is influenced by many adverse factors, such as relative humidity, unpredictable climatic conditions, solar radiation, heat penetration, degradation of insulating materials , and heat transfer between container wall, refrigerated air and product(Artuso et al., 2019; James et al., 2006). Furthermore, refrigeration transport is mainly responsible for maintaining the temperature of the product rather than reducing the temperature of the cargo. (Tassou et al., 2009). A thorough knowledge of the mechanisms of heat and mass transport, spatial and temporal optimization of temperature and humidity in a refrigerated space are thus currently relevant research directions and are usually accomplished by improving the internal configuration of refrigerated boxes. (Rai et al., 2019).

2.2.1 Marine Transportation

Marine transportation drives 80–90% global trade, moving over 10 billion tons of containers, solid and liquid bulk cargo across the world's oceans annually (Schnurr & Walker, 2019). New Zealand being a geographically isolated island nation has an economy that is highly reliant on trade via seaports. New Zealand began its exports by shipping oil and other non-perishable goods from the country in the early 18th century. The first refrigerated shipment of frozen mutton and lamb was sent to London from Otago, New Zealand, in 1882

(James et al., 2006). Other countries also started to focus more on their exports after the success of the first refrigerated shipment from New Zealand.

According to Hinton (2019), the export value of New Zealand products increased by 23% from 2015 ($67.86B) to 2019 ($84.04B). In 2019, the New Zealand horticultural industry exported $6.2B in which kiwifruit made up 37% ($2.3B) of the total share. The yearly export quantity of the kiwifruit has risen by 50 % from 350,000 to 540,000 tons in the last decade and air freight carries less than 1% of the countries' trade by volume, with marine transportation carrying the remaining share for the country.

Marine transportation is the economical mode of transport when compared to air transport especially in large volumes of products (Tanner, 2016). The different kinds of refrigerated transported systems that have been used by New Zealand to export the goods are:

- Conventional refrigerated ships
- Conventional refrigerated container carriers’ ships

The maritime reefer market was approximately split between conventional refrigerated ships reefer containers evenly 15 years ago, contrasting with the current significant dominance of refrigeration containers contributing a share of about 80% (Castelein et al., 2020).

2.2.1.1 Conventional refrigerated ships Conventional refrigerated ships are specialized cases of ships that are designed to carry large quantities of product by utilizing the maximum storage space of the ship. The internal environment is controlled by a refrigerated unit present on the ship. Generally, the storage area of the vessel is 80-90 % of the total interior space of the ship. Usually, refrigerated units in these vessels are large. In some cases, the internal space for the storage unit will be equal to the total floor space of the ship for the most extent. Depending upon the design of the ship the loading and unloading of the cargo is done either by a side door or top hatch door using forklifts and cranes. The vessel will be sealed from all directions to prevent the exposure of the stow to the outside environment. These bulk carriers are used to transport large quantities of a single product or similar products which have the same or similar ideal storage conditions (Wild, Y. 2009)

2.2.1.2 Container Ships Conventional container ships carry cargo in the form of units (containers). Each container has its separate refrigeration system. These containers are also known as reefer containers (Čudina & Bezić, 2019) The introduction of the integrated refrigeration containers had started in the 1970's (Castelein et al., 2020). The reefer container ships help to transport different kinds of cargo in one shipment. Advantages of a container ship with respect to a reefer vessel are also significant and they can be summarized as follows: -

- Loading and unloading the cargo is easier.
- Container ships are cheaper than bulk ships
- The maintenance of cargo hold is cheaper and easier
- In one shipment cargo of different kinds can be transported (Čudina & Bezić, 2019).

The introduction of containerization created changes in marine transportation (Guerrero and Rodrigue, 2014).

2.2.1.3 Refrigerated Containers Reefers have become a standard solution for transporting temperature-sensitive goods (Castelein et al., 2020). Containers are designed with common design specification and hence used as standard unit and a container can be transferred from a ship to either truck or rail car with ease (Schnurr & Walker, 2019). Gac (2002) stated that '*Worldwide, there are … 400,000 refrigerated containers in use'*. With the increase of containerized refrigerated transport systems, there has been a major interest in optimizing the conditions and energy utilization for running the containerized unit by reducing the vehicle weight, optimizing the insulation and creating a new air distribution system (Panozzo et al., 1999). However more recent developments are focused on air distribution, controlled atmosphere and packaging in order to improve the range of products that can be transported at the required conditions (James et al., 2006).

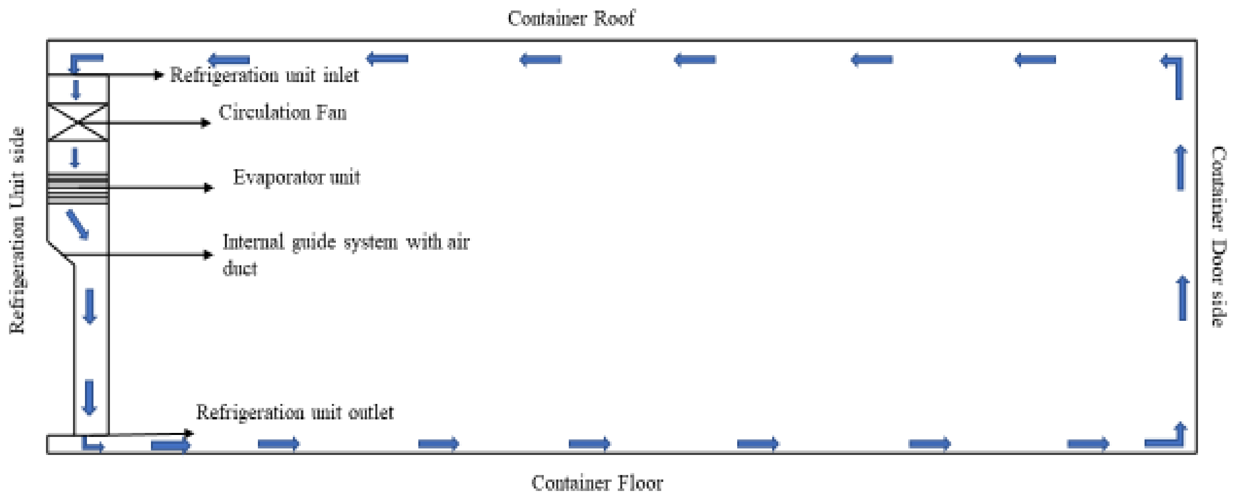
Most standard reefers are either 20 feet or 40 feet in length. The reefer consists of end doors for loading and unloading the cargo. The walls of the container are insulated to restrict the outside heat affecting the interior environment. To reduce the effect of temperature from solar radiation, the outer walls are usually painted white (Castelein et al., 2020; Wild, 2009).

Most of the refrigerated containers have cooling units inbuilt into their composition and the refrigeration units operate electrically, either from an external power supply on board a ship, port, or from a road vehicle generator (James et al., 2006).

The velocity stream from the refrigeration unit travels vertically into the container and turns into a horizontal jet around the container floor through refrigeration unit outlet for intermodal refrigerated containers (Heap, 1989). Warmer air will be returned from the headspace of the container to the cooling unit present at the top of the container through containers refrigeration unit inlet as described (Figure 2-1), all while cooled air circulates through and around the contents of the container. (Castelein et al., 2020). The refrigeration unit mainly consist of circulating fans, evaporative unit, internal guide system, and thermostat.

Figure 2-1:

Schematic Diagram of Airflow Circulation in a Reefer Container



Note. The air flow directions are the general description of the air flow in a modern reefer container.

In general, two circulating fans are located at the top of the container, in early design of refrigeration units in reefer containers, three- phase power supply motors were used. As motors with three phase power motors can generate both forward and backward rotation of the fan however this latter condition is not necessary. Today to eliminate the backward flow from the equation, most of the modern reefer containers are shifting towards using single phase motors for circulating fans. Two rotating speeds are typically assisted by these engines, allowing for high (normal mode) and lower (economical mode) speeds (Wild, 2009).

The evaporative unit mainly consists of evaporative coil, condenser, and compressor. Compressor and condenser cool down the coolant liquid transfers to the evaporative coil. The evaporative coil cools the air pumped by two fans. The modern trend has moved towards selecting scroll compressors among coolant compressors by replacing piston compressors. As the evaporator coil operates at negative temperatures, there will be accumulation of ice, impairing the efficacy of the machine, there arises a necessity of defrosting on a regular basis. The circulating fans in the container and the cooling circuit are halted during defrosting. Electric heaters will be placed near the condenser to defrost the evaporator coil when it is required. Although the hot air in the cooling unit increases steadily, during defrosting, the return air temperature sensor still displays reasonably high temperatures. In general, defrosting is time-controlled, i.e. for example, it happens every six, eight or twelve hours. Normally, the completion of the defrosting process is determined until an end temperature is reached above the air cooler at the defrost end sensor (Wild, 2009).

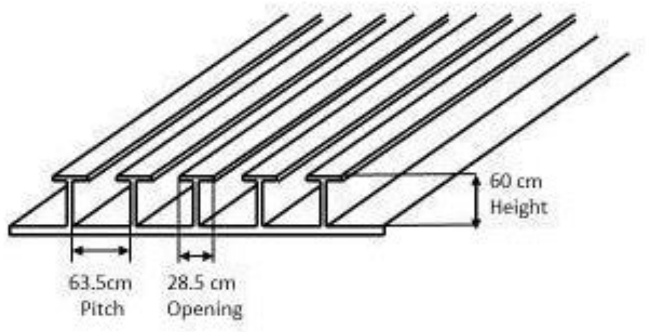
Internal guide system will be present inside the refrigeration unit to guide the circulating air throughout the refrigeration unit. There are fresh air ducts (flaps) in the refrigeration guide system from which fresh air is put into the container and air can escape from the container. On the suction side of the ventilators, fresh air is drawn in and dissipated onto the pressure side. Thermostat present in the guide system to measure the air temperature at the refrigeration unit outlet (Wild, 2009).

In order for the cooling unit to maintain the cargo temperature at the appropriate 'set point' temperature, the temperature of the warmer air fed back into the reefer unit is monitored. (Castelein et al., 2020).

Over time, reefer floor design has evolved from a flat floor structure to new and different floor designs which helps to distribute the delivered airflow throughout the internal spaces of the container. Modern reefer floor uses T bar floor as base model for the reefer design where T-bar design creates more uniform vertical air flow in the container when compared to the flat floor design Getahun et al. (2018). T bar floor design has longitudinal rectangular bars throughout the length of the container as shown in Figure 2-2 with 63.5, 28.5 and 60 cm of pitch, opening and height respectively.

Figure 2-2 :

T bar Floor Design in the Modern Refrigeration Container



The air adjacent to the refrigeration unit maintains the temperature similar to the inlet air temperature. But as and when it moves to the other end of the container, the temperatures might rise slightly. As such, pallets will receive significantly lower temperature near the refrigeration device, which raises the likelihood of chilling damage (Defraeye et al., 2016).

When reefer containers were introduced, for both frozen cargo and deciduous fruit the least acceptable rate of air circulation was 30-40 air renewals per hour with respect to the empty volume of the container. Over the time the acceptable rates have changed to 60 air renewals per hour for fruit and 30-40 air changes per hour for frozen cargo in case of few exceptional requirements (Scrine, 1982). This results in a vertical air flow condition in the stow with a flow rate range of 0.02–0.06 L $s^{-1}kg^{-1}$ (Wu et al., 2019). Modern reefers are equipped with two different modes in their refrigeration units (normal and economical).

Normal results in 70 - 80 air cycles per hour while economical results in 36 renewals of air (Tapsoba et al., 2006, Jedermann et al., 2013; Getahun et al., 2017a, 2017b, 2018). In the case of container services are used for carrying bananas an air change rate 70-80 per hour is required (Scrine, 1982).

The overall difference between delivery and return air should be less than 0.8°C when the containers are fully filled, and the cooled air is pushed evenly into the gaps between cartons. The whole product can be held within ±1.0 °C of the set point in a container.

2.2.2 Research in the Field of Marine Transportation

Defraeye et al., (2016) explored the ambient loading of citrus fruit into a reefer container by comparing newly designed commercialized horizontal airflow system (Swift Horizontal Airflow system, Cordstrap, Durban, South Africa, Patent SA2006/03644 (Provisional PCT) and PCT/IB/001811) vs channeling configuration (by reducing the bypass airflow between pallets) to traditional container cooling vs standard container airflow. The results showed that the horizontal arrangement in reefer conditions was weaker in all respects. This research has shown that the manner in which the container is convectively cooled has a direct effect on its cooling rate, fruit quality, shelf life, pest disinfestation effectiveness and related spatial consistency, and also on the energy consumption of the refrigeration unit**.**

To research the impact of container structures and working conditions on airflow patterns in a refrigerated container, Getahun et al. (2018) performed experimental and computational tests. With the influence of modern reefer container air flow conditions, two container floor designs were tested at two different airflow conditions of reefer container (i.e. normal and economical evaporator speeds), one with a T-bar floor and the other with a flat floor. In contrast to the container with the flat floor, the container with the T-bar floor had decreased air recirculation region and increased uniform vertical airflow.

In an effort to determine the spatial-temporal thermal differences during a trip from New Zealand to Belgium, Tanner and Amos (2002) carried out multiple experiments. To collect temperature data, twenty pallets of fruit were tracked using thermocouples. Pallets were loaded into a reefer container and shipped to Belgium from New Zealand. The findings revealed that there was a substantial variability both spatially throughout the length of the container and across the journey. In another study carried out by Tanner and Amos (2003) investigated the effect of temperature variations on firmness evolution of kiwifruit cargos, This analysis found that temperatures which are outside of the recommended storage range within the container, contributed to an acceleration in the loss of firmness. Thus, homogeneous temperature distribution throughout the length of the container plays a crucial role in maintaining the quality of the product (Tanner and Amos 2003).

With a view to observe the effect of cargo stacking modes on temperature distribution inside marine refrigerated containers, Kan et al., (2017) found that temperature distributions were disrupted by increasing stack height. The temperature differential increased with an increase in stack volume. The temperature appears to be isothermal as the space of the stack or the space between the stack and the sidewall surface increases**.**

The feasibility of cooling an ambient load of citrus fruits in refrigerated containers during shipping was investigated by Defraeye et al., (2015) and Defraeye et al., (2016). As an alternative to forced air pre-cooling, they investigated the practice of hot-loading citrus fruit into refrigerated containers for cooling during shipping. In principle, the refrigerated container was able to cool the product in less than 5 days; nevertheless, it was noticed that these refrigeration flow rates have low volumetric flow rates when compared to forced precooling; this cannot be applied for every horticultural product in real time practice. In fact, such cooling is only effective for the export of sweet oranges packaging in the horticultural industry (Defraeye et al.,2016).

In the horticultural industry, packaging is a significant component to preserve the quality of goods during transportation (Kader, 2002). One of the core functions of horticultural packaging within the transport system is to protect the product from mechanical forces and minimize moisture loss (Kader, 2002). The storage life of fruit in the same box is affected by the release of ethylene, resulting in early softening of the fruits induced by the damage to the fruit (Diab et al., 2001).

The packaging plays a vital role in the speed of cooling and in the uniformity of temperature control within the supply chain (Galić et al, 2011; Mditshwa et al., 2013; Defraeye et al., 2015).

The cooling kinetics of packaging for horticultural products are mainly contingent on:

- Physical and structural design of packaging boxes.
- Vent area with their aspect ratio and their positions.
- Arrangement of fruits inside a carton.
- Stacking and storage parameters of carton (Pathare et al., 2012; Smale et al., 2002).

By using various cooling rates and storage temperatures, the ability to store kiwifruit of various maturities and chilling sensitivities, while avoiding chilling injury, can also be achieved (Burdon et al., 2016

2.2.3 Kiwifruit packaging

In transporting kiwifruit to different parts of the globe the New Zealand kiwifruit industry uses three major packing methods:

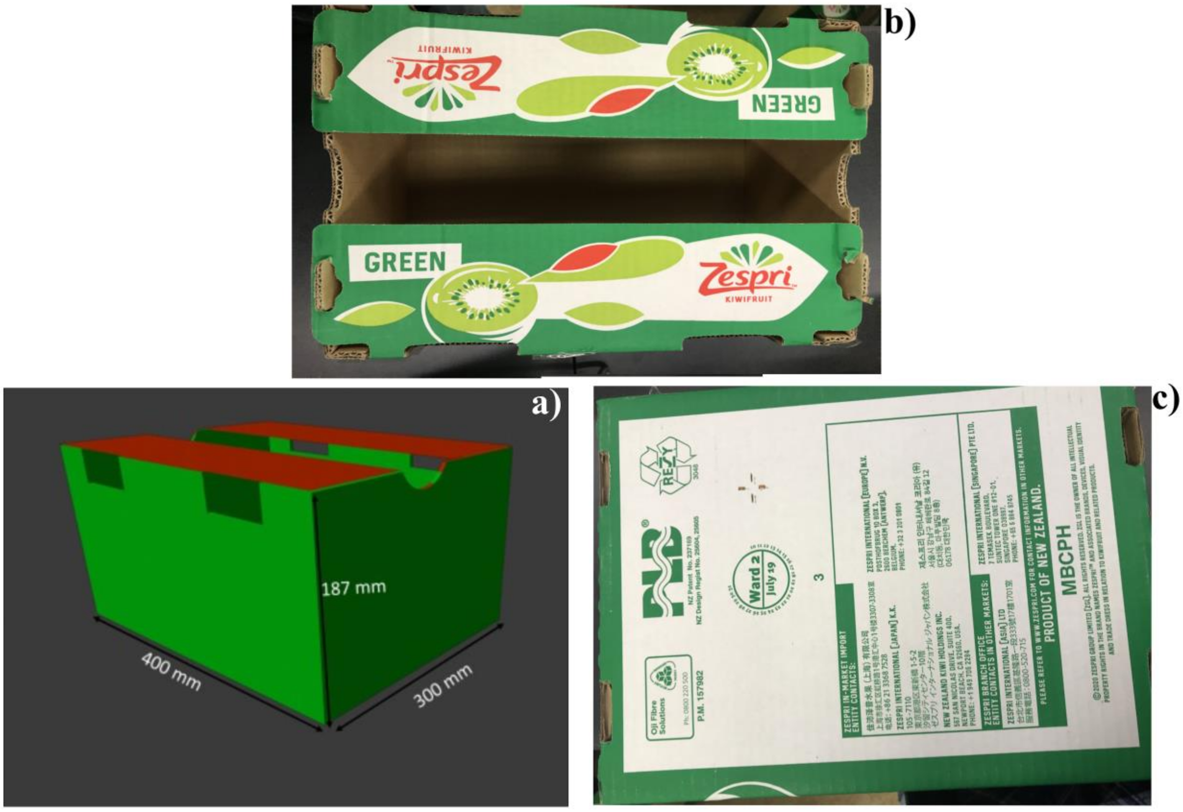
1. International tray (IT)
2. Modular loose box (ML)
3. Modular bulk box (MB)

Each box design holds different weights of kiwifruits ranging from 3.6 kgs to 10 kgs. The IT uses pocket packs to individually locate kiwifruit. The ML and MB uses only one polyliner bag that wraps around loosely packed fruit. A polyliner bag is used for kiwifruit (East et al., 2013), to help in fruit moisture preservation during the storage period.

The MB box is used for exporting bulk quantities of Hayward kiwifruit. MB box packaging method has best volumetric efficiency when compared to other packaging methods with kiwifruit weight to cardboard weight ratio of around 17.4:1. The MB packaging consists of a cardboard box with a top-folding cover, with a gap of 7 cm in the centre (Figure 2-3). The external dimensions are 40 cm, 30 cm and 19.5 cm in length, breadth, and height, respectively. The box contains vents to facilitate handling and to allow cold air during cooling to pass through the package. At the top of the front and back sides are two rectangular vents (hand vents) each of dimension 75 x 35mm (length x breadth). At each end face there is a hemi-spherical vent at the top. Within the cardboard box, kiwifruit is encased with a HDPE polyliner bag to restrict the moisture loss from the product (East et al., 2013). If there is more than 4% of total weight loss due to the water evaporation, fruit can develop shrivel, affecting both appearance and weight of the product (Burdon & Lallu, 2011). The MB box weight can vary in the range of 490 to 560 g pending on the box manufacturer. (Figure 2-3).

Figure 2-3 :

Kiwifruit MB Box



Note. a) 3-D diagram of kiwifruit MB box b) Top view photo of kiwifruit MB box c) Real time bottom view of kiwifruit MB box

Unlike several other horticultural products, prior to being put in the carton, kiwifruit is packaged inside a polyethylene bag ('polyliner'). Although there are holes within the carton to enable airflow, there are no holes or perforations in the polyliner, and thus pockets of stagnant air are located between the fruit and the liner, with a substantial resistance to heat transfer (Carson and East, 2018). This significantly increases the time frame for cooling down the fruit to the required conditions in comparison to scenarios that don't have a polyliner (Mukama et.al., 2019).

