Temperature control during containerised sea transport of fresh fish

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60 ECTS thesis submitted in partial fulfillment of a
Magister Scientiarum degree in Mechanical Engineering

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Abstract

Insufficient temperature control in cold chains has negative effects on fresh fish quality and storage life. Until recent years fresh fish fillets and other high-value, short storage life products have generally been transported by air freight but large volume exporters now take advantage of better temperature control and the lower cost option of refrigerated sea transport. The focus of this study is to analyse temperature control in sea transport of palletised chilled fish products in reefers. The temperature distribution inside reefers was mapped in an outside, stationary environment and influences of variable pallet stowage patterns, reefer types and seasons were analysed. A field test of real sea transport was also studied. The results showed that there is room for improvement in sea transport cold chains. The field test demonstrated the importance of correct operating procedures during loading of reefers and their handling from processor to end location. Furthermore, it showed that the temperature control during sea freight may be improved by selecting the reefer types most suitable for fresh fish transport and selecting different set point temperatures during summer and winter. The mappings of temperature distribution inside the reefers showed spatiotemporal variability and imply that a more uniform distribution can be achieved by means of forced air circulation and modification of pallet setups.

Útdráttur

Ófullnægjandi hitastýring í kælikeðju hefur neikvæð áhrif á gæði og geymsluþol ferskra fiskafurða. Undanfarin ár hafa sjóflutningar kældra fiskafurða aukist á kostnað flugflutninga vegna betri hitastýringar í sjóflutningum og með frekari úrbótum má búast við að framleiðendur nýti sér hagkvæmari flutningamáta í auknum mæli. Markmið þessa verkefnis var að greina hitastýringu við sjóflutning á kældum fiskafurðum. Hitadreifing í kæligámum var kortlögð við staðbundnar aðstæður og lagt mat á áhrif mismunandi uppröðunar bretta, tegunda kæligáma og árstíða. Einnig var hitastýring í raunverulegum sjóflutningi rannsökuð. Niðurstöður benda til þess að þörf sé á endurbótum í sjóflutningskeðjum. Sýnt var fram á mikilvægi verklags við hleðslu kæligáma og meðhöndlun þeirra frá framleiðanda til kaupanda. Hitastýringu við sjóflutninga má bæta með því að velja markhitastig og kæligáma sem hæfa best til flutninga ferskra fiskafurða. Kortlagning á hitadreifingu kæligáma sýndi fram á breytileika, bæði í flutningsferlinu og með tilliti til staðsetningar innan gámsins, og leiðir hún líkur að því að jafna megi hitadreifingu með því að þvinga loftflæði innan gámsins og breyta verklagi við uppröðun bretta.

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Abbreviations

ATP	Agreement on the international carriage of perishable foodstuff and on the special equipment to be used for such carriage
BMS	Boulogne Sur Mer
CBC	combined blast and contact
CIMC	CIMC Containers
CP	corrugated plastic
DVK	Dalvík
EPS	expanded polystyrene
rpm	rounds per minute
ft.	foot/feet
MCI	Maersk Container Industry
Reefer	mechanically refrigerated container
REY	Reyðarfjörður
RTM	Rotterdam
RU	refrigeration unit
RVK	Reykjavík

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1 Introduction

A large part of Iceland's economy is based on exported marine products. Their share is around 40% of the total value of exported goods, of which the value of fresh and chilled fish amounted to over 150 million Euros in 2010 (Statistics Iceland, 2012a,c). Fresh fish export from Iceland has increased substantially in recent years and in the last 10 years it has almost doubled. The total fresh fish export, mostly to Europe, in 1999 was around 45.000 tons and increased to roughly 88.000 tons in 2008 (Hallgrímsson, 2009). Fresh fish fillets and loins have been exported mainly by air freight while container shipping is more common for whole gutted fish (Seafish, 2010). However in recent years there has been an increase in transport of fresh fish fillets by sea freight to Europe in mechanically refrigerated containers (reefers). In 2010, the total export of fresh fish fillets and loins was around 9.900 tons via air freight and 3.850 tons by sea (Statistics Iceland, 2012b). Figure 1.1 shows the ratio of sea export to air export of fresh fish fillets and loins, chilled or on ice, from 1997 to 2010. This ratio is expected to continue growing, despite a reduction in 2008-2009 due to an economic crisis in Iceland.