2.2.4 Packaging research in Refrigeration Transport

Dehghannya et al., 2012 had stated that with the distribution of a certain number of vents on the packaging design wall, appropriate air pathways can be provided, to uniform cooling to the design. Furthermore, it was verified that increasing vent area doesn't always reduce the cooling rate and if the vents are not properly spaced on the packaging design, it may also increase the cooling time of the design. Increasing the vent area above a certain level may also not have a positive impact on uniformity and cooling time of the design.

To research airflow and heat transfer in a refrigerated container packed with apples, Getahun et al. (2017b) used a CFD model. The influence on the aerodynamic and thermodynamic characteristics of the container of three widely used apple package designs was investigated and it was reported that the rate and uniformity of cooling was affected by the vertical airflow. The installation of vent holes at the bottom surface of the package lowered the vertical airflow resistance by 75%, which in turn decreased the fruit cooling time by 37% relative to the package without bottom vent holes.

To understand the effects of vented packaging designs in a different cold chain scenario which can affect the cooling dynamics of citrus fruit inside the packaging, Wu et al., (2019) studied three different designed boxes (standard packaging, open top packaging and supervent packaging) in pre-cooling, refrigeration transport and storage conditions. The results showed that in refrigeration transportation the super vent packaging cools quicker than other two packages. This is partly due to the unique configuration of the vent hole, where the openings of the vent are located along the side edges of the box. As such, the vertical ventilation of cold air is observed through the packaging design. With the coordination of central opening at the bottom and the top, a very uniform distribution of cooling air through the package is achieved.

While studying the Feasibility of ambient loading of citrus fruit in refrigerated containers Defraeye et al., (2015a) stated that the cooling unit of the reefer was not utilized to its full capacity because of the present citrus box design's vent positions and packaging designs with respect to the vertical airflow conditions of a reefer container. Although the mounted airflow and cooling ability are fixed design variables for a reefer container, more changes can still be made to current practices such as box design to increase the heat removal rate from the fruit and their stacking patterns can be optimized for vertical cooling on the pallet. Defraeye et al., (2015b) agreed to explore vertical airflow with the packaging design, which was due to the nature of the box design because it has vent holes that facilitated vertical airflow pathways.

To investigate the resistance to air flow and cooling patterns in a multiscale packaging of table grape Ngcobo, et al., (2012) studied the various package components (boxes, polyliner and pads), product stacking and cooling processes influence ventilation, heat transfer and mass transfer processes. The results show that the liner films contribute by far the greatest resistance to airflow relative to the rest of the packing components of the multi-packaging. In 2013 Delele et al., (2013c) results had shown that non-perforated liners yield the highest Relative Humidity (RH) within the package, which results in the lowest moisture loss with highest condensation.

Mukama et.al (2019) has researched on redesigning the vent-holes of packaging for handling pomegranate fruit. The results showed that it took 8.1 h longer for fruit wrapped in a polyliner to cool than fruit with no liner. The results of this study show the influence of polyliner on the fruit's cooling characteristics is more than the vent hole configuration. The efficiency of the fruit cooling process is dramatically improved by ensuring unrestricted airflow in the stack of fruit during precooling. Similar results for the polyliner bags have been seen in the research of O'Sullivan et al., (2016) where the polyline had diminished the effect of energy transfer between the kiwifruit and kiwifruit surroundings during a pre-cooling process.

The effect on the environment induced by various ventilated packaging designs is different (Defraeye et al., 2016). The cooling speed and process uniformity are significantly influenced by the ventilation design of packaging of fruits and vegetables. This can be demonstrated by the product packaged in a pallet (Galić et al., 2011; Mditshwa et al., 2013; Defraeye et al., 2015).

The number of air renewal rates [h^{-1}] can be used in expressing the rate of airflow for systems with a closed circuit, such as a refrigerated container or closed storage, which can be used as to comprehend the box ventilation potential rate (Ambaw et al., 2014; Defraeye et al., 2015c; Wild, 2009).

2.3 Parameters that Affect Cooling Process

Pflug & Blaisdell, (1963) state that the ultimate objective of food cooling studies is to provide data to improve the cooling conditions of the system. Within the reefer, the airflow around the horticulture product has a significant influence on the product's environment as it can eliminate the heat either by direct contact through the ventilation or by cooling down the package surface (Smale et al., 2002). The time taken by food products to cool are primarily influenced by:

- Heat transfer characteristics of the food products
- Properties and physical dimensions of the food products
- Heat transfer characteristics of the cooling medium
- Heat transfer characteristics and geometric details of the packaging material used. (Dincer, 1997).

Prediction of heat transfer during transportation can be done either by considering the change in the environment with the air flow inside the transportation unit or concentrating on the temperature of the product. Sometimes these aspects can be combined in understanding the conditions of transportation unit (James et al., 2006)

2.3.1 Heat Transfer Mechanisms

Heat flows by various transport mechanisms: convection, conduction, and radiation, from a higher temperature region to the lower temperature region (Das, 2005; Rohsenow et al., 1998). This section will briefly review this knowledge given that the work to be conducted is a cooling problem.

2.3.1.1 Conductive Heat Transfer Conduction is a mode of heat transfer that occurs within solids and between objects that are in contact. This is a molecular level of energy transfer in which transmission of energy takes place between higher energetic molecules to the lower energy level until the molecules attain equilibrium state between them (Das, 2005; Rohsenow et al., 1998). Heat transfer by conduction can be described by Fourier's law

$$Q = -kA\frac{\mathrm{d}T}{\mathrm{d}x} \tag{2.1}$$

Where, Q is heat transfer rate (W) Δt is time is taken (s) k is conductive heat transfer coefficient (W/m.K), A is the surface area (m^2) dT is the temperature difference (K), dx is the distance (m).

2.3.1.2 Convective heat transfer Heat is transferred from solids to a fluid by convective heat transfer. This process may be either carried out naturally or as forced (Das, 2005; Rohsenow et al., 1998). It can be described using Newton's law:

$$Q = h_C A dT \tag{2.2}$$

Where Q is the rate of heat transfer (W), $h_C$is convective heat transfer (W/m^{2}K), A represents heat transfer surface area (m^2) and dT represents the difference in the temperature (K).

2.3.1.3 Thermal Radiation. Thermal radiation is the exchange of infrared radiation between bodies with different surfaces (Das, 2005; Rohsenow et al., 1998)). It can be described by Stefan-Boltzmann's law:

$$Q = \sigma T^4 A \tag{2.3}$$

Where Q represents heat transfer per unit time (W), σ is Stefan-Boltzmann constant (5.6703x10^{-8} W/m^{2}K^4), T is the absolute temperature (K) and A is the area of the emitting body (m^2).

2.3.1.4 Heat Transfer Mechanism in Kiwifruit For removing the heat from a horticultural product such as kiwifruit, the heat transfer from the fruit is multifaceted (Figure2-4)**.** Heat moves from the centre of the fruit to the surface through conduction, accompanied by convective heat transfer from the surface of the product to the surrounding. Through moisture depletion and the subsequent elimination of latent evaporation heat, additional heat from the surface of the fruit may be lost (Chuntranuluck et al., 1998a; Redding et al, 2016). Eventually, continued respiration after harvest often contributes heat to the product. In relation to experimental error, the net radiation effects on packaged goods are minimal and, if possible, can be sufficiently defined as pseudo convection (Alvarez and Flick, 1999; Tanner et al., 2002a; Le Page et al., 2009). The thermophysical properties of the kiwifruit are given in Table 2-1 below.

Table 2-1

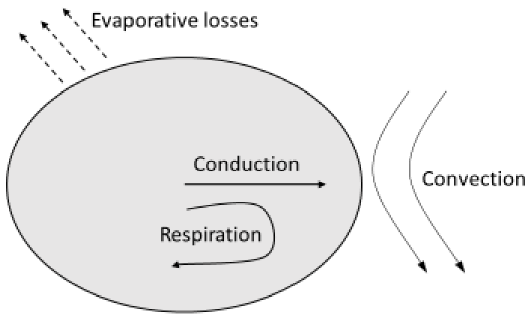
Thermophysical parameters for kiwifruit

	k (W/m K)	α (x10^6 m^2/s)	ρ (kg/m^3)	*c* (J/kg K)	*L* (x10^3 m)	*q* (x10^3 W/kg)
Kiwifruit	0.40-0.45	0.11	940-1040	3893	21-26	39 (at 10 ℃)

Note: Retrieved from Redding et al, (2016)

Figure 2-4 :

Heat Transfer Mechanism in Kiwifruit



2.3.1.4.1 Evaporative cooling The heat loss by evaporation from the product is proportional to the driving force between the saturation vapor pressure in the air to the surface of fruit. These are measured by the environmental air's temperature and relative humidity and the water activity at the surface of the fruit, respectively. In general, the amount of water loss on the surface of the product is proportional to the susceptibility of the skin to transpiration and thus depends on the form and condition of the product (Maguire et al., 2001).If the temperature of the product decreases, the partial pressure differential between the product and the airstream often decreases quickly, which ensures that evaporative losses are less significant as cooling continues (Redding et al, 2016). Usually, horticultural cooling and storage processes are carried out around >85 percent relative humidity levels (Tanner et al., 2002c). A humidified surrounding air therefore decreases the evaporative driving force and thereby eliminates the loss of evaporative heat (Chuntranuluck et al. 1998b; Redding et al, 2016) found that the evaporative heat losses in a carrots had shown in a slightly faster cooling in a peeled carrot than unpeeled one, which had proved that moderate skin resistance was adequate to turn the evaporative loss in the product to negligible. Usually for common agricultural products, the mass loss over the duration of pre-cooling process will be less than 0.1 (Tanner et al., 2002a).

In precooling and storage conditions of the kiwifruit, the moisture loss from the fruit for the complete process (from farm to consumer) should be kept under below 3% (to avoid commercial risk). Therefore, by considering the environmental conditions and moisture loss of the kiwifruit, the evaporative cooling for the kiwifruit for short term experimental conditions (i.e. 24-48 hr.) can be considered as a negligible factor.

2.3.1.4.2 Respiration heat It is widely believed that heat produced through the respiration of the substance is a negligible portion of the heat load (Tanner et al., 2002a, Ferrua and Singh, 2009a, Dehghannya et al., 2010). Tanner et al., 2002a says that the heat added by respiration is 0.5 percent of the heat load in a standard pre-cooling process. Respiration heat is used as part of the heat load of the product, but in precooling heat load measurements, it can usually be dismissed as the cooling is rapid (Brosnan and Sun, 2001). According to the standard industrial procedures, it is not advisable to directly place the kiwifruit in a transport unit (reefer container) by not following pre-cooling procedures. Hence, the kiwifruits are precooled to its optimum storage conditions (0-2 ℃) before transferring it to the reefer for transportation.

It should also be remembered that during pre-cooling, there is a tendency for moisture loss which can change the thermal properties of the product. However, these properties are usually believed to be constant and unchanged by moisture loss, considering the typically minor moisture losses associated with precooling (Tanner et al., 2002c, Ferrua and Singh, 2009c; Redding et al, 2016). During the storage phase, the respiration of the kiwifruit is at its minimal. Though the respiration is minimal, there would be some amount of respiration heat generated. Vents in the packaging could aid in the removal of respiration heat to maintain optimum storage temperature for the fruit.

2.3.2 Artificial Fruit Simulators for Heat Transfer Experiments

Use of real fruit for commercial-scale experimental purposes is not always feasible due to the high expense. In addition, the changing properties of the fruit could influence the thermal properties and hence introduce errors. Therefore, a fruit mimic (simulator) that has similar properties as a real fruit provides a glitch-free constant environment allowing study of fruit cooling dynamics (Vigneault & de Castro, 2005). The interest in research in the field of horticultural packaging design has grown rapidly since the beginning of the 21st century, and the possible need for a simulator has increased (Redding et al, 2016).

Artificial fruit are helpful for simulating the thermal properties of the fruit in a cooling process (Defraeye et al., 2017; de Mello Vasconcelos et al., 2019). In contrast to real fruit, artificial fruit can be reused indefinitely without degradation (Defraeye et al., 2017). By matching the geometric shape of the fruit with the artificial fruit simulator, we can recreate the flow field experiments and combining with the thermal properties of the produce can reproduce the heat transfer mechanism in an air-cooling design system, where evaporative, respiration heat and pseudo convection can be considered as negligible (Redding et al, 2016). The construction of simulators is divided into two sectors i.e., single domain simulators and multiple domain simulator.

Single domain simulators are made of one material, or multiple materials with similar significant resistance to heat transfer and thermal mass. This simulator may be used to simulate heat transfer in materials in which the properties of heat transfer are sufficiently homogeneous. A thermally matched output simulator can sufficiently balance the thermal conductivity, thermal diffusivity and volumetric heat power of the product being simulated to mimic internal heat transfer.

Accurate representation of certain products can involve splitting into several sub-domains, such as skin, flesh, and heart. This would require materials with different thermophysical properties for different subdomain regions. Such simulators are represented as multiple subdomain simulators.

Defraeye et al., (2017) successfully created multiple subdomain artificial apple fruit in place of real fruit with a thin plastic shell to mimic the exterior shape, size, surface and color of the fruit and the hollow shell is filled with water-carbohydrate-air gel (WCA) to match the thermal properties of the fruit. De Mello Vasconcelos et al., (2019) had manufactured subdomain artificial fruit prototype for ‘Tommy Atikins’ variety of mango with poly lactic acid (PLA) with 5% wood powder for skin and 15 % concentrated agar solution for flesh.

2.3.3 Artificial kiwifruit simulators

Huang et al., (2017) created a single domain artificial fruit simulator for kiwifruit. The prototype was developed using casting resin with metal filler, involving a procedure of creating silicone molds using kiwifruit (count size 36, class A) and then making simulators measuring a length of 61.7 ± 2.1 mm, width up to 51.8 ± 0.5 mm and thickness accounting to 48.3 ± 0.8 mm. The thermal conductivity of the real kiwifruit is almost mirrored and assessed using line source method (Rahman, 2009). Differential scanning calorimetry (Q2000, TA Instruments, USA) is used to estimate the specific heat capacity and density is calibrated using Archimedes’ method (McGlone et al., 2002). The linear relationship between volumetric specific heat capacity and cooling rate was demonstrated by Redding et al., (2016) had been represented in Equ.2.4**:**

$$\frac{t_k}{t_s} = \frac{\rho_k c_k}{\rho_s c_s} \tag{2.4}$$

Where t_k, $t_s$are time (s) taken for cool down (e.g half cooling time). ρ_k,$\rho_s$are densities (kg/m^3) and c_k, c_s are specific heat capacity (J/kg.K) for the kiwifruit and simulator respectively (Huang et al., 2019; Redding et al., 2016). The density and thermal conductivity for the real kiwifruit and artificial simulator kiwifruit created by Huang is mentioned in the Table 2-2 below.

Table 2-2

*Thermal Properties of kiwifruit and Simulators***.**

	Density (kg/m^3)	Specific heat Capacity (J/kg.K)	Thermal conductivity (W/m.K)
Kiwi fruit	1066 ±3	3710±14	0.56±0.04
Simulator	1537±16	1050±20	0.51±0.04

Note. Retrieved from (Huang et al., 2019)

By calculating the temperature variance using Equ 2.4 between the artificial kiwifruit simulator with the real kiwifruit from the Table 2-2 the simulator cooling was predicted to be at a faster rate of 2.5+/- 0.2 times.

2.3.4 Pressure and Velocity at Constant Volumetric Airflow

Bernoulli's equation, which is derived from the law of conservation of energy describes the relationship between pressure and velocity in an inviscid incompressible flow.

$$P_1 + \frac{1}{2}\rho v_1^2 + h_1 = P_2 + \frac{1}{2}\rho v_2^2 + h_2 \quad (2.5)$$

Where P is the pressure (Pa), ρ is density(kg/m^3), v is velocity(m/s), and h is height (m) of the point. Subscripts 1 and 2 represent two different points at the given flow. When considering a flow of a fluid with constant density in a closed tunnel, ignoring gravity and assuming that the pressure at the inlet and the outlets remain constant, then the Bernoulli's equation and the one-dimensional continuity equation turn to Equ.2.6 below apply:

$$p_1 - p_2 = \frac{1}{2}\rho(v_2^2 - v_1^2) \quad (2.6)$$

An insight from equations 2.5 and 2.6 is that when there is a decrease in the cross-sectional area, the velocity of the flow is increased. This increase in velocity of the flow leads to decrease in the pressure at the point and vice - versa (Heys et al., 2010).

$$A_2 v_1 = A_1 v_2 \tag{2.7}$$

Where ‘A’ represent cross-section area (m^2) and ‘v’ represent velocity (m/s) at the given point and subscript 1 and 2 represent the two different points at the given flow.

2.3.5 Airflow Measurement Techniques

Airflow is a vector quantity. Airflow has both magnitude and direction. Over time researchers have discovered and used numerous methods for defining the airflow speed and patterns for horticultural products in a refrigeration context. A visualization technique was adopted using hot smoke in earlier times and created with colored gases or gas detectors in the path of the gas to track the airflow pattern in the model (Choiniere et al., 1988). Techniques such as Laser Doppler Anemometer (LDA), Particle Image Velocimetry (PIV), hot wire anemometry, film and thermistor, with pressure technique using pitot tube, using the speed of sound as a sonic anemometry and introducing wind propeller by measuring its rotation to calculate the speed as vane anemometry, using a different type of probe sensors and tracer gas methods (O’Sullivan et al., 2014).

2.4 Summary of Literature

New Zealand is an isolated nation with a share of its economy dependent on exports of horticultural products. Transportation and storage are pivotal components in any horticultural industry. During the transport of the product from the field to customer, the cold chain system which primarily consists of pre-cooling, cool storage and refrigeration transport take up the primary responsibility for ensuring the optimum quality of the product. The reefer is the most commonly used transportation method. The main difference between refrigerated transport and other cold chain supply strategies is that the refrigerated transport consists of vertical air flow conditions whereas horizontal air flow conditions are employed in other techniques. The refrigerated transport system continues to have occasions in which the basic objective of ensuring the quality is not met. Improving the reefer's efficiency and conditions will deliver great economic advantage to New Zealand.

To refine the uniformity of cooling and temperature control, the packaging can be matched to perform in the parameters present in the reefer condition. Packaging design is one of the key aspects determining fruit conditions. Vertical ventilation has shown a substantial improvement in the air flow pattern within the reefer. The majority of Hayward kiwifruit exports are carried out using modular bulk box packaging – a format that currently has no design features to facilitate vertical airflow. Potential improvements to the cooling performance of the existing packaging design can be studied by incorporating vertical ventilation elements and evaluating the consequent airflow and heat transfer through the package.

3 Goals and Objectives

The goal of this project is to study the impact of base ventilation in a kiwifruit MB box on potential vertical airflow with a reefer container environment. This can be achieved by measuring cooling efficiency of the box at vertical air flow conditions with the introduction of base ventilation. The thesis is aimed to compare and analyze the cooling efficiency results of the present MB box design, with new potential MB box designs that had been altered by introduction base ventilation and/or removing the polyliner bags.

The specific objectives of the work were to:

1. Design a laboratory scale apparatus to hold a column of kiwifruit MB boxes in order to create similar vertical airflow conditions of a reefer container.

2. Construct and validate the performance of the designed apparatus.

3. Test the influence of introduced base ventilation, and the polyliner, at different airspeeds, by evaluating the cooling of the kiwifruit MB box in the apparatus.

It is hoped that the work will design a package design for the New Zealand horticultural industries especially with respect to maintaining temperature uniformity in a reefer container environment.

4 Design of the Apparatus for A Column of Stacked Boxes with Reefer Airflow Conditions

4.1 Introduction

Supply chain conditions have a significant bearing on the quality of horticultural produce (Tanner & Smale, 2005), and optimizing such processes is an important part of ensuring delivery of high quality of produce (Carson & East, 2018). The global transport of food is facilitated by the cool chain system. These supply chains are often reliant on refrigerated containers as they are capable of being loaded onto sea, road, and rail vehicles. Researchers often seek to understand the cooling conditions within the reefer, especially with respect to interaction of the packaging design used (Dohring, 2006; Smale et al., 2006; Dodd, 2012; Issa & Lang, 2016; Kan et al., 2017; Getahun et al., 2018). The package design has a substantial impact on temperature maintenance of the product (Carson & East, 2018). Presently most researchers study the air flow and resulting heat transfer from the packed horticultural product in reefer containers using mathematical models (Jedermann et al., 2013; Defraeye et al., 2015b; Getahun et al., 2017a; Getahun et al., 2018). To validate mathematical modelling, experimental data is required.

In this work, a laboratory sized apparatus was designed, built, and evaluated in order to enable investigation of the conditions of a stacked column of boxes in the vertical cooled reefer condition. The laboratory scaled apparatus was designed to hold different scenarios of single column boxes that may be seen in real reefer transport systems. The major design objectives of the apparatus were to create an airtight device with a constant vertical air flow that mimics the air flow conditions seen in a modern reefer container for a column of stacked boxes.

4.2 Constraints

With regard to the present knowledge and available resources in the facility, a laboratory scaled apparatus was planned, designed and constructed. For creating a refrigeration unit and constant air flow into the apparatus a Temperature Controlled Room (TCR) and fan was used to pump the required conditioned air into the system. To design the main structure with vertical airflow reefer condition, a number of parameters needed to be controlled, maintained or monitored throughout the duration of the experiment. These parameters are discussed below.

4.2.1 Volumetric Airflow Rate

The air circulation in a reefer container can be measured as air number of volumetric renewals changes per hour (Ambaw et al., 2014; Defraeye et al., 2015b; Wild, 2009). To create similar air flow conditions as a reefer container, the volumetric flow within the apparatus is to be of equivalent values. The volumetric flow rate (VF) can be determined by Equ.4.1.

$$VF = N * IVS \tag{4.1}$$

VF is volumetric flow rate (m^3/hr), N is number of renewals (1/hr) and IVS is internal volumetric space of the apparatus (m^3)

Modern reefers are usually equipped with two different modes, normal and economical. The evaporator fans operate at high speed in normal mode, with an air exchange of 70- 80 renewals per hour, whereas they operate at low speed in economic mode, with an air exchange of approximately 35-40 renewals per hour (Getahun et al., 2018). These values could vary based on the manufacturer.

In earlier refrigeration container studies, where the researchers used CFD models to investigate one air mode, an airflow of 5800 m^3/hr. to a 40-foot container system was used

(Tapsoba et al., 2006; Moureh et al. 2009). For the 70 m^3 free space of a 40 ft container this flow produces approximately 82 air renewals per hour. With the manufacturers' introduction of two distinct air flow modes in a reefer, a reasonable research question would be to understand the impacts of packaging design changes in two different volumetric air flow rates (Getahun et al., 2018). Therefore, the apparatus needs to be configured with at least two distinct modes to understand the characteristics of air flow and heat transfer for a packaging design at these two potential set points.

The volumetric flow rate through a system can be described by the mean velocity of the flow at a given point in the system and the system’s cross-sectional area (Equation 4.2).

$$VF = CA_C \tag{4.2}$$

Where *VF* (m^3/s) is volumetric flow rate, and C (m/s) is the superficial air velocity and A_C (m^2) is system cross-section area at the point of measurement.

4.2.2 Pressure

In a pneumatic air conveying system, understanding the superficial air velocity is important as it helps in controlling specifications of air requirement into the apparatus. To verify the maintenance of a constant air flow in a closed experimental system, the conditions should be monitored throughout the duration of the experiment. This can be achieved by observing the pressure drops at certain points throughout the apparatus as the airflow always travels from high pressure to low pressure and variance in the pressure readings will be reflected in the air flow conditions. Hence, during the experimental duration, the volumetric flow rate in the system is regulated by the pressure drop generated throughout the apparatus.

4.2.3 Temperature

To study the design efficiency of a box with respect to air flow movement (in and out of the box), temperature of the product inside can be considered as the one of the major constraints and observable variables to understand the packaging design efficiency. In a laboratory scaled apparatus, care must be taken that there is negligible heat flow through the experimental system either into or from the surroundings for an accurate measurement. This is most easily attained by insulating the outer walls. By creating an apparatus with a heat loss of less than 5% from the total heat transfer of the system can be considered as a good system. Placing the entire apparatus with thick insulating walls in a TCR throughout the duration of the experiment can result in very little heat transfer from the apparatus to the surroundings.

The assessment of cooling performance of any system is determined by observing the temperature change of the product with respect to its position. The readings are obtained through thermocouples at regular intervals of 1 minute. The wires from the monitoring device in the apparatus need to be arranged in such a way that it causes minimal disturbance to the air flow. These readings measure the changes that take place within the box, providing us with the insight to the effects of the design of the box on cooling.

4.2.4 Reefer Constraints

Given that the experimental system is to be used to simulate conditions that exist in a commercial reefer container, it is important that the system has similar physical properties to the reefer.

Inlet air needs to be directed to all corners of the container to monitor the climatic conditions inside a standard reefer. In a standard reefer the air enters the container in horizontal direction through the inlet valve. Over the length of the container with the help of the floor design the horizontal air flow changes into vertical direction and creates a vertical air flow condition throughout the cargo present in the container. The air travels back into the refrigeration unit through the outlet valve present at the top of the containers (Figure 2-1). This scenario is created by linking the reefer's inlet air ducts to the T bar of the floor design.

The T-bar floor (Figure 2-2) is the most common floor design in modern reefers (Vigneault et.al 2009). It has longitudinal aluminum bars extending over the length of the container's cargo space with pitch of 65 mm and height 60 mm (Lukasse & Staal, 2016). It generates a pressure factor within the reefer which switches the direction of air from horizontal to vertical. As for primary experimentation purpose, the concept of wooden pallet below the stack of boxes was removed, as it would have created a complex variable in the system by not allowing to concentrate more on the design feature of the packaging. By removing the wooden pallet from the system, assumption is made that should the venting in the packaging be found to be beneficial, redesign of the slats in the pallet may be required to ensure these vents are open to the air flowing through the floor of a refrigerated container.

There is a free space, known as the headspace, in a reefer over the stacked boxes, which allows the air to return to the refrigerated unit above the stacked boxes. The height of the stack influences the air channel and the circulation of air over the stack. The headspace narrows with the increase in the height of the stacks, which in turn will produce an irregular distribution of temperature in the headspace (Kan et al., 2017). For kiwifruit, pallet heights consist of 10 MBP (Modular Bulk Packaging) in a pallet. This scenario generates 350 mm of headspace in a standard reefer over the column of MB boxes (difference between standard reefer internal height and stacked pallet height).

4.3 Design Decisions

Design decisions were made by considering the constraints identified above. These design decisions are detailed below.

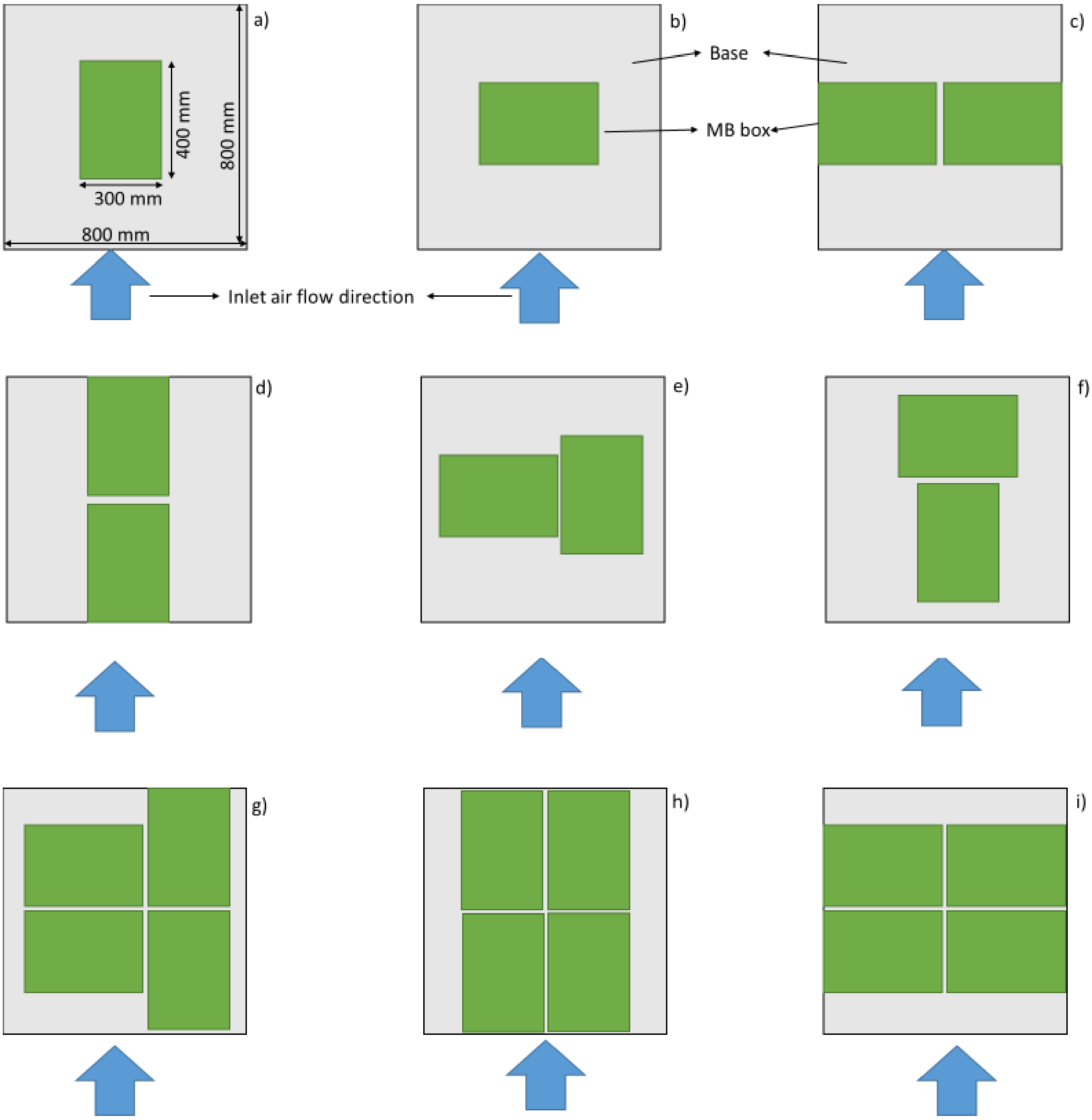
4.3.1 Apparatus construction decisions

A column of stacked MB boxes in packed pallets can be placed in different orientations i.e. as parallel or perpendicular to the inlet airflow, positioning the stack at the centre or end of the pallet, placing the column adjacent to the wall or adjacent to another column of MB boxes.

We can mimic most of the conditions of a 1200×1000 mm pallet set up by positioning the MB box in different orientations in an 800×800 mm square cabin base. The possible combination of box orientations on the base have been displayed in the Figure 4-1 below. Working with a full scaled pallet footprint size (1200×1000 mm) demands more effort, time, and material (sensors, fruits for study, etc.). Hence, it is preferable to use an 800×800 mm square cabin base with more orientations to create required experimental trial conditions.

Figure 4-1 :

Top view for a column of kiwifruit MB packaging with Possible Scenarios on Storing in the Reefer container with Inlet air flow Directions



Note. a) Position 1- Longer side of box parallel to inlet air flow. b) Position 2- Longer side of the box perpendicular to the inlet air flow. c) Position 3-Two columns of boxes were longer side perpendicular to the inlet air flow. d) Position 4- Two columns of boxes where the longer side of the box is perpendicular to the inlet air flow e) Position 5- Two columns of boxes perpendicular to each other where the experimental column's longer side is parallel to the air flow. f) Position 6- Two columns of boxes perpendicular to each other where the experimental column's longer side is perpendicular to the air flow. g) Position 7- 4 column of boxes with two boxes longer side is perpendicular to the inlet air flow and two columns longer side is parallel to the air flow) Position 8- 4 column of boxes where all the boxes longer side is parallel to the air flow. i) Position 9- 4 column of boxes where all the boxes' longer side is perpendicular to the air flow.

To create a vertical air flow, the horizontal air flow on the T-bar floor should be redirected to the apparatus. An airtight base design with a single opening (footmark of the box as per experiment requirement) at the top of the base can accomplish this. The direction of airflow changes from horizontal to vertical due to the pressure gradient generated inside the airtight cabin. The sides of the stack are sealed to sustain the direction as constant across the apparatus. Primary experimentation (position one and half a pallet boxes) is the smallest experimental setup that can be done under this apparatus and for experimental setup kiwifruit simulators created by Huang et al., (2017) was used in place of real kiwifruit. The primary experimentation consisted of 500 simulators (5 boxes and each box having 100 simulators).

The total heat energy stored in the system can be calculated using heat energy Equ.4.3

$$Q = n_p m c_p \Delta t \tag{4.3}$$

where Q is the heat energy in Watt(W), n_p is number of simulators m (kg) is the mass of the simulator cp (J/kg.K) is the specific heat of the simulator and delta Δt (K) is the difference in the temperature.

The simulators consist of a specific heat capacity of 1050±20 J/kg.K at an average weight of 0.14 kg with a temperature difference of 20 °C. Therefore, the total heat energy stored in the primary experimentation is 1470000 J or 1470 kJ.

As most of the heat transfer in the system occurs by conduction or convection, the walls need to be thick and made of low thermal conductivity material to maintain the heat loss from the apparatus at its minimum. Polystyrene was chosen as the walls of the apparatus for experimental ease. By calculating different thickness of polystyrene for the walls using the convective heat loss equation, (Equ.2.1) 0.1 m thickness polystyrene was selected as the walls for the apparatus as the heat loss (q) through 0.1 m thickness for a 1.89 m^2 surface area (lateral surface area of the apparatus with primary experimentation measurements) for a temperature difference of 20 °C will be 13.23 W or 13.23J/s (where 1w =1 J/s) which can be considered as a negligible amount of energy loss from the apparatus.

To mimic the conditions of a reefer container, the apparatus should consist of 350 mm headspace. By providing the outlet valve on the side wall, the apparatus can create similar air flow conditions in the headspace of the reefer container, with the air returning from the same direction as the air delivery.

The TCR would be preset to the required experimental conditions a week prior to the experiment in order to attain stable equilibrium conditions.

Pumping a volume of 40 and 75 times the IVS of the apparatus leads to the creation of economic and normal modes of the reefer respectively. These two modes will be tested in the experimental section. For the experimental convenience ±3 times was taken as range for each mode which gives an error of 7.5% and 4% for respective modes.

4.3.2 Fan selection

By considering various scenarios of the experimental work, (Figure 2-1) position 7, 8 and 9 with full pallet height (10 boxes) was found to be having the highest holding capacity in the apparatus with a headspace of 350 mm. This scenario gives way to an internal height of 2.25 m (10 box height + headspace) and a base area of 0.48 m^2 (0.8 m length ×0.6 breadth) which resulted in an internal volumetric space of 1.08 m3. As normal flow is the highest flow rate in this experimental design. Normal air flow should pump air equal to 75 renewals of volumetric internal space of an emptied apparatus into the system, which is a volumetric flow rate of 86.4 m3/hr or 0.024 m3/s (Equ.4.1). A fan which can produce a volumetric flow rate of 100m3/h is required, so that the apparatus can be maintained and run according to the various defined scenarios. For this volumetric flow rate, the average superficial velocity across the boxes would be 0.05 m/s (as volumetric flow rate is equal to the multiplication of average superficial velocity to the base area Equ.4.2).

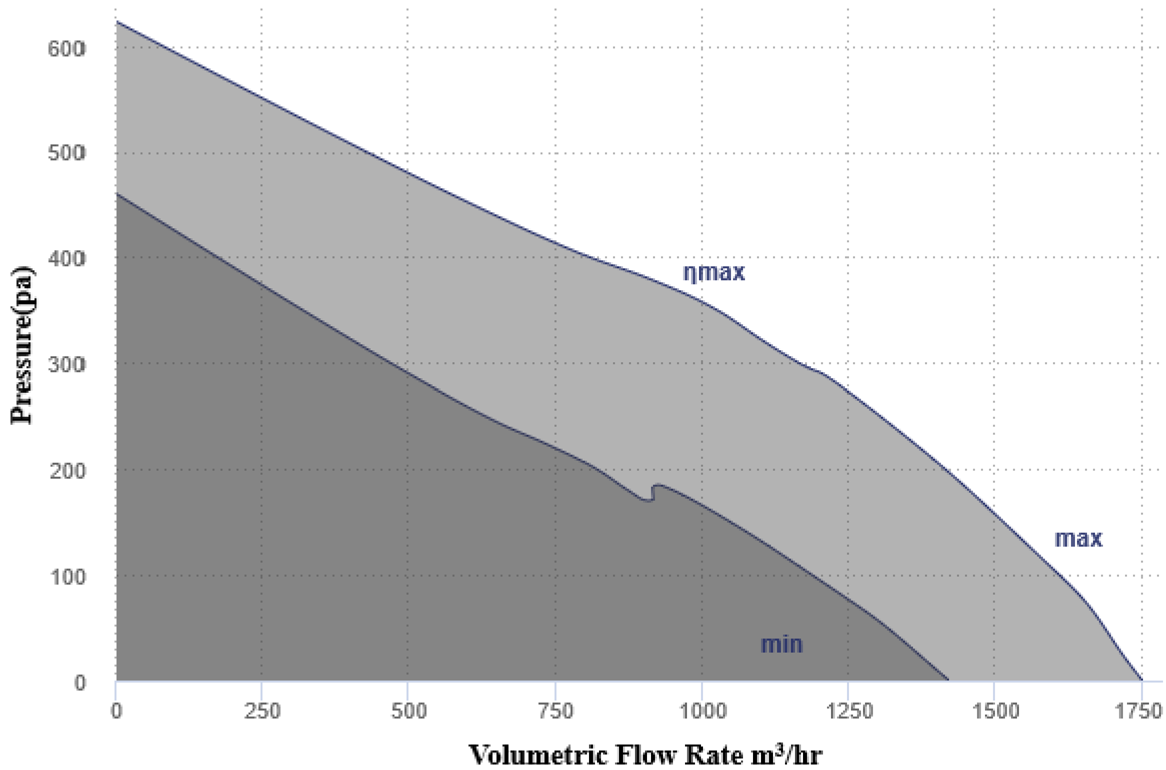
The fan for the apparatus was selected using the fan curves. The fan curves can be studied by the range of volumetric flow rate and the pressure drop under which the fan should generate the required volumetric flow rate. For the pressure drop readings Getahun et al., (2017) generated experimental pressure drop vs superficial air velocity plot for vertical through a half pallet. and the plot had shown that for generating 0.05 m/s superficial velocity over a tightly packed pallet can generate a pressure drop from 300- 600 pa. Maximum pressure drop of 703 Pa has been observed, when generating 0.3 m/s superficial velocity for 1-meter height stacked orange fruit boxes in vertical air flow conditions (Delele et al., 2013b). By analyzing different fan curves over the market and with the funding restriction, Blauberg ‘Turbo 315 max’ fan with 230 V single phase 50/60 Hz from the manufactures Blauberg Ventilatorean GmbH, Aidenbachstr Str.52. 81379 Munich was selected. The Turbo

315 Max's can generate 86.4 m^3/hr volumetric flow rate at pressure drop ranging from 300 - 600 pa as shown in the fan curve (Figure 4-2) presented from the manufacture company.

The fan was controlled with a digital variable speed drive connected to the fan's power supply, enabling it to regulate the system's airflow as per the experimental requirement.