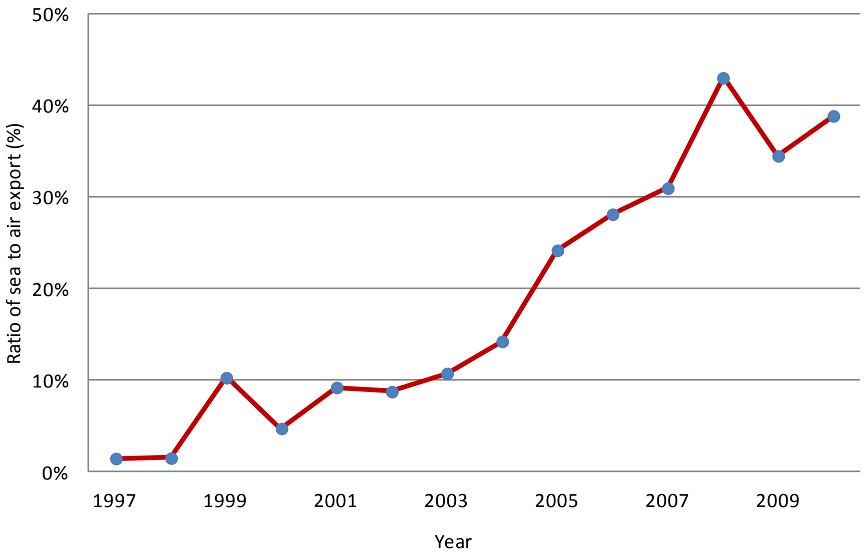


Figure 1.1: Ratio of sea export to air export of fresh fish fillets from 1997 to 2010 (Statistics Iceland, 2012b).

The main reasons for this development are increased demands for more economic transport and efficient temperature control from producers and consumers. A breakdown in temperature control at any stage of the fresh fish cold chain will have impact on the product´s final quality and sea freight generally has fewer and relatively more secure handover points in the cold chain compared to air freight, making it a feasible option despite of the longer transport time (Mai et al., 2011). Factors such as increasing air freight prices and consumer environmental awareness have an influence as air freight can generate over 150 times more CO_2 gases (Soil Association, 2007) and the transport cost of flying is two to three times higher than shipping (Geirsson, 2009). As temperature control of refrigerated sea freight is better than in air freight, the need for insulated packaging is greater in air freight and that also increases costs for producers.

Reefers rely on the flow of cool air around its cargo to complete cooling and remove additional heat. In containerised sea freight, where environmental conditions can be harsh and ambient temperatures can range from very warm to freezing, reefers must be able to maintain the desired temperature throughout the whole container. Ambient temperature, the cargo´s initial temperature, evaporator defrosting cycles and palletisation cause temperature variability within this system, resulting in increased variability of product quality (Smale, 2004). The design of transport systems and operating procedures should aim to reduce this variability. There are several factors to be considered when determining an appropriate rate of air circulation and temperature, and a single design is unlikely to provide the optimum solution for all cargo types. Air temperature inside the reefer should be kept between -1 and 0 °C with minimum temperature fluctuations for optimal storage of chilled whitefish products (Lauzon et al., 2010). As reefers are designed to maintain temperature, rather than to cool down the transported cargo, it is important that chilled products are cooled down to the intended freight temperature before transport.

This thesis focuses on the transport of palletised chilled fish in reefers. The aim is to map and analyse temperature distribution inside reefers that are used for transportation of chilled fish from producers in Iceland to buyers in Europe. The study aims to answer the following questions:

- Do different palletisation patterns influence temperature distribution inside the reefer?
- Which reefer types are most suitable for marine transportation of chilled fish?
- How does seasonally variable ambient temperature influence the reefer performance?

In order to answer the questions above the following temperature mapping experiments were carried out:

Experiment 1:	For variable pallet patterns (during summer).
Experiment 2:	For variable reefer types (during summer).
Experiment 3:	During winter time in a single reefer.
Experiment 4:	During real sea transport.