Figure 4-2 :

Fan Curve for Turbo 315 Max and Turbo 315 Min Fan



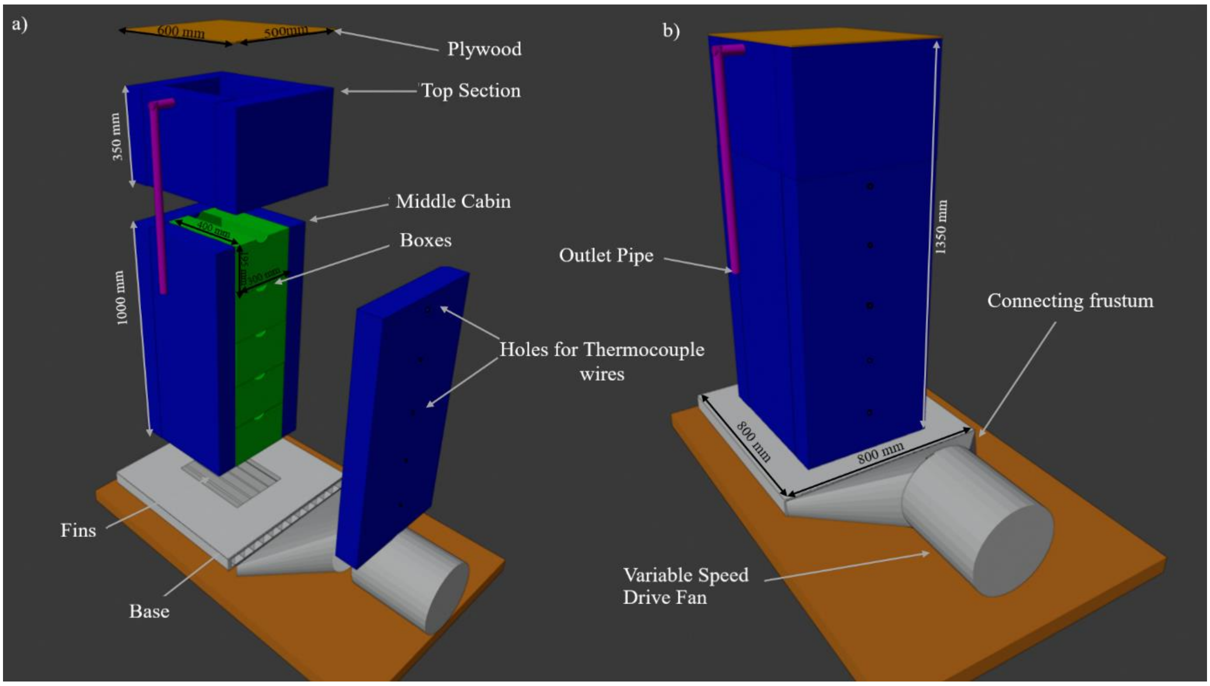
Note: Shaded area for ηmax represents the working conditions of Turbo 315 Max model and ηmin represents the working conditions of Turbo 315 Min model fan

4.3.3 Design of Apparatus

Primary experimentation setup with a single column of 5 MB boxes with the longer side of the box parallel to the inlet flow was chosen for the experimental work (discussed later in chapter 5). The entire apparatus is split into three sections: the base, the middle and the top (Figure 4-3)

Figure 4-3

Full Design of the 5 MPB Single Column Apparatus with Dimensions



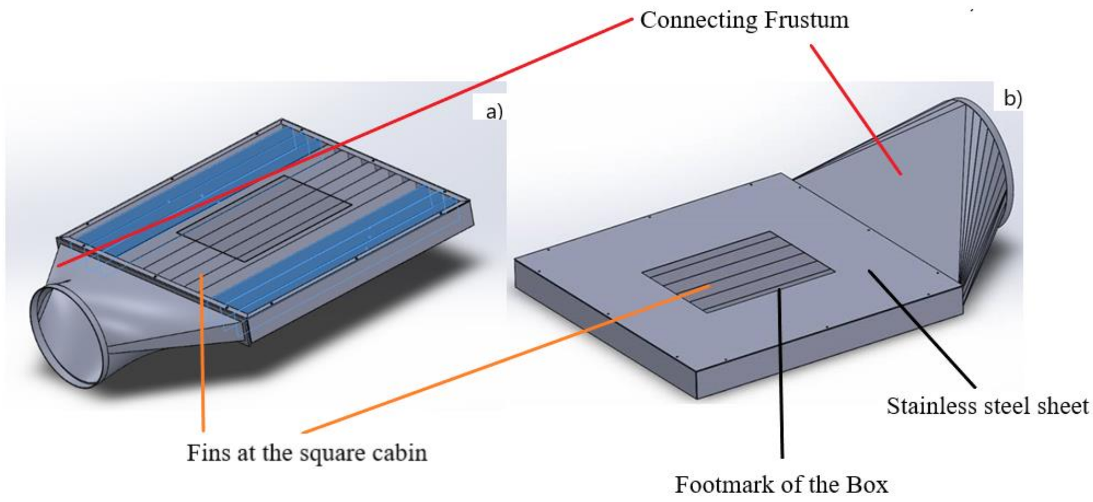
Note. a) Dismantled apparatus; b) Assembled apparatus

4.3.3.1 Base The base segment is the floor of the apparatus, designed as a square cabin of 800 × 800 mm with a height of 60 mm. A lateral surface of the square cabin is removed in order to let the inlet air flow. 12 Longitudinal bars (fins), were inserted at an optimal spacing of 60 mm **(refer 2.2.3)** in such a way that they are perpendicular to the open surface of the square cabin thereby acting similarly to the T bar floor in refrigerated containers. The square cabin should be sealed in order to make it airtight as shown in Figure 4-4(b).

A hole was traced on top of the sealed square cabin (Figure 4-4) as per the specifications of the experiment, in order to study the effect of base ventilation (chapter 3). By positioning the longer side of the box parallel to the air flow, the T-bar floor results in less obstructed surface area at the base of the box when compared to other setups. A frustum (connecting tube) was designed to connect the open face of the square cabin and the inlet of the fan to facilitate inlet air flow.

Figure 4-4

3-D Design Diagram for the Base with a Single Footmark of an MBP



Note. a) Base without stainless steel sheet b) Base with stainless sheet. Blue marking represents non useful area for the primary experimentation.

4.3.3.2 Middle cabin The middle cabin was designed by sealing the column of boxes using a polystyrene material which formed an airtight sealed cabin with no leakage all around the lateral surfaces. As the apparatus was constructed to test the packaging conditions of a single column of MB boxes, the inner length and breadth of the middle cabin exactly coincided with the length and breadth of the box. The height of the middle cabin was equal to the height of the stack of boxes. The dimension of the middle cabin varied with respect to the dimensions of any stack of boxes as per any experimental requirement.

In order to accommodate the wires of the (temperature) monitoring devices from the experimental boxes, holes were required in the insulated walls, allowing connection to their respective data loggers. These holes were situated along the center of the outer insulating material covering the boxes. The diameter of these holes was kept at a modest 15mm and they were placed 0.187m apart from each other. It was also made sure while placing the holes that they aligned exactly with the top surface of the boxes in the stack, placed within the layer of insulating material.

4.3.3.3 Top section Top section is the headspace of the apparatus. Except for the internal height being 350 mm to create a headspace over the stack of boxes and a sealed top section, it is built identical to the middle section with the inner length and breadth matching the length and breadth of the box with a height of 350 mm and sealed using insulating material on its lateral surface. Two ratchet tie downs extended from top to bottom over the system and were tightened to make the apparatus airtight before the experiment.

4.3.4 Volumetric flow for single column 5 MB box apparatus in reefer conditions

The superficial velocity at the inlet is difficult to determine due to the construction of the device. As a direct consequence, the volumetric flow of the apparatus is measured at its outlet, which is located at the top and centre of a side wall, adjacent to the holes of the middle cabin to enable an outlet of the air from the system. Hence the VF through the apparatus was determined by using Equ.4.1**.** As reefer containers have low flow rates and that was considered as constraints in the apparatus, the flow rate in the apparatus will be low. For creating a noticeable velocity at the outlet, different cross-sectional area outlets were verified using the Equ.4.2. For creating a noticeable airflow, the superficial velocity was supposed to be more than 2 m/s, which made it convenient to measure using a hot wire anemometer. Out of different cross section areas a small circular outlet with 30 mm diameter had generated noticeable air velocity for both modes as described in the Table 4.1. The aerodynamics of the head space might be disturbed by a smaller outlet. However, this disturbance occurs in every trial of the experimental setup, we consider this aspect to be inconsequential. For creating a circular outlet, a circular pipe with inner diameter of 30 mm was selected as outlet for the apparatus. For measurement convenience, L- bend circular pipe was designed as an outlet valve for the apparatus.

Table 4-1

Describing the air flow measurements for a single column 5 MB box apparatuses

	40±3 Renewals (Economical mode)	75±3 Renewals (Normal mode)	Units
Volumetric internal space	0.162	0.162	m^3
Total volumetric air flow rate (VF)	6.48±0.486	12.15±0.486	m^3/hr
Amount of air pumped in per second	0.0018±0.000135	0.003375±0.000135	m^3/s
Superficial Velocity at the end of 30 mm outlet pipe with surface area of 0.00070714	2.5±0.2	4.7±0.2	m/s

4.3.5 Instrumentation

For this research, the superficial velocity at the outlet pipe was measured 5 times at the start and as well as at the end of the experiment using Velocicalc Air Velocity Meter 9535. It has a range to measure from 0 to 20 m/s and accuracy of ±0.015m/s with a certificate of calibration. The average value of the 5 readings was taken for verifying the range of superficial velocity at the end of the 30mm outlet pipe as per the experimental requirement.

Pressure drop pipes were used to measure the pressure drops in the apparatus. 3 pipes at the base (Figure 4.5 c) and the 2 pipes at the top of the apparatus were installed to observe the pressure drop values in the apparatus. These pressures drop pipes were connected to a differential pressure pipe of squirrel 2040 series made by Grant Instruments, Cambridge, United Kingdom. The pressure sensor pipes will be connected to a 32 channel SQ2040-2F16 Squirrel Portable Data Logger, which records difference in the pressure drop with respect to atmospheric pressure in the form of voltages. The voltage readings can be converted into pressures values using the Equ.4.4 and 4.5**.**

$$P = (V_r - V_i)R \tag{4.4}$$

$$R = \frac{P_{Max} - P_{Min}}{V_{Max} - V_{Min}} \tag{4.5}$$

Where P is pressure reading (Pa), V_r is voltage recorded (V), V_i initial voltage (voltage recorded before the start of experiment)(V), R is the conversation factor for 32 channel SQ2040-2F16 Squirrel Portable Data Logger, P_{Max},P_{Min} and V_{Max}, V_{Min} are maximum and minimum, pressures (Pa) and voltage (V) recordings for SQ2040-2F16 Squirrel Portable Data Logger respectively.

Table 4-2 :

Voltage to pressure conversion readings for 32 channel SQ2040-2F16 Squirrel Portable Data Logger

	V_{Supply}	V_{logger}	V_{Max}	V_{Min}	P_{Max}	P_{Min}
Value	5 V	2.5 V	4.5 V	0.5 V	249.082 Pa	-249.082 Pa

The pressure drop at the base was measured by taking an average of 3 pressure readings present at the side of the fins at the base. Pressure readings at the top were calculated using the average of two different pressure pipes from the top of the apparatus. Care was taken in the placement of the pressure pipes such that the pipes were not obstructed or closed by any other obstacle. For the experimental setup the pressure drop pipes were installed at the center of the headspace of the box to record the variance in the pressure drop inside the box.

Type -T thermocouples were used for measuring the temperatures for inlet and outlet air of the apparatus, temperature of the fruit inside the experimental setup and room temperature during the time of the experiment. 4 thermocouples were installed at the base of the apparatus (Figure 4-5 d). These thermocouples were connected to 32 channel SQ2040-2F16 Squirrel Portable Data Logger made by Grant Instruments, Cambridge, United Kingdom, with an error of 0.05% approx. Settings in the Squirrel portable logger were set to measure 1 reading per minute, as reading for every minute can give a good picture about the heat transfer in the system during the experimental time with an estimated error of ± 0.5℃. The temperature of the inlet air was measured by an average of 4 thermocouples which were inserted inside the base of the apparatus. Temperature reading of air at the outlet pipe was measured by averaging the readings of two thermocouples installed at the end of the outlet pipe. For recording the temperature of the environment around the apparatus (TCR), 3 thermocouples were glued to the side of the apparatus and the average value will be recorded as the temperature of TCR.

4.4 Apparatus Construction

4.4.1 The Base

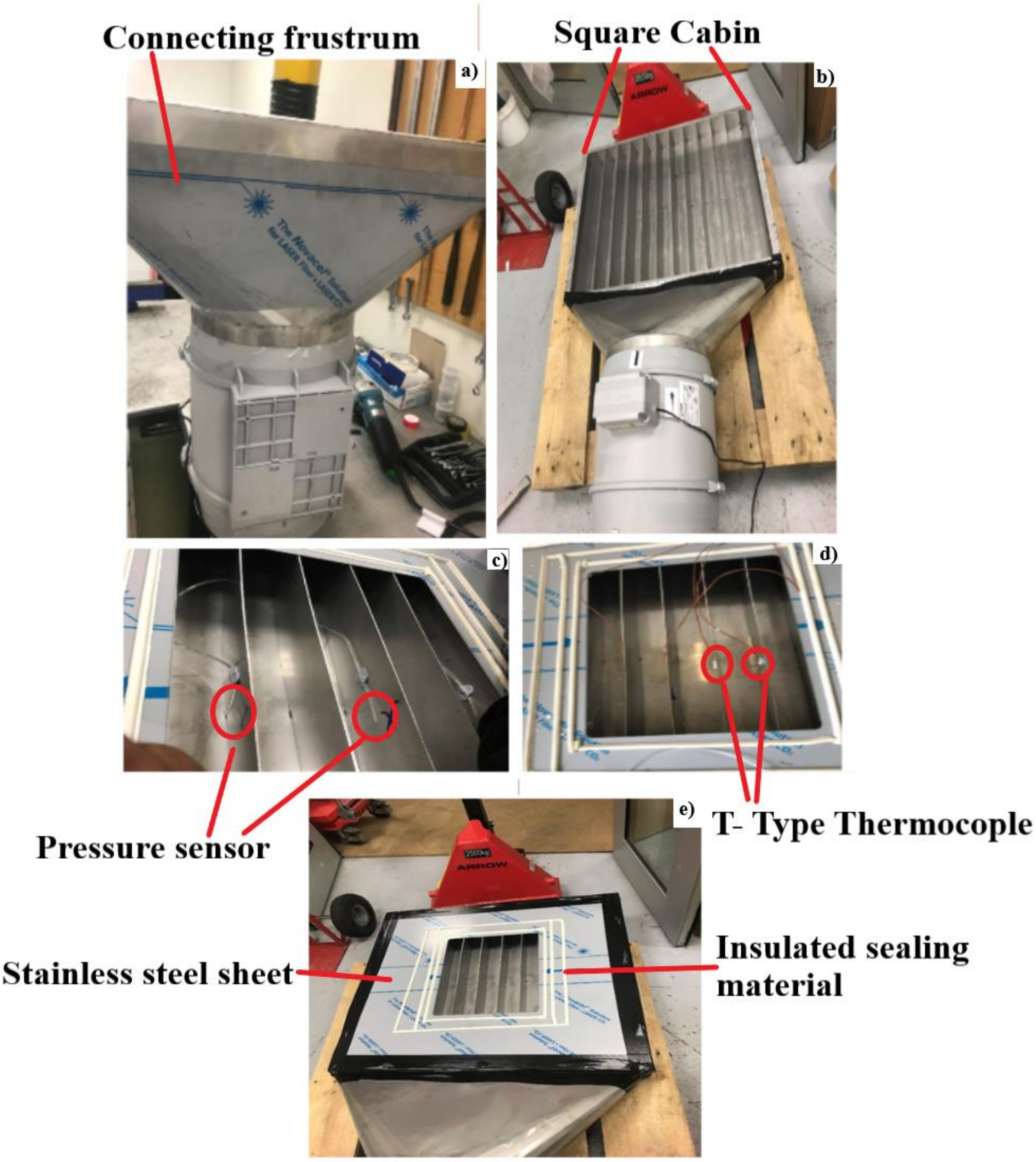
Food grade stainless steel was used to build the base of the apparatus. A stainless sheet was molded into a square cabin as per the system design, followed by the removal of the face of the square cabin and the welding of the fins in the pre-designed orientation. The height of the square cabin was modified to be 80 mm owing to construction constraints.

The circular end of the stainless steel frustum was connected to the outlet of the variable speed drive fan and the flat end was joined to the square cabin using bolts at regular gaps and sealed using duct tape (Figure 4-5a,b).

Two rows of insulating sealing material were glued around the footmark on the stainless-steel sheet and was bolted to the square cabin (Figure 4-5-e). Layers of duct tape were used on the edges of the base to seal any leaks.

Figure 4-5 :

Experimental Assembly of Base



Note. a) Connecting the fan to the connecting frustum with screws b) Connecting frustum joined to the square cabin c) Pressure sensor at the side of the fins below the footmark of the box. d) T- type thermocouples to the base to measure the inlet air flow during the experiment. e) sealing the stainless-steel sheet with two layers of insulated sealing material.

4.4.2 Middle Cabin

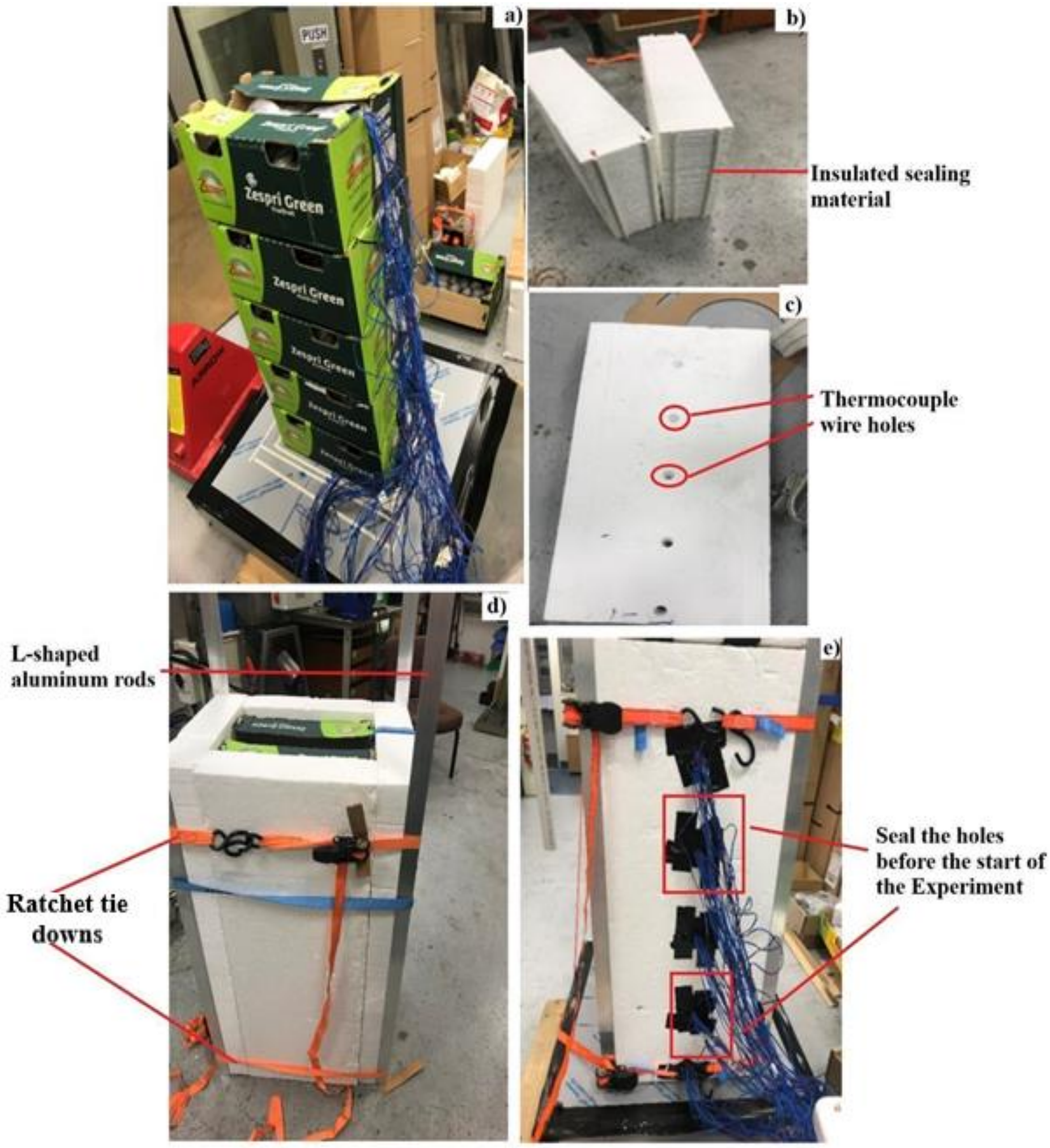
Considering the thermal conductivity, economic availability and flexibility of various insulating materials, polystyrene, with a thickness of 100 mm was selected for the construction of the middle cabin. Two 400 × 950 mm and two 500 × 950 mm polystyrene blocks of 100 mm thickness were used to construct the middle cabin. In order to maintain the setup, four L-shaped aluminum rods and two bungee cords were used – to strap and hold the middle cabin in place. Two rows of insulating material were glued to the polystyrene sides (Figure 2-6b), to create an airtight environment.

Initially, boxes were stacked, and the polystyrene blocks were positioned around the stack so that the stack was completely wrapped as shown in Figure (4-6d) and the thermocouple hole positions were identified. Holes were drilled on the side of the middle cabin, thereby creating a passage for thermocouple wires from the system.

MB boxes were stacked in a column for the construction of the middle cabin. Wires from the thermocouple line up with the connecting tube (Figure 2-6a). The polystyrene block with holes was attached to the side to remove the wires from the system. Remaining sides of the stack were covered using the other polystyrene blocks as per the predesigned alignment. To create the required airtight sealed environment inside the middle cabin, two rows of insulating material between the polystyrene blocks, L-shaped aluminum rods at the corners and ratchet tie downs were tightly wrapped (Figure 4-6e). The holes for thermocouple wires were sealed using duct tape right before the experiment to minimize the pressure loss.

Figure 4-6 :

Experimental Setup for the Middle Cabin



Note. a) Boxes stacked on the base with T-type thermocouples. b) Two rows of insulated sealing material were glued on the sides of polystyrene c) Thermocouple wire holes on 500 length polystyrene d) Middle cabin is wrapped with the help of L-shaped aluminum rods and a couple of ratchet tie downs. e) Sealing the holes before the experiment using duct tape.