Experiments 1 to 3 were carried out in an outside, stationary environment. Experiment 4 was a field test on multimodal reefer transport from Iceland to France. The purpose of the study is to use experimental results to improve temperature control during reefer transport by selecting palletisation patterns, reefer types and set point temperatures that are best suited for chilled fish products. The field of refrigerated transport will benefit from improved temperature control during storage and transport by decreased product variability and a slower rate of quality deterioration in fresh fish.

2 Background

In this chapter the background of the project is stated. In recent work on fresh fish transport much emphasis has been placed on comparison between air and sea freight, without analysing variable temperatures within the reefers. Studies on reefers and temperature mapping have mainly focused on transport of fruit and frozen cargo. Research studies by Axelsdóttir (2002) and Björnsson (2005) have confirmed the importance of stable temperature during storage and reefer transportation of frozen seafood products. High temperatures and frequent fluctuations during frozen storage and transport were found to cause formations of frosting, resulting in reduced product quality and price. Transport of frozen products allows for 2 to 3 °C temperature fluctuations, but for chilled whitefish fillets around 0 °C the fluctuations should be considerably less to preserve quality, preferably not exceeding ± 0.5 °C (Lauzon et al., 2010).

2.1 Fresh fish cold chain

A cold chain is a temperature controlled supply chain that will help extend the storage life of products such as fresh fish when kept unbroken. The main purpose of maintaining sufficient temperature control during refrigerated transport of fresh fish is to decrease the rate of microbial growth and hence maintain the safety and quality of the product. Because of the importance of storage and transport temperature, almost all countries in Europe, USA and many others have signed the ATP – *Agreement on the international carriage of perishable foodstuff and on the special equipment to be used for such carriage* (ATP, 2010). According to the ATP, temperature control in fresh fish cold chains should keep the fish temperature as close to 0 °C as possible without freezing the product. Some studies however have shown that temperature control in fresh fish cold chains is often far from those demands (Giannakourou et al., 2005; Mai et al., 2011; Margeirsson et al., 2010).

The results of temperature mapping of transport chains in the Icelandic research project *Thermal modelling of chilling and transport of fresh fish* ("*Hermun kæliferla"*) and the European project *Chill-on*, have shown that the temperature control during transport of fresh fish products is better in refrigerated sea freight than in air freight. Results of storage life studies simulating air- and sea transport also indicate that the storage life of fresh fish fillets and loins by sea freight could be comparable to air freight if the temperature is carefully controlled (Mai et al., 2010).

The main advantage of transportation of fresh fish by air freight is the short delivery time. Common transport time from Icelandic fish processors to retailers in Europe is around two days by air and around five to seven days with sea transport (Mai et al., 2010; Margeirsson et al. 2010). However the product is normally subjected to temperature abuse during the freight transport; at unchilled conditions during handover points, loading, unloading, storage and holding. The temperature of storage during flight can be 15-20 °C, which means that the product may be unprotected for up to 80% of its journey via air freight (James, 2006). Multimodal reefer transport optimally allows for an unbroken cold chain via land and sea, when reefers are loaded at the processor and transported to the receiver (Rodriguez et al., 2006). The reefer transport cold chain is, however, not always optimal, as fresh fish pallets are commonly transported to shipping ports by refrigerated trucks and containerised at the port by the shipper. Then the cargo is broken up for handling in unsheltered conditions and can stand unprotected for 15-30 minutes before being containerised or stored in a cold store (Sigurðsson, 2010). Figure 2.1 shows fresh fish pallets handling at a shipping port in Reykjavik (RVK). The reefer set point temperature depends on the producers wishes and for fresh fish it ranges from -2 to 0 °C, most commonly set at 0 °C in Iceland (Sigurðsson, 2010).

Figure 2.1: Fresh fish handling at a container terminal in RVK. Pallets are unloaded from a refrigerated truck stored outside before being containerised.

Mai et al. (2010) mapped temperature for sea transport of fresh cod loins in three trips from the producer in Dalvik (DVK) to retailers in Grimsby (UK) and Boulogne-Sur-Mer (France). The total transport times of the three trips were 115, 142 and 160 hours. In two of those trips the product was kept in a reefer for the whole trip. One trip involved the handling of the pallets from road transport in a refrigerated truck and loading/unloading of reefer at shipping port. EPS (*expanded polystyrene*) boxes on free sides of the pallet, especially the corner boxes, were found to be more sensitive to ambient temperature changes than boxes deeper in the pallet stack. Exact locations of pallets inside the reefers were, however, not specified in those studies.

In a field test by Martinsdóttir et al. (2010) the temperature of superchilled cod loins by means of CBC (*combined blast and contact*) cooling equipment, packaged in EPS boxes was measured, during transport via air and sea freight from Iceland to Bremerhaven, Germany. The total transportation time by air and sea freight was 42 and 140 hours, respectively. At the end point, the average product temperature was 3 °C lower when transported by sea, compared to air freight. Figure 2.2 shows the average temperature inside EPS boxes with (dashed lines) and without (unbroken lines) gel packs. Little difference was noticed between mean product temperatures, with and without gel packs for air and sea freight. According to a sensory evaluation the storage at -1 °C resulted in a prolonged storage life of about 3 days compared to air freight temperature conditions.

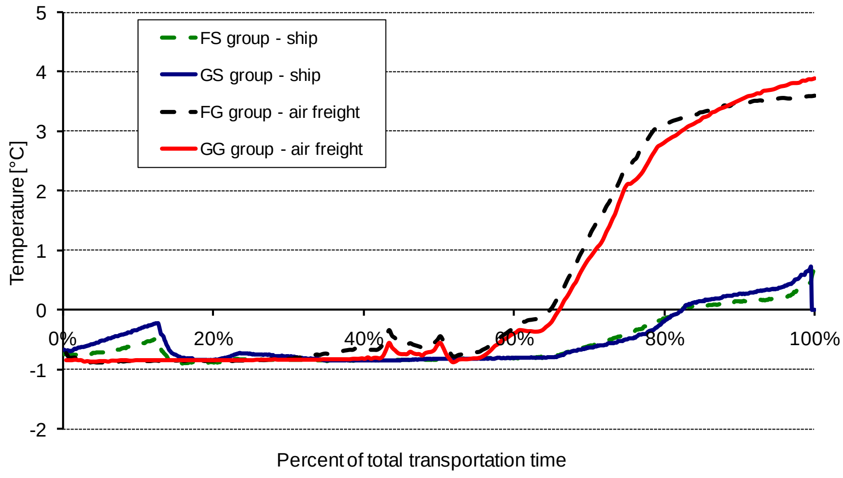


Figure 2.2: Average temperature inside EPS boxes with and without gel pack (Martinsdóttir et al., 2010).

In a transport simulation study, Margeirsson et al. (2010) compared cod loins in air freight to cod loins stored at around -1 °C, which could be achieved during non-interrupted and well temperature-controlled containerised sea transport. The authors concluded that at steady temperature the freshness period for fish loins was estimated to be 6-7 days and storage life 11-12 days while at dynamic temperature, simulating an airborne supply chain, the estimated freshness period was 2-3 days and storage life 6-7 days. The simulation used a typical air freight route temperature and close to the best possible cold chain situation for sea transport from Iceland. Based on the results, well temperature controlled sea transport can be expected to extend the freshness period by 1-5 days and storage life by 3-5 days compared to typical air freight.

Estimation based on cod trials by Lauzon et al. (2010) showed that raw material and storage conditions affect the fish freshness period and storage life. Results from the study in Table 2.1 show an extended freshness period and storage life for storage at -1 °C, compared to storage at 0.5 °C. The authors showed that an increase in mean product temperature of 0.5 °C may reduce the freshness period and/or the storage life of processed fish by approximately one day.

Table 2.1: Estimated duration of the freshness period and storage life of cod products influenced by raw material age at processing and mean product temperature post-packaging (adopted from Lauzon et al. (2010)).