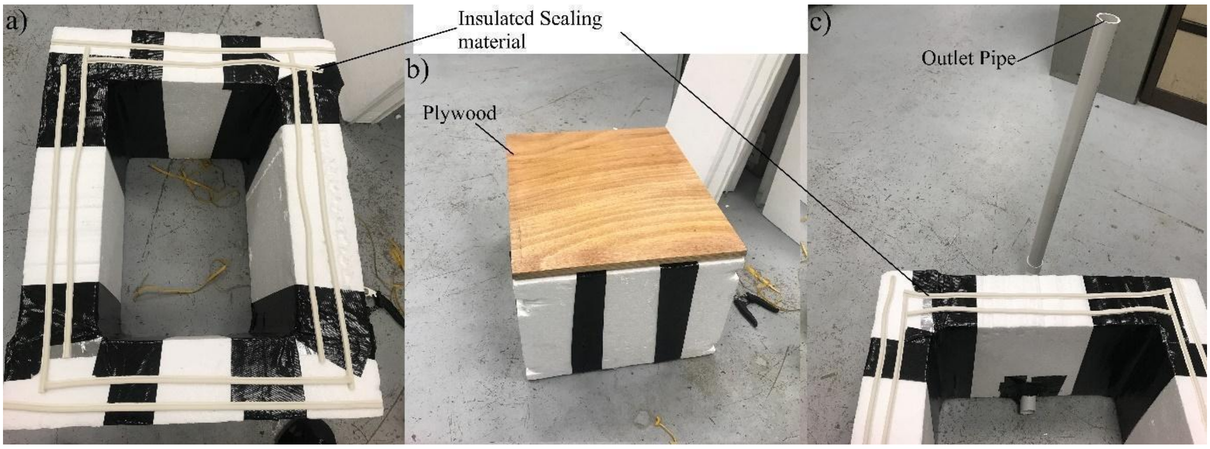
4.4.3 Top section

Two 400 × 350 mm and two 500 × 350 mm polystyrene blocks with a thickness of 100 mm were glued together in the top section using a solid adhesive with two rows of insulating sealing material on its sides. The top section was placed parallelly above the middle section. The edges of the top section were wrapped with layers of duct tape as shown in Figure 2-7a. Two rows of insulating sealing material glued on top and bottom of the rectangular block to seal it with ceiling and middle section respectively. Plywood with a plastic coating (600 × 500 × 20 mm) was used as ceiling material for the apparatus.

For the outlet valve, a 30 mm L-shaped pipe was attached moderately high above the centre of a 400 × 350 polystyrene block. Pipe was anchored to the section using strong glue and tape (Figure 4-7c).

Figure 4-7 :

*Real photos of Top section***.**



Note. a) Top section with insulated sealing material. b) Top section with plywood. c) Top section focusing the outlet valve of the apparatus.

4.5 Apparatus Testing

The major objective of the apparatus is to create a constant vertical airflow condition at a constant temperature with two different modes of a reefer container having MB kiwifruit boxes. If the apparatus produces constant superficial velocity throughout the duration of the experiment trial, that assures a constant vertical airflow in the apparatus. For calibration of variances in the superficial velocity in the apparatus during the experimentation time, certain monitoring parameters were observed i.e. temperature, pressure.

4.5.1 Trials to Test the Working Condition of the Apparatus

Three trial runs were performed with stacked columns of 5 MB boxes to evaluate the working conditions of the apparatus.

- Trial 1- The MB packaging with polyliner
- Trial 2- The MB box without polyliner
- Trial 3- The MB box with extra vent and no polyliner

For these trial tests 500 kiwifruit simulators were incubated at 0 °C for 48 h prior to each trial and packed into 5 MB boxes. The apparatus was placed in TCR at 0 °C and was run using economical air flow conditions (36 renewals per hour) by maintaining 2.5±0.2 m/s average superficial velocity at the outlet. As soon as the fan attained required air flow conditions, an anemometer was used to measure the superficial air velocity. Hot wire anemometer readings were used to adjust the outlet velocity at the beginning and to verify the velocity at the end of the experiment. The test runs ran for a duration of 4.5 h. Before the beginning of the experiment, all the corners and potential leak locations were marked and sealed using duct tape. Throughout the length of the trial, care was taken to keep the variable speed unperturbed. To identify any anomalies in the velocity that may have occurred during the course of the experiment, the constant measurement of pressure as a check was used. For each trial, the average pressure readings at the base and top of the apparatus is presented in Figure 4-8. Due to the technical malfunction anomaly in trial 1, the pressure readings recorded were discarded. The average temperature readings at base, outlet of the apparatus and TCR environmental readings are represented in Figure 4-9.

4.5.2 Testing results

The average value of the superficial velocity in each trial measured at the start and end of the experiment was in the required range of 2.5±0.15 m/s, But the VSD knob was not in the same position for every test trial. When compared, trial 3 had utilized the least amount of energy (fan rotation) to generate similar flow conditions. which can also be observed in Figure- 4-8 b.

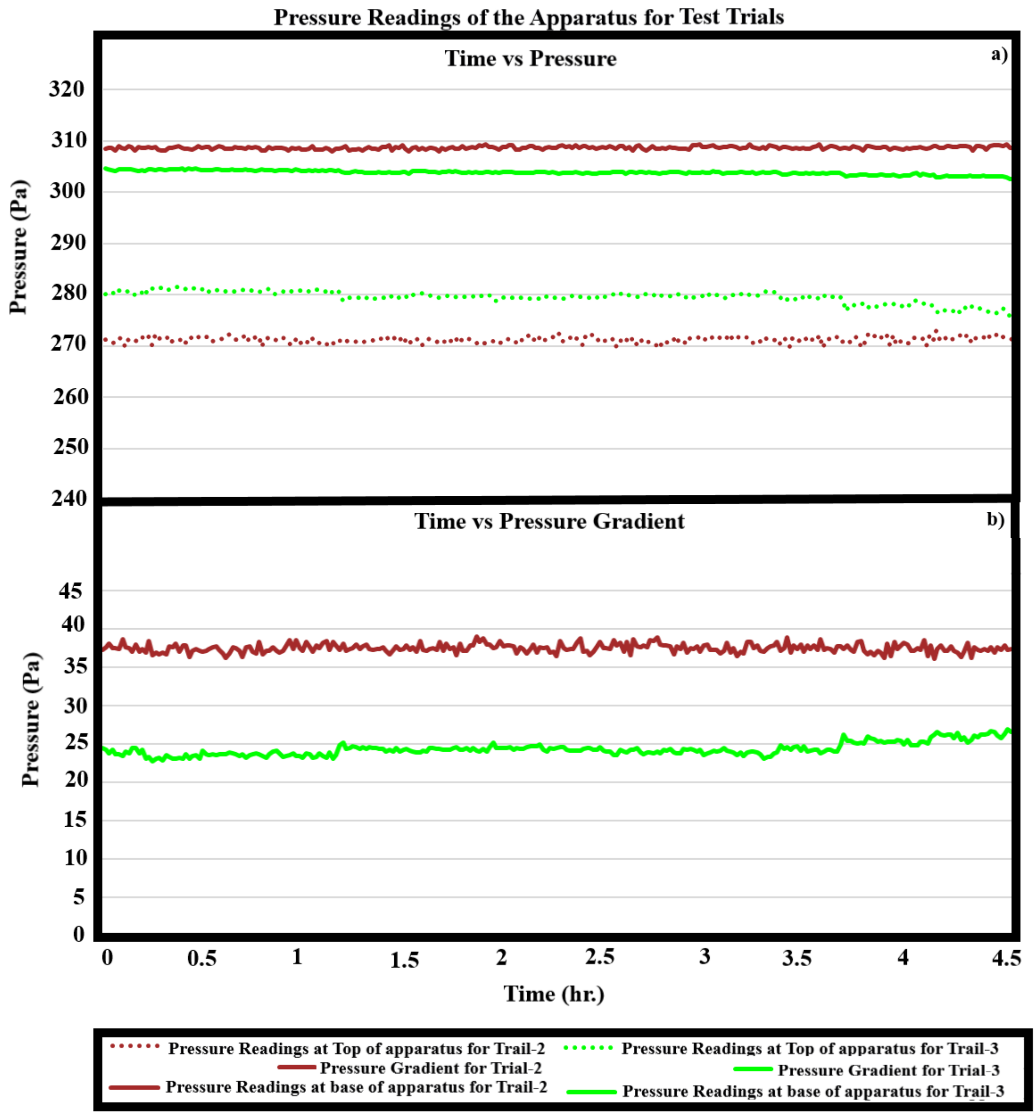
Throughout the duration of the trial, constant pressure measurements were recorded (Figure 2-8a), resulting in the pressure gradient graph (Figure 2-8b) asserting that there was no observable pressure difference that occurred throughout the experiment. The variable speed drive was kept undisturbed throughout the experimental trial. This suggests that the air velocity inside the apparatus was constant throughout the experimental trial.

Due to the 0 °C simulators in the box, there was an expectation of minimal heat transfer through the system. The temperature results of the apparatus indicate that in general inlet and outlet temperatures were constant throughout the duration of experiment (Figure 4-8b). Throughout the experimental time approximate increase of 1 °C in the inlet air temperature was recorded, which may be a consequence of the heat generated by the fan rotation. which can be seen in Figure 4-8a.

These combined results thus imply that the built apparatus can establish constant vertical air flow conditions in the range that would be expected in a reefer container.

Figure 4-8 :

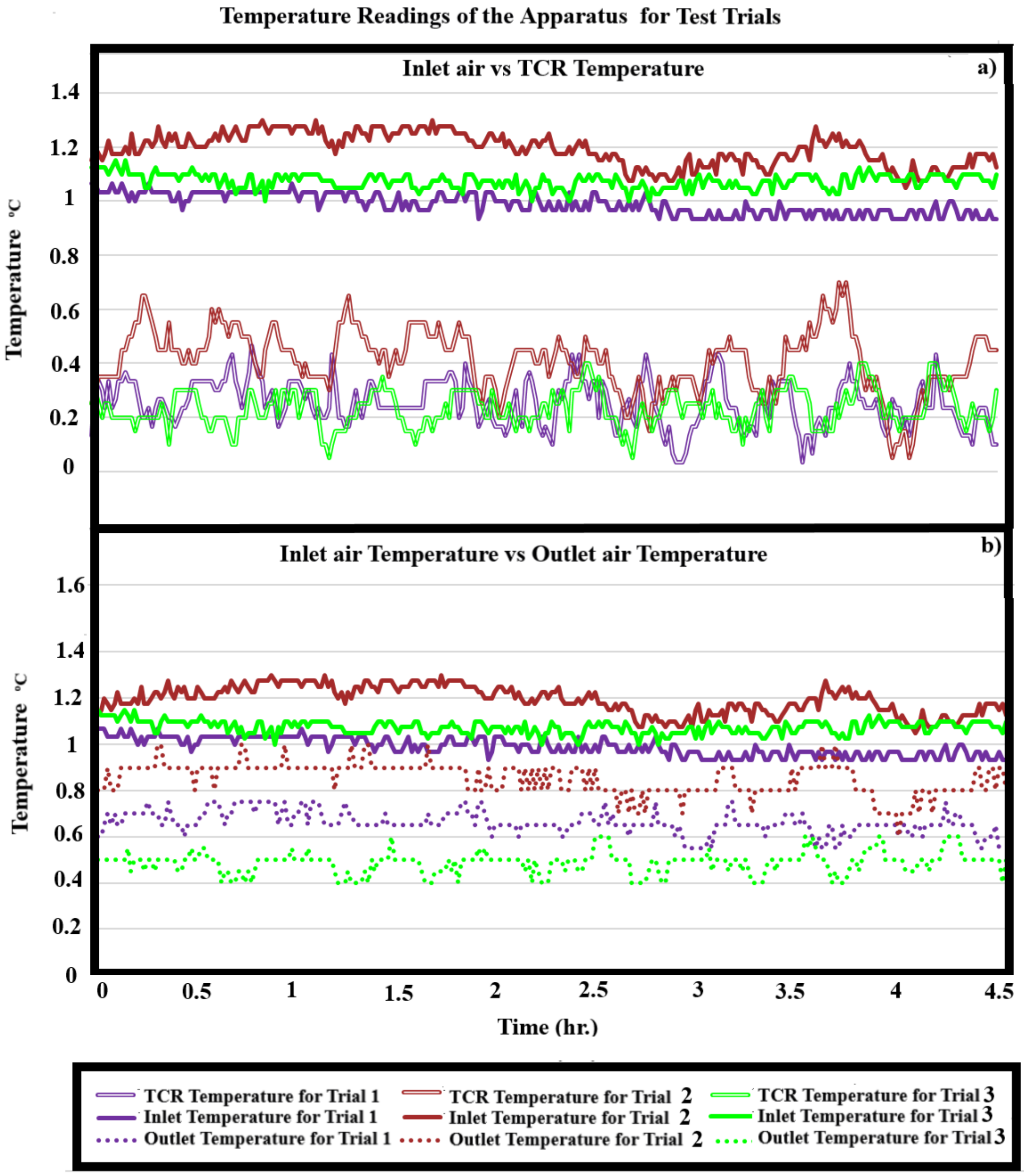
Apparatus Pressure Results for the 3 Different Trials for the Duration of 4.5 h



Note. a) Time vs pressure line graph between the base and and the top of the appatarus during the testing trial experiment at economical mode reefer conditon. b) Time vs pressure gradient line graph between the base and the top of the apparatus at econmocal mode reefer condition. Due to the technical disturbances Trial 1's pressure data had been discarded.

Figure 4-9 :

Apparatus Temperature Results for the 3 Different Trials for the Duration of 4.5 h



Note. a) Time vs temperature line graph between the inlet air and the TCR room temperature of the trials. b) Time vs temperature at the inlet and outlet of the apparatus for the testing trials at economical mode reefer conditions.

4.6 Conclusion

A laboratory scale vertical airflow reefer simulation apparatus for a single column MB box which was designed, constructed and tested. The refrigerated unit of a reefer container was mimicked with a TCR set to 0ºC, and a fan with a variable speed drive. 100mm thickness polystyrene was used as an insulating sealing material, ratchet tie downs and duct tape created an airtight insulated cabin within the apparatus to attain the required reefer conditions. The use of a circular outlet with a diameter of 30 mm created significant airflow that was measurable for both air flow modes of a reefer. Even though the apparatus generated the required pressure drop across the stack of boxes as expected, this laboratory scaled apparatus can now be used to evaluate various design parameters, such as the effect of ventilation, the impact of different airflow conditions on packaging and the cooling efficiency of new packaging designs in these mimicked reefer airflow conditions.

5 Effect of Packaging Design in Reefer Containers

5.1 Introduction

The New Zealand horticulture industry's income majorly depends on the export of domestic grown produce. In the horticulture industry, storage and transportation plays a pivot role in preserving the quality and upholding the value of the product. To uphold the desired qualities in the storage/transportation phase, packaging technology plays a vital role. Since New Zealand is an island country, 99 % of volume of trade is done by marine transportation while refrigeration containers contribute 80% share of transports in marine transportation (Castelein et al., 2020).

Vertical air flow conditions are predominantly seen in refrigeration containers (reefer). Vertical cooling conditions in a reefer may be optimized by adjusting the box design and their stacking pattern (Defraeye et al., 2015a). Future research needs to focus on improving cooling efficiency in vertical air flow conditions (Berry et al., 2017). In recent times, researchers like Getahun et al., (2018) have started exploring the conditions of different modes in a reefer container and its effects to understand the modern reefer container conditions.

Kiwifruit represents 32 % of New Zealand's total horticultural export's revenue (NZKGI 2018) and the most commonly used packaging system for transportation of kiwifruit is polylined MBP. Polyliner bags are used as a standard within the MBP. The purpose of polyliner is to provide a barrier against moisture loss of the fruit. A total weight loss of approximately 4 % from a kiwifruit can lead to shriveling of the fruit and deteriorate its value (McDonald, 1990). The polyliner film creates highest resistance to the airflow compared to other packaging designs (Delele et al., 2012). Fruit wrapped in the polyliner takes much more time to cool down than fruit with no polyliner (Mukama et.al 2019). O'Sullivan et al., (2016) found that cooling of a MB box was affected by the airflow conditions, position of box (distance from refrigerated air), temperature of refrigerated air, and air flow distribution in the MB box packaging. However, it is expected that the polyliner bag will hinder air flow constraining heat transfer, as seen in previous pre-cooler trials (O'Sullivan et al., 2016).

In horticultural packaging research, vents are added in many packaging types to improve the air penetration and to enable even air flow distribution within the box (Pathare et al., 2012). Vent size and location has a significant effect on air exchange rate (Smale et al., 2002). Poorly distributed vents will have no effect on the cooling rate of packaging (Dehghannya et al., 2012). In reefer conditions, introduction of base vents to enhance the vertical airflow condition through the packaging has improved the cooling efficiency of apple packing design (Getahun et al. 2017). In vertical airflow conditions, a very uniform distribution of cooling air through the package is achieved by coordinating the central opening at the bottom and the top (Wu et al., 2019).

To explore the possibility of vertical ventilation in a MBP to improve the cooling efficiency of the packaging by enhancing the vertical airflow condition of a reefer container, design parameters of present MBP were explored. Design parameters such as introduction of base ventilation to the design and existence of polyliner in the design was studied in different airflow modes of a reefer container. The airflow movement inside the packaging was evaluated by observing the heat transfer mechanism of the product in the packaging.

5.2 Methods

To study the cooling efficiency of a MB packaging design, a laboratory scale tested apparatus which could generate modern reefer container airflow conditions by holding a single column of 5 vertically aligned MB boxes (chapter 4) was used. The experimental trials began by placing a packed MB box into the apparatus and conditioning the column of boxes with 0°C air with modern reefer airflow conditions. The product inside the MB box was incubated to a higher temperature right before the start of the experiment, so that by observing the changes in cooling profile of the products inside the box, the effects of design parameters of packaging design was analyzed.

5.2.1 Experimental Design Parameters

The effects of various conditions such as base ventilation, polyliner bags and air flow velocity were assessed in this chapter. The different experimental design parameters that were studied are:

a) Holes in the bottom of the packaging.

b) Existence of polyliner bags in the box.

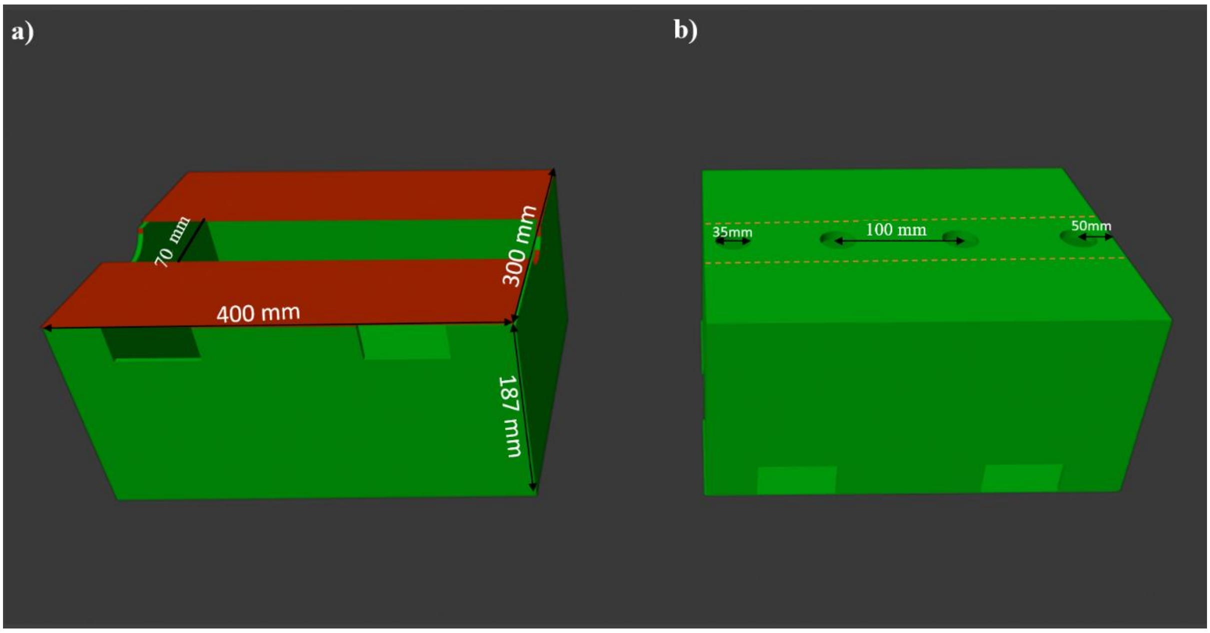
c) Different air flow modes of a standard reefer container.

For this research, the standard kiwifruit MB boxes provided by OJI Fibre Solutions with dimensions 400 × 300 × 187 mm were used as the case study. Kiwifruit sized count 36 artificial kiwifruit simulators developed by Huang et al., (2017) was used as replacement for real fruit in experimental trials.

5.2.1.1 Holes for Base Ventilation The top surface of a MB box had a rectangular vent of dimension 70 x 400 mm (Figure 4-3) and the base of the present design MB box had no ventilation. In a stack, the bottom of a box was positioned over the top of the previous box and locked with lugs in place. To study the impact of vertical ventilation in MBP and to establish a possible vertical ventilation path, base vents were installed on the bottom surface of the boxes to establish a potential vertical ventilation path to align with the existing vent on the top surface (Figure. 5.1b).

Figure 5-1 :

3-D design of Kiwifruit MB box with 3% base ventilation



Note. 3-D design of Kiwifruit MB box with 3% base ventilation. a) Top side of the base b) Base of the box.