Age at processing	1 day old from catch		3 days old from catch	
Storage conditions after fillet processing (mean product temperature)	superchilled (-1 °C)	chilled (0.5 °C)	superchilled (-1 °C)	chilled (0.5 °C)
Estimated freshness period (days)	10+	8	10	6
Estimated storage life (days)	15-17	12-13	15-16	10-12
Sea freight (6 days)				
Storage life at delivery	9-11	6-7	9-10	4-6
Freshness period	4+	2	4	0

An experiment on the effect of box positions on pallets and packaging types was conducted by Margeirsson et al. (2012). The packaging materials used were EPS (*expanded polystyrene*) and CP (*corrugated plastic*) boxes. The experiments were carried out at a steady storage temperature of -0.4 °C and at dynamic temperatures, representing a well temperature-controlled sea transport and a relatively well-controlled air transport chain, respectively. The storage life of cod products in palletised boxes was determined as reported in Table 2.2. The box position on the pallets and storage temperature were both found to influence the storage life.

Table 2.2: Storage life of cod products determined by sensory or microbial analysis. Samples are taken from boxes at the middle/corner of the pallet stack. Product temperatrue is calculated from the box centers and tops (Margeirsson et al. (2012)).

Group	Storage life (days)	Prod. temp. at box center until end of storage life, mean ± std. dev. (°C)	Mean prod. temp. at box top and center until end of storage life, mean ± std. dev. (°C)
Steady storage temperature, EPS box	11	0.3 ± 0.7	0.2 ± 0.8
Dynamic storage temperature, middle EPS box	9	2.7 ± 0.5	2.8 ± 0.5
Dynamic storage temperature, corner EPS box	8	2.5 ± 1.2	2.5 ± 1.3
Steady storage temperature, CP box	11	0.4 ± 1.0	0.3 ± 1.1
Dynamic storage temperature, middle CP box	9.5	2.1 ± 0.7	2.1 ± 0.7
Dynamic storage temperature, corner CP box	8	1.9 ± 1.6	1.9 ± 1.5

The importance of pre-cooling the product to the intended storage temperature before packaging has been shown and the thermal protection from external environment by insulated boxes has been tested and optimized by Valtýsdóttir (2011). The pre-cooling of fillets before packaging was found to protect them from temperature fluctuations during storage and transport (Valtýsdóttir et al., 2011; Magnússon et al. 2009). With proper temperature control, ice inside fillet packaging may be reduced or not required at all, which will minimize the risk of cross contamination and contact between the product and melted ice (Lauzon, 2010).

2.2 Reefer temperature mapping

Many studies have been done on refrigerated container shipments of chilled products. The majority of the published work, however, refers to 20 ft. containers and transport of fruits. The work that has been done on 40 ft. reefers by Billing et. al (1995) and Amos (2001) focused on temperature variation in palletised stows of fruit. Billing et al. (1995) found variations in delivery air temperatures across containers of up to 2 °C and previous studies by Punt et al. (2005) and Tanner et al. (2003) have also shown significant temperature variability in 20 ft. and 40 ft. reefers during shipping of fresh product cargo at constant set temperatures. Tanner et al. (2003) found that there was a significant variability both spatially across the width of the container as well as in time.

A study on different stowage patterns and floor coverage in a 40 ft. reefer carrying lily bulbs was done by Montsma et al. (2011). The results did not show a significant difference between stowage patterns but covering of a T-bar floor helped to deliver more air towards the reefer door-end. Moureh et al. (2004) conducted a study on forced air temperature distribution inside a refrigerated truck loaded with pallets of frozen cargo. The use of forced air circulation resulted in better flow of chilled air throughout the container space, shown in Figure 2.3. The results revealed that the thin air space located between pallets and lateral wall (1-2 cm) represented the most sensitive area in the load, generating the highest local temperatures.