The count 36 kiwifruit size resembles a large hen's egg with weight in the range of 95 to 105 grams, length of ≈ 70 mm and diameter of ≈50 mm (Olatunji et al., 2019). To create a suitable vent at the base of a kiwifruit MB box, the surface area of the hole should be considered and constrained by the dimensions of the kiwifruit so that the fruit neither blocks the vent nor falls through it. The reported optimal vent area is lower for polylined horticultural produce, ranging from 2.5 % for peaches (Singh et al., 2003) to 5 % for table grapes (Aswaney, 2007 cited in O'Sullivan et al., (2016)). O'Sullivan et al., (2016) indicated that in kiwifruit MBPs, the total open area is approximately 4% (6 % on the hand vent faces). Increasing the vent ratio larger than this range in MB kiwifruit packaging is unlikely to enhance cooling. As a result, a decision was made to create 4 equal sized circular vents with a diameter of 35 mm where each vent added a vent ratio of ≈ 0.75% to the face of the surface, and hence the resulting base ventilation was 3%. Considering the top vent surface area and the structural integrity of the box, the 4 circular vents were separated from adjacent vents by a length of 100 mm between its centers and the center of vents at the edge of the box are placed 50 mm away edge of the surface (Figure 5-1b).

5.2.1.2 Influence of polyliner Polyliner bags were used to wrap the kiwifruit in the MB box. The polyliner was intended to provide a barrier to minimize the loss of moisture from the fruit. For a kiwifruit, approximately 4% total weight loss can lead to fruit shrivel (McDonald, 1990), this can be avoided with the presence of polyliner bags. In 2012 Delele et al., (2012) had stated that within the packaging design for grapes, the polyliner bag had created highest resistance to airflow into the packaging when compared to other components of packaging, O'Sullivan et al., (2016) proclaimed that the polyliner in the design had decreased the impact of energy transfer between the kiwifruit and its surroundings in a forced air cooling conditions and Mukama et.al (2019) presented that pomegranate fruit wrapped in polyliner bag had taken longer time to cool than the fruit with no polyliner. Thus, indicating that polyliner bag can inhibit the transfer of heat as it impedes the flow of air. To check this phenomenon in a reefer condition with MBPs, two distinct packaging approaches were used in the experimental trials to test this occurrence. One with a conventional method of packaging using polyliner bags and another without polyliner packaging. With the pressure of time restriction of master’s thesis, the impact of polyliner was studied only in economical speed conditions. The standard polyliner bags were provided by Zespri International.

5.2.1.3 Different Modes of Standard Reefer Defraeye et al., (2016) has proved that conventional cooling of reefer containers (vertical airflow cooling) has a direct effect on the cooling rate of the product in packaging design. In modern reefers, integral refrigerated units operate at 2 different inlet airflows (section 4.2.4). Getahun et al., (2018) introduced testing of two different air flow modes of a reefer container for analyzing the packaging features for horticultural products. To get a better understanding with respect to the reefer airflow conditions on the kiwifruit MB packaging design, two different reefer conditions was selected with two modes as normal mode and economical mode in a standard reefer (section 4.3.4)

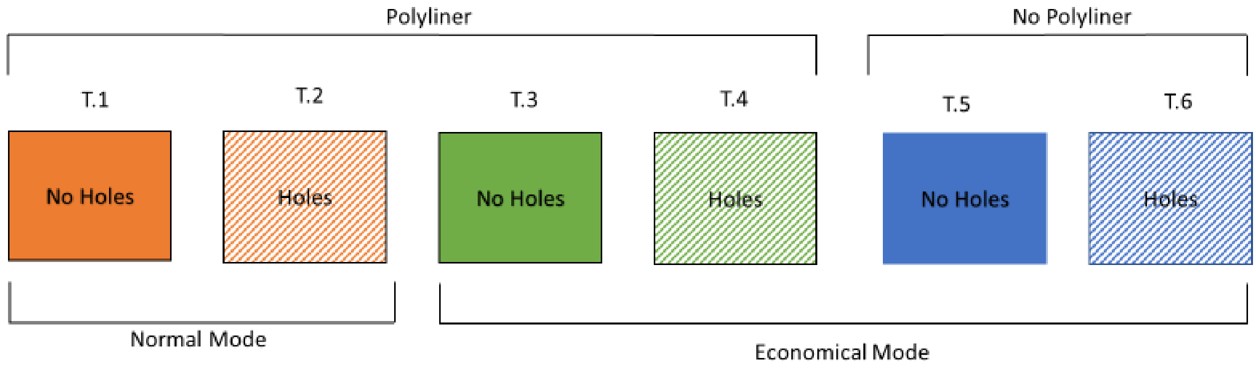
5.2.2 Experimental Trials

The experimental trials were structured using the above-mentioned variables. Study of the design parameters produced 6 experimental trials (T1-6; Figure 5-2):

- T1 is implemented on a box with polyliner bag, no base ventilation and normal mode of air flow and could be considered as representation of the current system.
- T2 was performed on a box with polyliner bag with base ventilation at a normal mode of airflow, testing the introduction of base ventilation to the current box.
- T3 was conducted on a box with polyliner bag, no base ventilation at an economical mode of airflow representing cooling rate of the current packaging at a lower air speed.
- T4 was conducted on a box comprising a polyliner bag and base ventilation at an economical mode.
- T5 was carried out on a box having no polyliner bag, no base ventilation at an economical mode enabling quantification of the effect of the polyliner on cooling.
- T6 was held with a box having no polyliner bag but with base ventilation at an economical mode.

Figure 5-2 :

Experimental Trials List



Note. Six (6) different experimental trials for studying and testing the cooling efficiency of the kiwifruit MB box with of 3 % base ventilation, polyliner bag packaging and different modes of a reefer in vertical air flow conditions.

5.2.3 Data Conversion

To improve existing cooling systems and provide optimum operation conditions, the primary objective is to produce usable and comparable data and technical information of the system. The comparison of the data can be done fairly using a dimensionless factor.

5.2.3.1 The Fractional Unaccomplished Temperature change A dimensionless factor to depict the temperature profile of a commodity is Fractional Uncompleted Temperature Change (FUTC). FUTC reflects the ratio between the change in temperature over time and the product's maximum possible temperature difference (Y. Hui & Sherkat, 2005). FUTC is computed for the individual product n using the Equ.5.1 below.

$$Y_{t,n} = \frac{T_{t,n} - T_{ref}}{T_{i,n} - T_{ref}} \tag{5.1}$$

Here $Y_{t,n}$ represents FUTC, $T_{t,n}$(K) and$T_{i,n}$(K) represents the temperature at a point n and initial point for the product n respectively. T_{ref}(K) is the control or reference temperature.

The FUTC of a product n begins at$Y_{t,n}$ = 1 and ends at 0.0 in a progressive cooling process. Characteristic time factors were observed in the continuous profile, i.e. half cooling point (HCP) and seven-eight cooling point (SECP), to acknowledge the cooling profile of the product over time. Such pivotal time factors help to differentiate the changes in a product's cooling profile when it is exposed to various techniques. Time taken to obtain HCP (Yt,n=0.5) is known as half cooling time (HCT). The average HCT value of a process is determined by computing the average FUTC of the group. Average FUTC of the group is attained by the following Equ.5.2

$$\bar{Y}_{X,t} = \sum_{i=1}^{m} Y_{X,t,i}/m \tag{5.2}$$

Here $\bar{Y}_{X,t}$ is the average FUTC value for the group of products. m is the total number of products in the group. For the present thesis, this specific time factor was used to analyze the effects of design parameters (section 5.2.1) during the experimental trials.

5.2.3.2 Statistical analysis (Logarithmic Transformation) A significant factor is the measure of influence that a parameter has on the data. A statistical study of data is important to determine the significant factor of a parameter. High significant factor of a parameter implies a considerable deviation in the data was due to the parameter. Low significance factor of a parameter implies there is a negligible deviation in the data.

The logarithmic transformation of data can be used where the standard deviation of data is proportional to its mean. In this transformation, the original data value t will be transformed into Log(t). If the data set has small values (less than 10) then the Log(t+1) transformation is used.

5.2.4 Experimental setup

A laboratory scale apparatus with a single column of 5 vertically aligned MB boxes was used for conducting the experimental trials. Measuring devices were installed in the apparatus as mentioned in the instrumentation section (section 4.3.5).

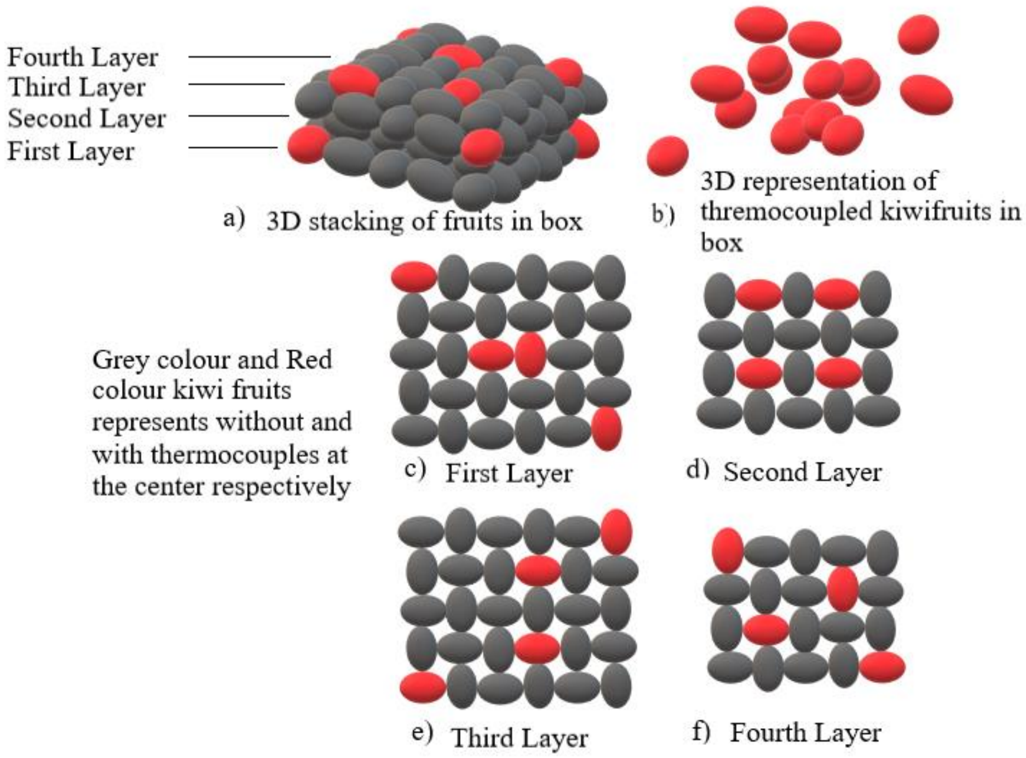
5.2.5 Fruit arrangement inside the box

For the experiments, count 36 kiwifruit artificial simulators were used. For count 36 size approximately 100-102 kiwifruit are loosely packed in a MB box commercially. For experimental consistency 100 simulators were stacked into each box.

Stacking patterns as detailed in Figure 5-3 was followed for the research. 16 simulators in each and every box were fitted with thermocouples. Simulators were drilled to their centroid and T-type thermocouples were inserted into drilled simulators and sealed using clay glue - these simulators will be referred to as thermocouple simulators. For all the boxes in the experiment, this packing sequence was followed to ensure that the location of the thermocouple simulator in every experimental trial was at identical locations. Each fruit was placed perpendicular to adjacent fruit. Thermocouple Simulators are represented in red and others are represented in grey. The first layer (Figure 5-3c) comprises of 30 fruits (5 rows and 6 columns). The second layer (Figure 5-3d) contains 20 fruits (4 rows and 5 columns). The third (Figure 5-3e) and fourth layers (Figure 5-3f) mimic the first and second layer respectively. Pressure pipes were glued to the inner wall of the top surface of the MB box to record the pressure readings inside the empty space of the box. The pressure sensors were placed in the same position on every box for each and every experimental trial. Simulators were incubated at 20°C or 25°C in a temperature-controlled room for at least 48 h prior to the experiment in order to bring the fruit to starting temperature.

Figure 5-3 :

The Repeatable Stacking Pattern of Simulators Used for All Experiments



Note. a) 3-D view of the stacking pattern b) 3-D representation of selected simulator to measure the temperature in the stack c) First layer (bottom layer) d) Second layer e) Third layer f) Fourth layer (top layer)

Figure 5-4 :

Experimental methodology for packing simulators

Note. a) Inserted T-type thermocouple simulators in MB box b) Sealing of polyline using the duct tape c) Final box representation.

5.2.6 Experimental trials

5.2.6.1 Commencement of Experiment Incubated simulators were placed in the MB boxes with the tested design parameters for the experimental trial along with required thermocouple simulators and pressure sensor pipe. The 5 packed boxes were stacked as a column on the base of the apparatus (according to footmark). The middle cabin was constructed by drawing out the thermocouple wires and pressure pipes from the boxes at the respective outlets. These outlets were sealed to create an airtight middle cabin. The top section was then placed on the constructed middle cabin and sealed using bungee cords (section 4.4). The variable speed drive was used to regulate the desired volumetric air flow for the experiment (refer Table 4.1).

Prior to the experiment, the temperature-controlled room (TCR) was operated at 0°C for a few weeks, so that the temperature inside TCR will be even all over the room. Immediately before the start of the experiment, the apparatus was placed into the TCR and the airflow velocity readings at the outlet were verified. As soon as the apparatus was set in the TCR and the airflow velocity of the apparatus was verified, time zero of the experiment was noted - the beginning of the experimental trial.

Before starting the experimental trials, pre experimental trials were conducted to understand the heat transfer conditions of present MB box design. During the pre - experimental trials, the experimental setup was left in TCR to run for 48- 60 hr.. These pre-experimental trials proved that after 44 hr. of starting the experiment either at 20°C or 25°C, the heat transfer between the product and air flow conditions had approached the equilibrium. By considering this condition the duration of experiment was decided as 45 hr. from the start of the experiment. Even though each experimental trial had run for more than 45 hr., but for data analysis only the first 45 hr. of the experiment was considered.

The air flow inside the apparatus was at the range of required experimental conditions. Economical flow and normal air flow required 2.5 and 4.8 m/s respectively at the outlet with a permissible variance of ±0.2 m/s. This condition was verified by the average velocity values (average of 5 readings) collected at the start and end of the experiment. The constant airflow conditions throughout the duration of the experiment was verified by observing the average pressure drop values between the base and top of the apparatus and were approved if there was a constant pressure drop throughout the duration of experiment. For Trial 1 and 3 due to the technical difficulties from the pressure sensor the pressure drop values were not collected.

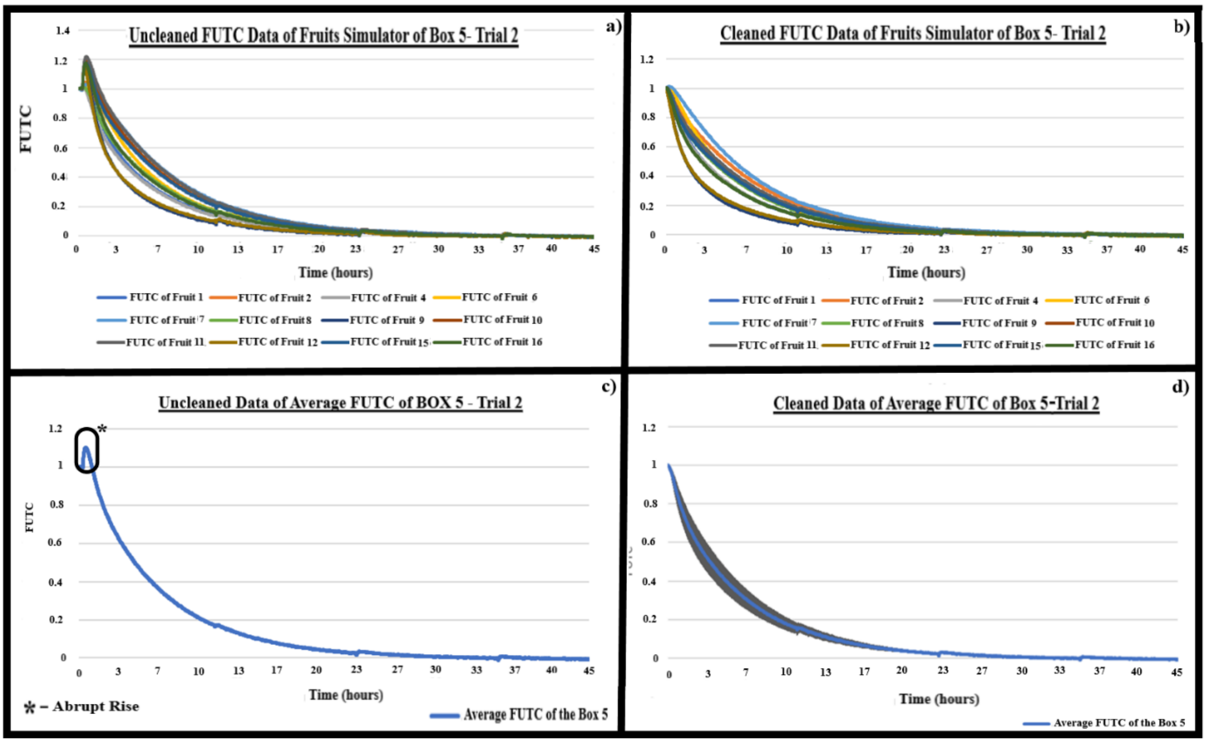
Temperature conditions inside the TCR were maintained at 0℃. TCR temperature conditions within each experimental trial was analyzed at the end of experiment by observing the 4 thermocouples which were installed around the apparatus to observe any anomaly conditions in the TCR, such as TCR failure or sudden rise or fall of temperature inside the TCR that might have occurred during the course of the experiment. 80 temperature data (16x 5) and 5 pressure sensor data were collected from the MB boxes from each experimented trial. This data was put through further processes such as data cleaning and statistical analysis to understand the effects of design parameters on packaging design.

5.2.6.2 Data cleaning When collecting large temperature data sets, it is not uncommon for a proportion of data to be lost due to errors or equipment malfunction. Some thermocouples did not report any data. In other cases, the temperature data showed anomalies such as very rapid cooling which is caused due to the thermocouple falling out of the simulator or unacceptable readings such as 90℃, 253℃ or 450℃ which are not possible during this experiment. On average 4 thermocouples (25%) out of 16 thermocouple readings from each box were removed from the data due to the issues identified above. Before every experiment, broken wires were identified and repaired, and care was taken in sealing the thermocouple within the fruit. However, these data problems remained throughout the trials. Due to these issues the raw data required preliminary data cleaning.

Due to a technical disturbance in the loggers an abrupt rise in the temperature was observed at the beginning of the experiment in one of the trials (T2) as shown in Figure 5.5 a and c. To remove this anomaly, the first 15 minutes of experimental data was discarded. The next 45 hr. data was used for data analysis. Despite the fact that the recorded peak (during the first 15 min) was discarded, the rest of the data collected for the experimental trial was within the expected temperature range.

Figure 5-5*:*

Example Data of Box 5 Trial- 2 for Comparison of Cleaned and Uncleaned Data Due to Logger Anomaly

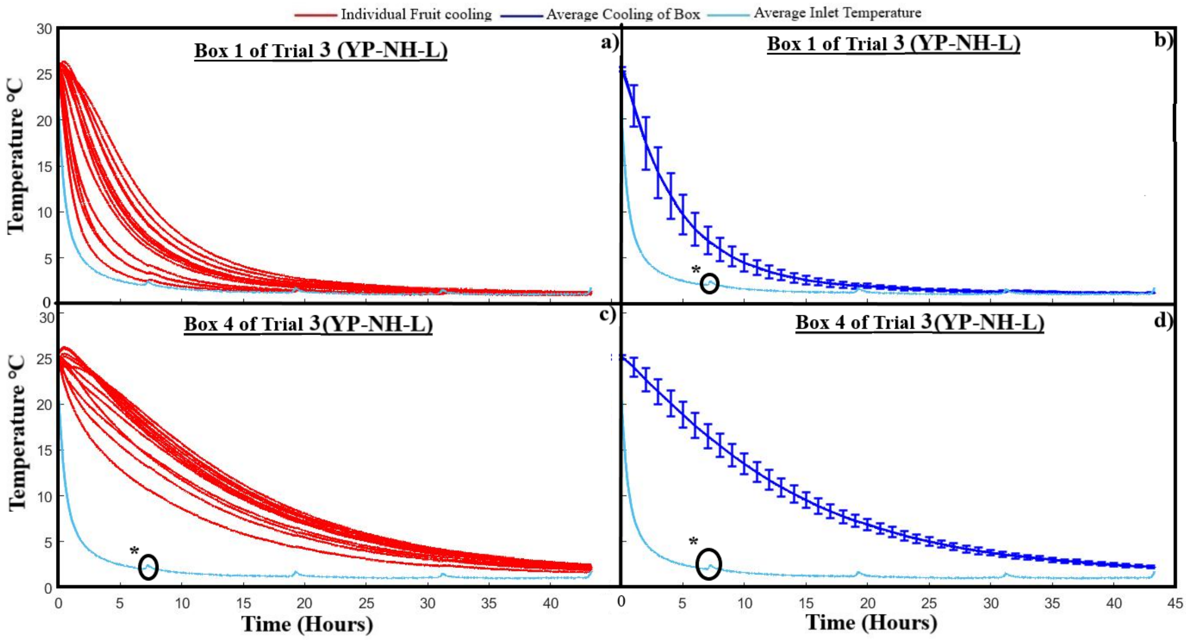


Note: Displaying the cleaned data vs uncleaned data for the fruit FUTC data and the average FUTC data of box 5 of trial 2. a) uncleaned FUTC of the fruit simulators of box 5 trial 2 b) cleaned FUTC data of fruit simulator of box 5 trial 2 c) uncleaned data of average FUTC of box 5 trial 2 d) cleaned data of average FUTC of box 5 trial 2. '*' represented the abrupt peak created from logger technical anomaly.