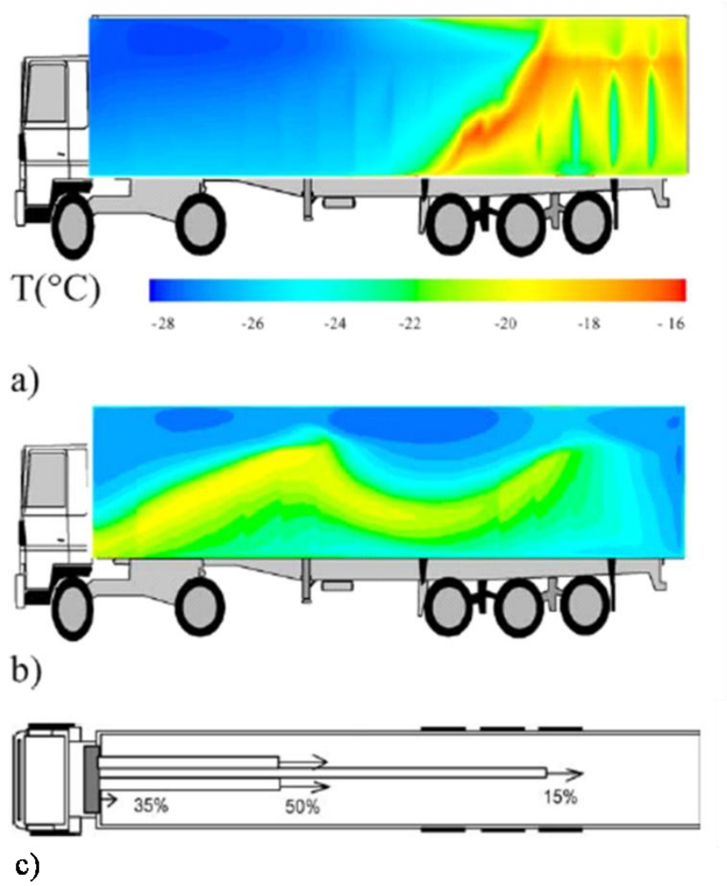


Figure 2.3: Numerical results of iso-temperatures in a) truck without air ducts and b) with air ducts. c) shows the layout of air ducts in the truck (Moureh et al., 2004).

Research by Rodriguez et al. (2006) showed that ambient temperature, particularly solar effect, has a significant influence on the temperature inside a container and that walls exposed to sun radiation show clearly different thermal patterns compared to shaded ones. The experiments were carried out in one part of a 20 ft. reefer divided into two compartments, separated by an isolated wall. It used set points of 0 °C and 6 °C with two cargo levels; empty and almost full (720 kg/m^3). It was also observed that the difference between the temperature inside the container and the set point was 2 °C, for both set point temperatures.

The refrigeration capacity required of a container is mainly affected by environmental impacts, insulation quality of the container, initial temperature of the cargo, rate of fresh air exchange and leakage (Keller, 2006). During sea freight refrigerated containers are usually carried on deck, as shown in Figure 2.4, because of problems in operating and maintaining the refrigeration units within closed holds (Sigurðsson, 2010). Reefers containing fresh fish cargo are also generally located on top of the container pile to minimize unloading time once in port, placing them in a crossfire of environmental impacts. On deck the containers are subjected to much higher ambient temperatures along with solar radiation and rain which has a great effect on the heat transfer through the containers´ insulated walls. These conditions will result in larger heat gains which make it far more difficult to control the temperature inside the container (James et al., 2006).

Conduction through the reefer walls can be 700 W/(m^2 K) when raining, compared to 25 W/(m^2 K) when dry (Keller, 2006). Rain in combination with warm environment and solar radiation can therefore lead to very undesirable environmental conditions.

Figure 2.4: Reefers on deck during sea freight (Eimskip 2012).

Due to the extreme environmental conditions containers are exposed to, they typically experience an increase in heat leakage of 3 to 5 % per year (Thermo King, 2007). Insulation quality of containers also decreases with age and is a factor that is difficult to monitor visually in reefers as moisture can leak between the container walls and affect the insulation quality. The ageing of the polyurethane foam insulation can be expected to increase cold losses at an average of 2 to 3 % each year of the container service life (IIR, 1995). Table 2.3 shows typical values for insulation depending on container age. The insulation value represents heat transmitted through the container walls.

Table 2.3: Container insulation quality (Heap, 1989; IIR, 1995)

	Insulation value [W / °C]	
	20 ft. container	40 ft. container
New containers	22	44
Older containers (moderate age)	26	52
Oldest containers (end of service life)	30	60

Results by Montsma et al. (2011) on 40 ft. containers insulation showed an insulation value of 46 W/°C for a 2 years old container and 55 W/°C for a 4 year old container (measured according to ATP standard). Smale (2004) developed a mathematical model to describe the flow of air during marine transport. The model showed that an increased circulation air flow rate slightly improved cooling throughout reefers; however, the magnitude of the improvement was relatively small and the increased fan power and refrigeration capacity were considered to weigh against the small improvement and render the increase of little benefit financially and environmentally.

3 Materials and methods

In this chapter the physical background of the study is stated. The field test experiment was carried out with fresh fish while other experiments done in static conditions, used bacalao (salted cod) from a shipper's cold store in Reykjavik. The reasons for using bacalao instead of fresh fish were easier accessibility to bacalao and that the temperature measurements were done over a period of time which exceeds the storage life of fresh fish.

3.1 Raw materials properties

Fish is highly perishable due to its high protein content, water content and fat content, and postmortem biochemical and microbiological changes will make fish unfit for consumption in a relatively short time (Gunnarsson, 2001). Chilled fish should usually be transported as close to its initial freezing point as possible, depending on the water and fat content in the muscle. At temperatures below 0 °C the deterioration of fish is greatly reduced due to less microbial growth and activity. According to Pham (1996) the initial freezing point (T_f) for most fresh foods is around -1 °C, that is the temperature at which crystallization of water is initiated. The temperature T_f for cod with 82% water content is -0.9 °C (Kramer, 2007). Figure 3.1a) shows an 5 kg EPS box of fresh cod loins used in the field test experiment. Other experiments used bacalao in waxed cardboard boxes, shown in Figure 3.1b). The cardboard boxes were wrapped in polyethylene sheet.

a) *b)*

Figure 3.1: a) Fresh cod loins in an EPS box and b) Bacalao in a waxed cardboard box.

Table 3.1 shows different properties values of the raw material used. Water activity, a_w, is a critical factor in preserving the quality and safety of food as it is an important factor in influencing whether and how fast organisms will grow in a product (AquaLab, 2012). Most bacteria will not grow at a_w below 0.91 and most molds cease to grow below 0.80. While the shelf life of fresh white fish can be prolonged up to 14 days at optimum storage conditions, bacalao however can be stored for up to a few years in favorable conditions, at temperatures around 0 to 4 °C and a relative humidity of around 76% (Runarsson, 2011).

Table 3.1: Properties of fresh and salted cod at 0 °C (Þórarinsdóttir, 2010)

	Water activity, a_w	Water content [%]	C_p value [kJ/kg/K]
Fresh cod	0.98	82	4.14
Bacalao (cod, wet salted)	0.76	55-58	3

3.2 Measurement devices

Temperature measurements inside the reefers were done with iButton temperature loggers (Micro-T DS1922L) from Maxim Integrated Products (Sunnyvale, CA, USA). The logger is round with a diameter of 17 mm and a thickness of 5 mm. Temperature values are recorded in a protected memory section and each logger can record up to 4096 16-bit individual readings, on a predefined interval set up by the user. A validation study by Lichtenbelt et al. (2005) found that tested iButton loggers performed better than producers specification (average accuracy of -0.09 °C (-0.4 °C at most)) and that these properties could be improved by calibration. The iButton loggers used in this study were calibrated in ice water. OnSet Tidbit v2 loggers (Onset Computer Corporation; Bourne, MA, USA) were used for ambient temperature measurements and HoBo U12 loggers were used for both humidity and temperature measurements. Table 3.2 shows specifications of the measurement devices used. For further information on measurement devices see References.

Table 3.2: Specifications of measurement devices

Device	Resolution	Range	Accuracy
Ibutton	0.0625 °C	-40 to 85 °C	± 0.5 °C between -15 and 65 °C
Tidbit v2	0.02 °C	-20 to 70 °C	± 0.2 °C between 0 and 50 °C
HoBo U12	0.03 %	5 to 95 %	± 2.5 %

a) *b)* *c)*

Figure 3.2: a) HoBo U12 logger b) iButton logger c) Tidbit v2 logger.