5.2.6.3 Data summary The cooling profile of a box was displayed as the average of the box, by computing the mean value of all the simulator's cooling data in the box (Figure 5-5).

Figure 5-6 :

Example Data for Box 1 and 4 of Experimental Trial 3



Note. Describing variance in the box data and its transformation of data representing mean value of the box with errors bars.'*' indicates defrost cycle. a) Individual thermocouple data in box 1 of experimental Trial 3 b) Mean value of the box 1 of experimental Trial 3 c) Individual thermocouple data of box 4 of experimental Trial 3 d) Mean value of the box 4 of experimental Trial 3.

The 95% confidence interval error bars for the box were calculated and presented in the results to display the range of variance within the box. The error bars were calculated using the standard deviation and mean of every individual point and substituting in the Equ 5.3 below.

$$E = \bar{X} \pm Z \frac{S}{\sqrt{n_o}} \quad (5.3)$$

where, E represents error bar, $\bar{X}$ represents mean value of the box, s represents standard deviation of the box, n_o represents number of observations and z represents the confidence interval coefficient. Confidence interval coefficient for 95% confidence interval is 1.96.

To fairly compare and evaluate the cooling curves of different experimental trials data, each and every temperature reading of a thermocouple simulator was converted to Fractional Unaccomplished Temperature Change (FUTC) individually. The raw temperature data was converted using the time zero's of respective simulators data points as the initial temperature of the simulator and the mean inlet air temperature from the duration of the each experimental trial as the reference temperature. FUTC data of a box was considered as the mean FUTC value of the individual simulators in the box. The FUTC variance of the box was displayed by error bars at every point (every minute data) with 95% confidence interval.

The Half Cooling Time (HCT) of a box was determined from the average FUTC of each fruit simulator value in the box. In order to convert the trial data (using fruit simulators) to equivalent cooling times (for real fruit), the simulator's HCT values were transformed into estimated HCT for real kiwifruit by multiplying by 2.450 (Section 3.1) along with error bars.

5.2.6.4 Statistical analysis with ANOVA The HCT values were primarily used to analyze the effect of box design on cooling performance. An ANOVA was used to determine if the measured mean HCT was statistically significantly different.

An assumption for an ANOVA test is that the data exhibits homoscedasticity (i.e. each population has a similar standard deviation). If the data exhibits heteroscedasticity (i.e. substantially different standard deviations), then the ANOVA analysis is not valid. For this work, there is a large range in average HCT from 1.8 to 12 h. This 1 log scale difference in the HCT suggests that it is highly likely that heteroscedasticity exists in the data set.

To resolve heteroscedasticity problems, with the given log scale change, a logarithmic transformation technique was applied to the data to remove the heteroscedasticity. When the data set has small numerical values (e.g. < 10) then the log(t+1) transformation can be more appropriate, and hence this transformation was conducted in this case. The resulting data proved successful in removing the heteroscedasticity from the data.

A multifactorial ANOVA analysis was used on the transformed data to test the significance as influenced by the packaging format (T1-6) or box position (height 1-5). Fruit position (1-16) was included as an ANOVA factor to account for the variance influenced by position of the measured fruit within the box. Tukey's test was applied to determine significant differences between means at $p < 0.05$.

5.3 Results and Discussions

5.3.1 Pressure values of the Trials

During the course of the experimental trials, from the collected pressure readings, average pressure readings for the base, respective boxes and top of the apparatus for each trial was calculated. As the weather and temperature can influence the real time pressure readings, the pressure drop across the boxes was calculated with respect to the base of the apparatus and is presented in the Table 5-1. Due to logger technical difficulties, the data is not complete.

Table 5-1:

Pressure drop readings of the experimental trials at inside the box, top of apparatus and base of the apparatus

Experimental trials	Box 1 (Pa)	Box 2 (Pa)	Box 3 (Pa)	Box 4 (Pa)	Box 5 (Pa)	Top (Pa)
1	-	-	-	-	-	-
2	45.7	49.7	89.3	64.9	74.3	72.9
3	-	-	-	-	-	-
4	26.4	-	31.8	-	43.6	37.4
5	15.4	-	17.3	12.0	26.4	22.1
6	22.0	7.9	8.5	10.8	22.4	13.2

Note: Described pressure drop values are the difference between the mean pressure values from the base of the apparatus and the respective pressures sensor positions collected throughout the duration of the experiment. Precision of the pressure sensor was 3.3 Pa.

The pressure drop readings state that the pressure drop change was observed over the column of boxes and at the top of the apparatus with respect to the change of either packaging design variables (introduction of vertical ventilation and removal of polyliner from packaging) or reefer variable. The pressure drop changes from the trial presents were as follows:

- Trial 2 v 4 represents data for normal v economical flow with base ventilation for the box design. This result shows a significant pressure drop from 73 Pa to 37 Pa at the top of the apparatus, and significant pressure drops on all the recorded boxes, with a maximum pressure drop which was observed in the middle box (box 3) of a value of 57 Pa.

- Trial 4 v 6 demonstrates the effect of polyliner vs no polyliner (with base ventilation), this exhibited a pressure drop change from 37 Pa to 13 Pa at the top of the apparatus. A slight variation in the pressure drop values are observed on the record boxes with the highest-pressure drop displayed in middle box with a pressure drop of 23 Pa.
- Trial 5 v 6 exhibits the effect of introduction of vertical ventilation without a polyliner in the packaging design at reefer conditioned at economical flow. Which demonstrated the smallest pressure drop across the stack of boxes with 22 Pa to 13 Pa. Very minimal variance was observed in the pressure drop values in this scenario with the greatest pressure drop variance observed in the middle box with a value of 8.7 Pa.

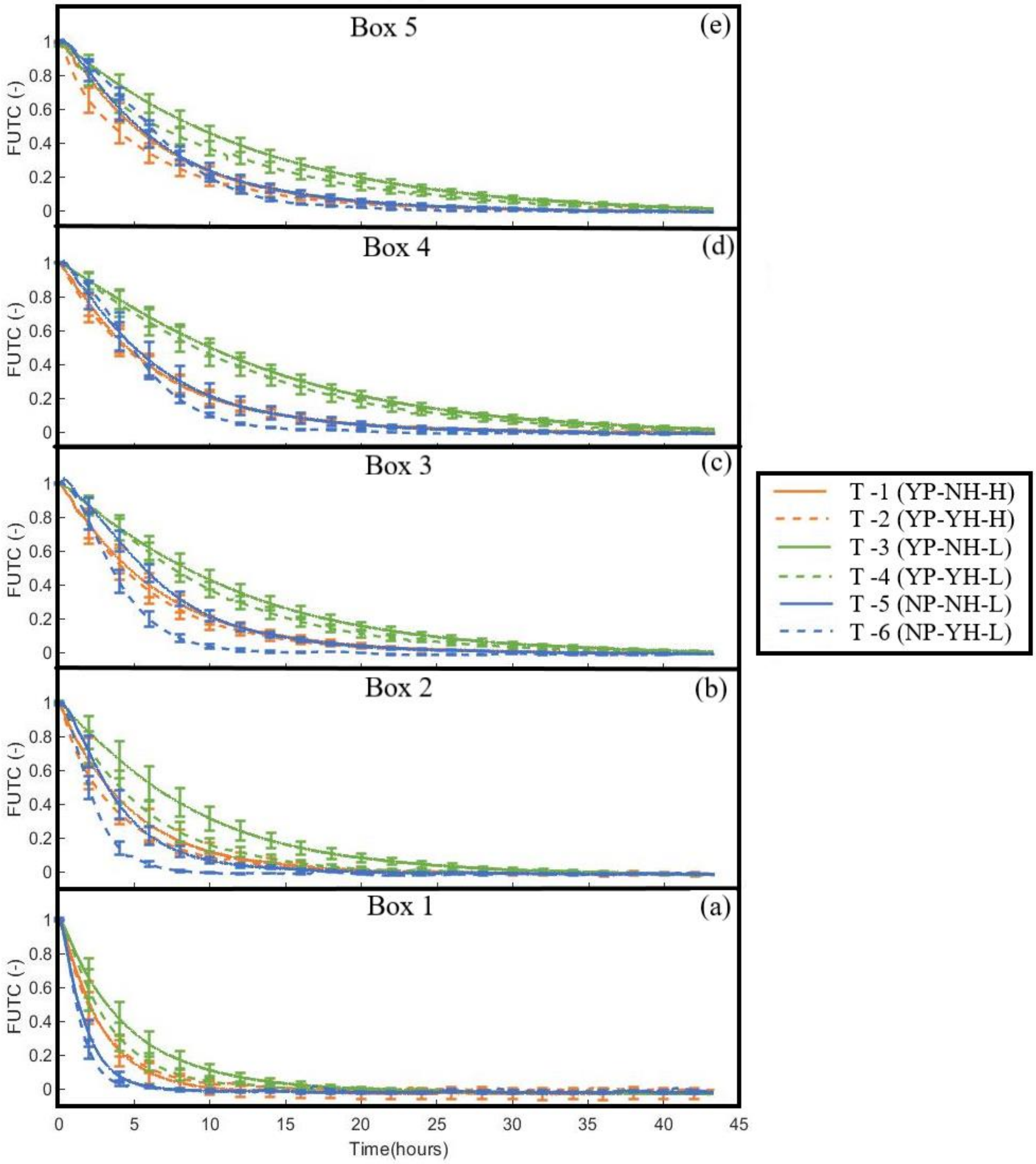
Thus, results demonstrate that with the reduction of resistance and barrier to the airflow and its direction can reduce the pressure drop within the packaging. In all conditions, the box 5 resulted in higher pressure drop than the headspace of the apparatus. In economical flow, box 5 resulted in higher pressure drop across the boxes, which states that the headspace air movement added substantial impact on the pressure readings for box 5, thus creating a constant trend with slightly increased pressure values.

5.3.2 Cooling rate of fruit

With the temperature data collected over the experimental trials, the results allowed to produce 30 mean HCT (6 experimental trials and 5 box positions) and was displayed as a line graph in Figure 5-6.

Figure 5-7 :

FUTC curves for vertical stacked column of 5 boxes



Note. Lines are averaged FUTC values of box with ± 95% confidence interval. YP= with polyliner; NP= without polyliner; YH= with holes; NH= without holes; H= Normal mode (75 rev/hr); L= economical mode (36 rev/hr); a) Box 1 b) Box 2. c)Box 3. d)Box 4. e) Box 5.

As TadhgBrosnanDa (2001) published, a similar rate of cooling was observed with the product inside the packaging as that is followed by a logarithmic function with initial rapid cooling accompanied by a slower and slower rate of cooling of the product.

Box 1 displayed the most steep drop in temperatures in every trial, as box 1 is the first box to encounter the inlet air flow. This second most steep decline in temperature was for box 2. However, the cooling curves for boxes 3, 4 and 5 are relatively similar to each other. Out of boxes 3, 4 and 5, box 5 showed less variance in cooling rate with respect to experiment trials.

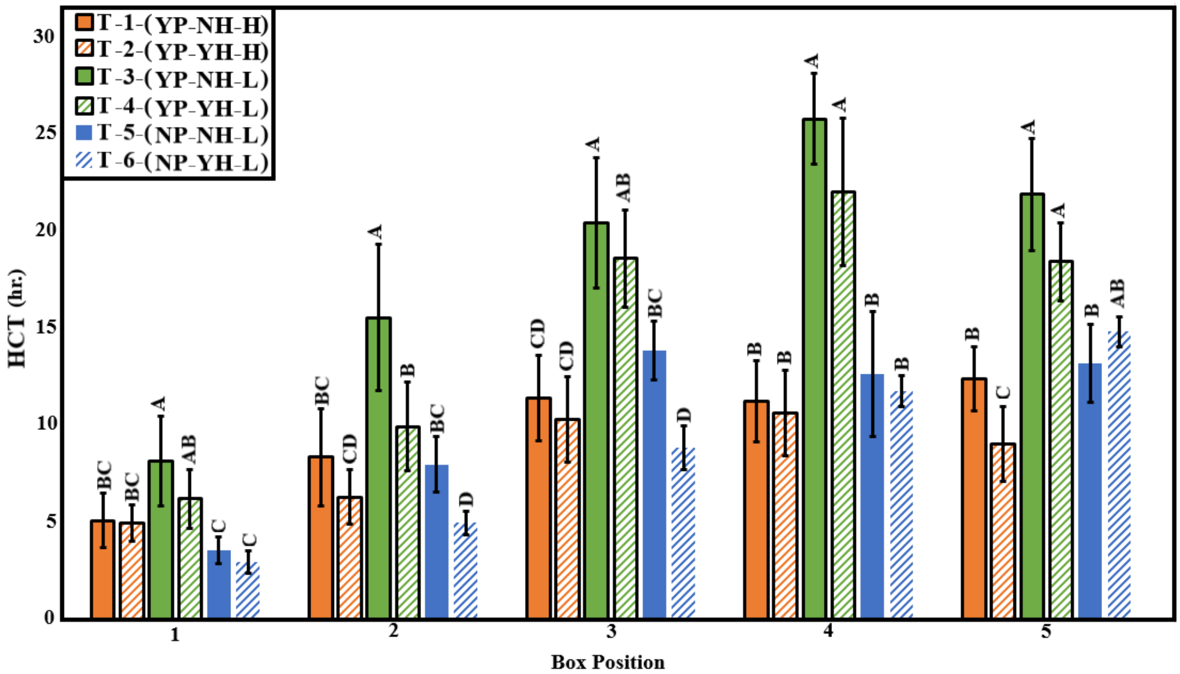
In all boxes, Trial 3 exhibited the highest FUTC values followed by Trial 4 with the present MBP and economical mode condition. For Trial 3 and 4, the boxes 3 and 4 displayed a similar FUTC curve with 95% confidence interval bars coinciding at most of the points. Trial 5 and 6 demonstrated the effect of removal of polyliner, which can be seen through the nature of FUTC curves with a potentially increased air movement through the box. When comparing the FUTC curves of Trials 1 and 5, except box 1 all other boxes showed significantly similar curves throughout the duration of cooling with maximum curve lines similar, within the error bar range of both curves.

In order to understand the results more accurately, the HCT results were analyzed and plotted in two ways in order to enable comparisons and discussions:

- Grouped by box position (Figure 5-7)
- Grouped by design (Figure 5-8)

Figure 5-8 :

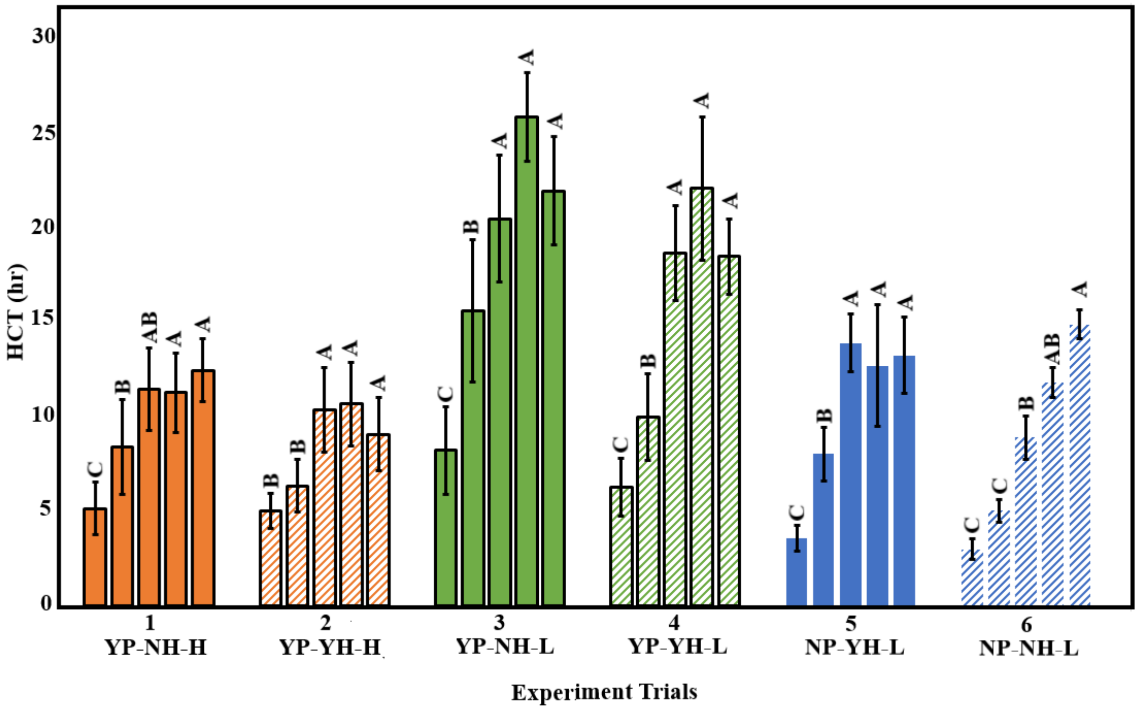
Average Half Cooling Time (HCT) Grouped by Box Position



Note. Average HCT time for fruit in a vertical stack of 5 boxes influenced the base ventilation in MB-boxes; existence of a polyliner; and volumetric airflow conditions. Data has been converted from that observed for the simulators to values representing real kiwifruit (section 3.2.3). Error bars represent 95% confidence intervals from the transformed kiwifruit measurements taken within each box. Letters indicating statistical significance ($p < 0.05$, Tukey's test) apply only for within each box comparison. Refer to Figure 3-8 for comparisons between box layers of the same data. Solid fill = no holes, dash fill = holes; solid border = polyliner; no border = no polyliner; orange = Normal mode (75 rev/hr.); green and blue = Economical mode (36 rev/hr.)

Figure 5-9 :

Average Half Cooling Time (HCT) Grouped by Trial



Note. Average HCT time for fruit in a vertical stack of 5 boxes as influenced the base ventilation in a Mb box; existence of a polyliner; and volumetric airflow conditions as in standard reefer conditions. Error bars represent 95% confidence intervals from the transformed kiwifruit measurements taken within each box. Letters indicating statistical significance ($p < 0.05$). Bars that do not share a letter are significantly different as determined by Tukey's test. Solid fill = no holes, dash fill = holes; solid border = polyliner; no border = no polyliner; orange = Normal mode (75 rev/hr.); green and blue = Economical mode (36 rev/hr.)

5.3.2.1 Base ventilation The effect of base ventilation was studied in three different scenarios

- Normal speed with a polyliner (Trial 1 v 2)

- Economic speed with a polyliner (Trial 3 v 4) and
- Economic speed without a polyliner (Trial 5 v 6).

For normal speed and with a polyliner (trial 1 v 2), only box 5 resulted in a substantial decrease (27%) of HCT (Figure 3-7). At economic speed with polyliner packaging (trial 3 v 4), only box 2 showed significant reduction in the HCT values with a 36% reduction (Figure 3-7). Even though only box 2 displayed significant effect, the same scenario can be assumed to be happening in box 1, as the impact on it was obscured by forced airflow conditions created by experimental conditions. At economic speed and without a polyliner packaging, the effect of base ventilation was extended up to box 3 with a significant drop of 37 % and 36 % HCT values for box 2 and box 3 respectively.

The introduction of vertical ventilation to the present MBP at economical airflow condition significantly increased the airflow movement in only box 2 which resulted in more convection through the fruit and also helped in increasing the conduction process inside the fruit in the packaging which can be observed by analyzing the results from Trial 3 v 4. As the bottom box or boxes near the inlet of a reefer condition gets maximum cooled air flow condition (Tanner and Amos 2003). The box 1's improvement with respect to box design has not shown any statistical significant effect in the cooling efficiency of the design, Thus states that vertical ventilation has not increased the air movement within the packaging of base box (box 1). At normal flow, the introduction of base ventilation has not shown significant changes in altering the heat transfer process i.e. convection or conduction to improve the cooling rate of fruit inside the packaging. Which declares that at normal mode, the air exchange rate within the stack of boxes cannot be altered by introduction of vertical ventilation to the design

Even though Defraeye et al., (2015a, 2015b) showed that introduction of vent holes and altering the present packaging design to facilitate the vertical airflow condition of the reefer container can improve the cooling efficiency of the box design. Getahun et al. (2017) had noticed reduction in the cooling time of apple packaging by 37% and lowered the airflow resistance by 75% with the introduction of bottom vents to the packaging in reefer condition. Wu et al., (2019) had observed uniform distribution of cooling air through the package with the coordination of top and bottom ventilation in the design in a vertical air flow reefer transport condition. However, the introduction of vertical ventilation in a kiwifruit MBP by providing 3% base ventilation to the design has not shown a significant drop in the cooling efficiency of the box design across the column of boxes in a reefer condition.

5.3.2.2 Polyliner The effect of polyliner was studied in two different scenarios

- Economic speed without holes in the boxes (Trial 3 v 5) and
- Economic speed with holes in the boxes (Trial 4 v 6).

The removal of the polyliner from the present MBP at economical speed (Trial 3 v 5) resulted in lowering the HCT values for all boxes varying from 32 % - 56 %. When the MB boxes had holes (Trial 4 v 6), eliminating the polyliner resulted in further lowering the HCT values for boxes 1 to 4 ranging between 46% - 52 % and removal of the polyliner resulted in the greatest and smallest significant reductions in HCT values at box 1 and 3 respectively. With the removal of polyliner, even the base box (box1) resulted in drop of HCT values in the stack and removal of the polyliner decreased the resistance of the vertical airflow through the stack by reducing the pressure drop values across the stack of boxes (section 5.3.1). This proves that removal of polyliner had resulted in more air movement within the boxes and promoted heat transfer from the fruit by increasing the convection and conduction rates of the product. Which inturn reduced the HCT values of all boxes in the stack. Similar results had been stated by O'Sullivan et al., (2016) that exclusion of the polyliner enables the air to flow through the box rather than prompting the temperature change to persist by conduction or natural convection within the polyliner space.

The non-perforated polyliner packaging yields the highest Relative Humidity (RH) and reduces the moisture loss within the product with high condensation (locks maximum water vapor inside the packaging) (Delele et al. 2013c). But polyliner bags can restrict the cooling conditions of a box in the refrigerated container (Jedermann et al. 2014). Likewise, presence of polyliner in the MBP design restricted airflow with packaging and obstructed the heat transfer between the kiwifruit and kiwifruit surroundings.

5.3.2.3 Effect of Air Speed The effect of different reefer airflow conditions was studied in two different scenarios

- With a polyliner and no holes- base model (Trial 1 v 3)
- With a polyliner and holes- base model with vertical ventilation (Trial 2 v 4).

With the present MBP (1 v 3), the change in the airflow modes from economical to normal mode had resulted in the reduction of HCT values in all boxes ranging from 37% - 56%. The introduction of base ventilation to the present MBP (Trial 2 v 4) also resulted in similar results with the reduction of HCT values in all boxes by 36% - 51%. Box 4 and 1 illustrated the largest and smallest reductions respectively within the stack.

The normal airflow condition created a higher airflow rate inside the box packaging, which had also been observed with the pressure drop values between trial 2 v 4. Thus, higher exchange rate of airflow through the box resulted in higher heat transfer mechanisms within the product in the packaging. Which resulted in reduction of HCT values of the boxes. Box 1 resulted in the lowest HCT values as it got maximum airflow within the stack in both airflow modes. This occurred as the airflow generated had traveled bottom to top, meaning the base box (Box 1) receives the impact first and to the maximum extent as compared to the other boxes. Major change was observed in box 4 which showed highest variance of heat transfer mechanism in both examples, as the influence of changing from economical mode to normal mode can affect the cooling efficiency and air exchange rates with the top boxes of the stack

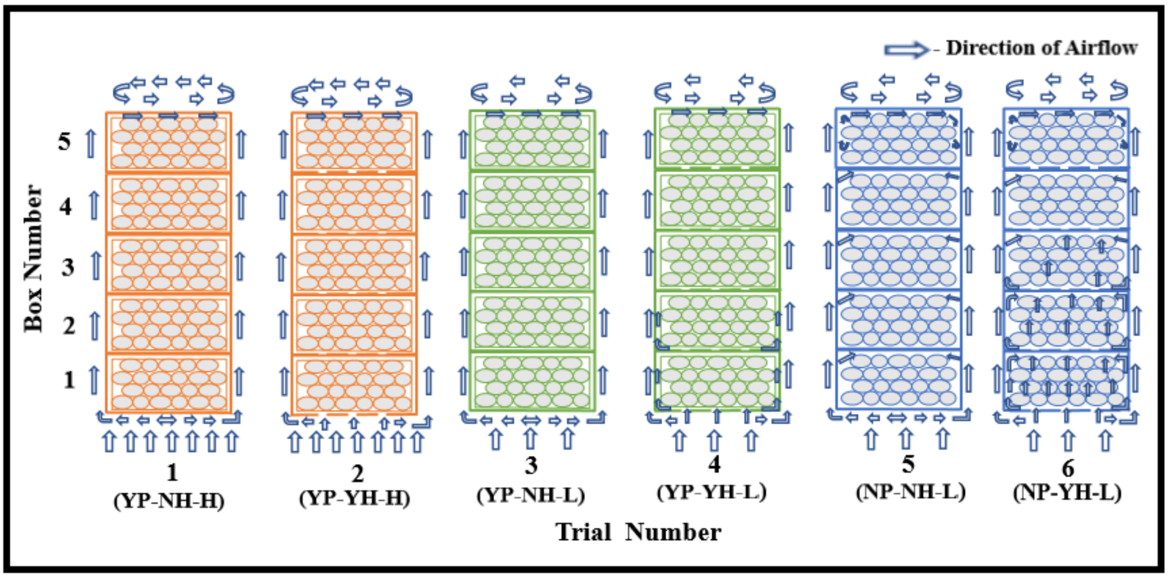
An interesting observation was made when comparing Trial 1 (the current box design with polyliner at normal speed) v Trial 5 (the current box design without polyliner at economic speed). Similar HCT values were observed in every box position in comparing these two sets of data (Figure 5-7 and Figure 5-8) and similar cooling curves in most of the boxes were observed in the FUTC results (Figure5-6). This result asserts that with the removal of polyliner bags from the packaging, economical flow conditions could be used to get similar temperature control in the packaging as polylined MBP in normal mode. This states that removal of polyliner from the packaging in MBP can reduce a significant amount of workload for the refrigeration unit for maintaining the cooling conditions of packaging in a reefer condition. But with the present technology, removal of polyliner from a kiwifruit packaging is not possible. Although investing the time and resource in altering the existence of polyliner bags from the MBP by creating a replacement solution for present polyliner design in the packaging can be a potential benefit for the kiwifruit industry.

5.3.2.4 Position of box The cooling efficiency of the MBP with respect to position of boxes can be clearly understood by observing Figure 5-9. Box 1 was the stack's fastest cooling box because it received the highest airflow condition in every experimental condition. Thus, irrespective of the packaging condition in every reefer condition (vertical airflow condition), the base box receives maximum airflow which encourages maximum heat transfer mechanism over the stack. At economical flow (Trial 3v4, 3v5, 4v6) box 2 showed significant cooling changes with respect to the packaging designs (base ventilation and existence of polyliner). Box 3 and 4 showed significant change in the heat transfer mechanism within the boxes only after the removal of polyliner from the design (Trial 3v5 and 4v6). At economical mode Box 5 had only shown a noticeable drop in HCT values in Trial 3 v 5, as introduction of base ventilation to the polyliner scenario (Trial 4v6), had created miscellaneous results in box 5. The combination of two factors (base ventilation and not having a polyliner, (Trial 6)), resulted in a different trend for the top 3 boxes when compared to all other experimental trials. Thus, the removal of polyliner and addition of base vents reduced the resistance inside the middle box and increased its cooling efficiency.

When comparing box 4 with box 5, although the boxes did not show a significant change in the cooling rate, there is a tendency for the 5th box to cool faster than the 4th, especially at economical mode at present MBP. This may be the result of a combination of top MBP surface and headspace of the apparatus, which can create potential addition for a convective heat transfer between the packaging top surface and the inner surroundings of the apparatus (headspace) and that can be found absent in box 4. However, this effect was not displayed in normal mode condition. The potential physical mechanism of the conducted experimental trials is represented in Figure 5-9 below.

Figure 5-10

Schematic of the Potential Physical Mechanism in Each of the Trial



Note. Describing the airflow direction and intensity over the stack of boxes for conducted experimental trials. Number of arrows representing the direction of flow gives the intensity of airflow flow.

For a full pallet height (10 box height) of MBP at normal mode reefer conditions, introduction of base ventilation to promote vertical ventilation will not create significant improvement of the cooling efficiency of the box design in the stack. At economical reefer condition, introduction of base ventilation can noticeably affect the cooling efficiency only on the base boxes of the stack. At economical flow, the removal of polyliner form the design can create a momentous change throughout the height of the stack with respect to heat transfer mechanism of the packaging design.

5.4 Conclusions

Experimental trials were carried out to understand and improve the present design of MBP with respect to vertical airflow conditions of a refrigeration container. To enhance the cooling efficiency of the box design, packaging design parameters i.e. introduction of base ventilation to enhance vertical airflow through the packaging and presence of polyliner bags in the design was studied in different air flow modes of a modern reefer. The results are as follows:

- The introduction of base ventilation did not create a significant effect on the cooling efficiency of the box design at the normal mode airflow reefer condition.
- At economical mode, the noticeable effect of base ventilation can be seen at the base box (box 2) of the stack.
- Removal of polyliner for the packaging design resulted in a remarkable drop in the HCT values of all the boxes at economical flow by increasing the cooling efficiency of box design to appreciable level. The combination of both packaging design parameters had resulted in an impressive change in cooling efficiency of the center box (box 3) of the stack.
- With the present MBP, the removal of polyliner from the design at economical mode can create similar heat transfer mechanism with boxes as packaging design with polyliner at normal mode of a reefer condition.
- Box 1 has the fastest cooling box of the stack in all experimental conditions. With the present MBP, Top box (box 5) displayed an additional heat transfer mechanism (convection between top surface of box and headspace of the apparatus) at economical mode, where this effect had been compromised in other boxes because of the stacking pattern in the stack.

The present design of the kiwifruit is a polylined MBP, the introduction of base ventilation to enhance the effects of vertical ventilation of reefer condition will not produce significant improvement in the cooling efficiency of the boxes through the column of the stack.

6 Discussion

6.1 Summary of Research Work

In order to understand the potential effects of introducing vertical ventilation on kiwifruit packaging in reefer conditions, a laboratory scale apparatus was designed. Two columns of kiwifruit MB boxes with different pallet orientations by creating similar airflow conditions as that of a reefer container. A single column of 5 MB boxes (half pallet height) was tested with different designs with similar airflow conditions as the reefer container.

Prominent features of the constructed experimental setup designed were:

1. Small scaled apparatus with realistic conditions of refrigerated containers.
2. Adjustable volumetric air flow.
3. Measuring devices to study the temperature profile of the product inside the packaging.

The cooling efficiency of the MB packaging designs were studied using the thermal profile of the product with respect to time. Along with the vertical venting, the effect of using polyliner bags and different air flow modes of a reefer were also studied. In place of real fruit, artificial kiwifruit was used to reduce random errors in the experiment. To ensure comparison of data between the experimental trials, temperatures were converted into dimensionless numbers using Fractional Unaccomplished Temperature Change (FUTC) and Half Cooling Time (HCT).

6.2 Challenges During the Project

When the project started defining the constraints for designing the apparatus to replicate the working conditions of a reefer container was required. When selecting a fan, the volumetric flow rate of the air into the system was determined from the total volumetric flow into the reefer container. However, the pressure drops for the container condition (tightly packed pallets of boxes) are not defined. Getahun et al. (2017a) previously provided information about pressure drop for a packed pallet at similar volumetric rates. However, the pressure drop for a polylined packaging system might be different to non- polylined packaging because of the resistance created by the polyline bags.

During the temperature measurement experiments, wired T-type thermocouple sensors, because of tangled and fragile nature resulted in difficulties during the experiment and caused an undeniable data loss (25%) in the results. Technical issues occurred with the pressure sensors leading to loss of data. The presence of that data would have provided additional valuable information to the experimental results

The pressure sensors on the head of the apparatus provided little to no data to analyze the movement of air at the headspace of the apparatus. If the number of pressure sensors were increased at the head of apparatus, that would have provided a better picture for understanding superficial velocity at the headspace of the apparatus, which might have been helpful for analyzing the cooling factors for the top box.

6.3 Project Findings

The primary objective of this project is to analyze different packaging design as it affects vertical ventilation in vertical air flow conditions of a reefer. The kiwifruit industry has vested interest in marine transportation to maximize the utilization of present working conditions. Similar studies were done to understand the air flow pattern around horticultural packaging in including for papaya (Rohani et al., 2005) to citrus (Tauriello et al., 2015) to apple (Getahun et al., 2017a, 2017b). Improvement can be done through either developing packaging design (Berry et al., 2017; Getahun et al., 2017b) or improving marine transportation operations (Dittmer et al., 2012; Jedermann et al., 2010; Lin et al., 2016).

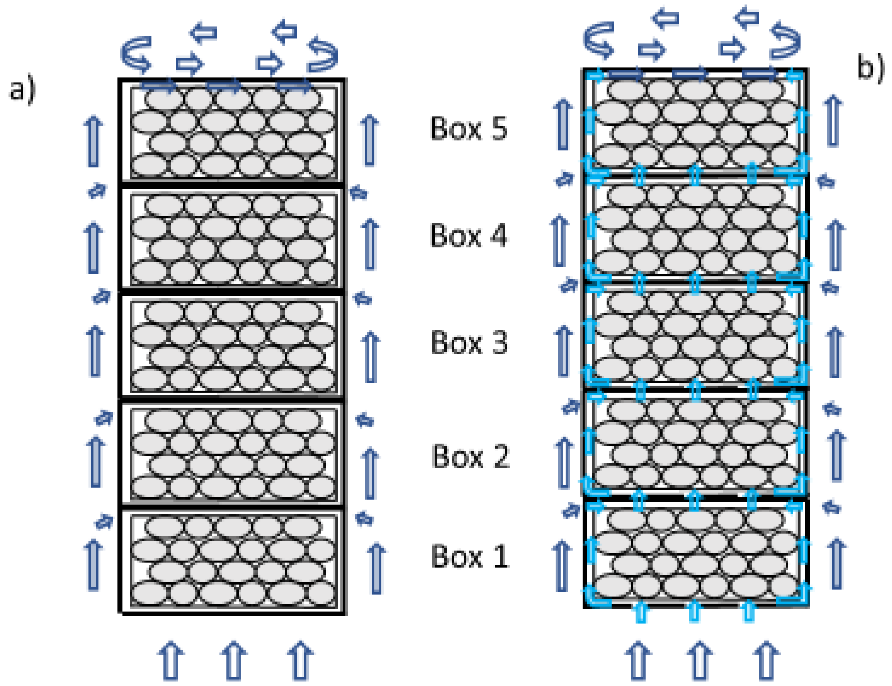
In reefer conditions, the combination of central openings at bottom and top of the packaging may result in a channel of cold air through the vertical ventilation, which in turn facilitates cooling in the packaging (Wu et al., 2019). This work explored the potential of vertical venting in polylined kiwifruit packaging designs in reefer conditions. For polylined horticultural produce, the reported optimal vent ratio is low, ranging from 2.5% (Singh et al., 2003) to 5% (Aswaney, 2007 cited in O'Sullivan (2016)). In this work only one vent design of 3% base ventilation was explored.

In analyzing the cooling efficiency of a packaging design, the results can be seen using dimensionless factors such as Half Cooling Time (HCT). The location of the box in the column can influence the effect of design parameters on the cooling efficiency of the box. Thus, HCT values was used to not only understand the experimental design parameters but also observed with respect to the box position. The primary cooling of the box was seen at the base box as the impact of newly entered air take place at the base box of the pallet and the effect continues towards the top.

The base ventilation was introduced into the design which created 3% of vertical vent area (with 4 circular vents with 0.75% vent ratio each) for the present kiwifruit MB box packaging. With the base vents, influence of vertical air into the box was expected (Figure 6-1.)

Figure 6-1 :

Expected Airflow Pattern Inside the Polylined Kiwifruit MBP



Note. a) without the base ventilation b) with base ventilation and expected added airflow was mentioned with light blue color.

While simulating the economical flow conditions, this study found that the introduction of base ventilation to the polylined kiwifruit packaging had only brought a significant drop in the HCT value for Box 2 (36% reduction) (Figure 5.-7). For box 1 there was no significant reduction in HCT, but the impact was considered as a consequence of forced air cooling on box 1 which gets maximum air flow as it was the base box in the setup. Removing polyliner variable to the present scenario only extended the effect of base ventilation up to box 3 with box 2 (37%) and box 3's (36%) displayed reduction in their HCT values. The reduction in the HCT values are occurred due to increase in the convective and conductive heat transfer from the fruit which was a direct result of increasing of air exchange rate created from the design variables in the experimental trials. but the impact of vertical ventilation had failed to occur until the top of the column.

In normal flow mode, base ventilation resulted in a substantial decrease in HCT of box 5 (26%) with no effect on the base boxes. With the introduction of the base ventilation to the design may have created different conditions over the headspace of the apparatus, which may have altered the air around the box 5. However, this condition cannot be concluded due to inconclusive evidence from the experimental results. To understand the cause of this phenomenon future researchers should analyze this condition with more focused objectives with respect to the headspace of the container.

The effect of vertical ventilation across the column of boxes may well have obstructed by the polyliner packaging of a box or by the fruit arrangement inside the box or may be by both. The removal of the polyliner from the packaging extended the effect of base ventilation to a certain level but the effects were not so significant as to affect the whole length of the column

The removal of the polyliner from the packaging resulted in reducing the HCT values of boxes by 32 – 56 % and pressure readings (Table 5-1) suggesting that the polyliner creates a barrier to the airflow in vertical direction, restricting ability to improve in the cooling efficiency through box design. This barrier to the heat transfer has also been observed in a horizontal pre-cooling experiment conducted by O’Sullivan et al. (2017) on the same packaging. This work demonstrates that the removal of polyliner from the packaging can create similar HCT results for the boxes in economical reefer flow conditions as in with polyliner packaging in normal reefer air flow conditions. Practically speaking, the removal of the polyliner from the packaging can lead to moisture loss from the fruit, degrading the value of the fruit. But the resistance created from the polylined packaging obstructs the air flow and heat transfer mechanism in the packaging. Therefore, while polyliner packaging exists in kiwifruit exports, exploring the conditions of vertical ventilation may not be fruitful.

Adding vertical ventilation with having removed the polyliner slightly reduced the HCT values even more (46-52%). The smallest and largest variations were observed in the middle and base boxes of the column. This with removal of the polyliner from the packaging, addition of vertical ventilation can enhance the heat transfer mechanism of the product inside the packaging by improving the cooling efficiency of the box.

Hence, with the present design of kiwifruit MB polylined packaging, the introduction of base ventilation is unlikely to improve the cooling conditions significantly in the vertical airflow reefer conditions.

6.4 Recommendations and Conclusion

However, general recommendations from this project can be implemented to enhance the cooling efficiency of polylined horticultural products. Alternate packaging configuration of polylined horticultural products in reefer conditions can be studied through experimental setups, numerical models or by different research methods.

Exploration of different ventilation sizes, locations and patterns will be possible by using the primary experimentation data and conducting the experiment in a more detailed manner without any time constraints. This would lead to better indices to help understand the MBP’s in reefer conditions.

6.4.1 Designing an apparatus model for packaging in reefer conditions.

The constraints for a laboratory scale reefer container apparatus was defined in this project, which can be used to recreate similar type apparatus as per research requirement.

This structure can be modified to collect real-time data and test different kinds of packaging technology designs for reefer transport system conditions. For a closed system (i.e. reefer container), a constant air renewal system can create consistent environmental conditions for different experimental trials. The researcher should be cautious of getting lower flow rates with high-pressure while working with packaging systems of polylined goods relative to the conventional packaging system of non-polylined products. The tricky part for the research would be to achieve the required flow rate for a polylined product.

For studying the effects on polylined horticultural packaging design using a heat transfer mechanism, the contribution of radiation, evaporative cooling and heat of respiration can be considered as negligible as most of heat transfer in the system would be either convection or conduction or both. Usage of artificial fruits in place of real fruits can help in minimizing errors of real-time experiments.

The sources of experimental uncertainty can be minimized by fewer wires, particularly those wires that make some slight volumetric air flow rate into the polyliner and those that block airflow ways between MBPs.

6.4.2 Improving the cooling performance of polylined horticultural produce in reefer conditions.

A laboratory scaled experimental setup has been designed which can create current operating conditions of modern reefer containers and can be used to test alternative design features and output results without any need of numerical models or new experimental rig. It is also possible to integrate external ideas (questions appeared in the scientific community regarding the packaging in reefer containers) into the experimental setup to test and analyse their effects. In terms of effects of new packaging design, cooling rate, uniformity of cooling,

cooling efficiency, pressure drop, or energy requirements effects can be analyzed using this rig.

The analysis of vertical ventilation in the packaging design for kiwifruit MBP are anticipated to be applicable to similar types of polylined horticultural produce. The key design feature (vertical ventilated packaging in reefer container) of the present project can be beneficial for non polylined horticultural packaging for increasing the uniformity of cooling without compromising the cooling rate and the energy requirement. There is a decent amount of literature about the packaging design for non-polylined produce in reefer conditions. It is possible to incorporate work involving polylined products and general insights from non-polylined products to construct a new box configuration to maximize cooling uniformity or to decide what operating conditions to use.

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