3.3 Reefer cooling system

The same reefer types are used for transportation of both refrigerated and frozen products, with a typical operating temperature range between -30 °C to +25 °C. Air flow in a reefer is directed through the cargo via floor gratings and returns by the container ceiling. Figure 3.3 shows air flow around the chilled content of a container. Air is blown from the refrigerator unit (RU) fans through floor ducts to the door-end and ideally also along the chilled product sides as it is drawn back to the ceiling. In addition to temperature regulation, integral units also allow a controlled fresh air exchange for transport of respiring cargo. For fresh cargo the air flow should be directed around and upward through the cargo, so it must be stacked inside the container in a way that does not interrupt or block air flow. A load limit line, which limits the height of the cargo, will ensure free space above the cargo for return air. Reefers have an integrated refrigeration unit, generally powered by a 3-phase electric power supply. The power supply is connected to a power generator during transport by ship or truck. It is connected most of the time but during transport from loading terminal to ships or trucks the supply is temporarily disconnected. When transported by ships, reefers have to be connected to the on-board power supply system.

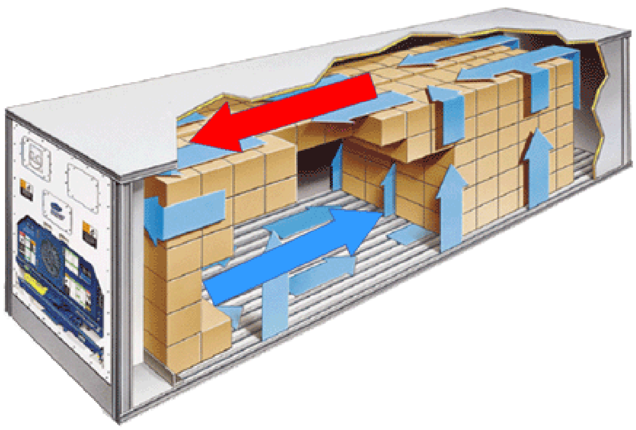


Figure 3.3: Air flow around chilled cargo in a reefer (Wild, 2011).

The refrigeration system operation uses four main components as shown in Figure 3.4; a compressor, a condenser, an evaporator and an expansion valve. The refrigerant flows through the system and absorbs heat from inside the system and releases it to the ambience. The compressor moves the refrigerant through the system to carry heat. It creates high pressure on one side of the system and low pressure on the other side. These pressures control the boiling point of the refrigerant causing it to boil in the evaporator and condense in the condenser. The condenser is a radiator located on the outside of the refrigerated compartment and releases heat to the outside air. Refrigerant vapor condenses in the condenser. The expansion valve controls flow of high pressure liquid refrigerant from the condenser to the evaporator. The evaporator is located inside the refrigerated compartment and absorbs heat from it. Low pressure liquid refrigerant passes through the evaporator, absorbs heat and begins to boil.

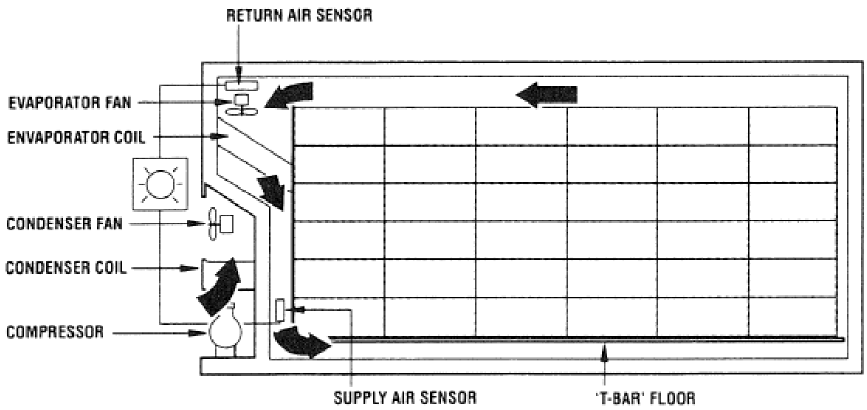


Figure 3.4: Main components in a mechanically refrigerated container (IIR, 1995).

For temperature control of the refrigeration unit, air temperature inside the reefer is measured at two locations; in the return air i.e. at the entry to the evaporator coil and in the supply air, at the exit of the evaporator coil. For chilled cargo, reefer temperature is controlled at the air delivery and the refrigeration capacity modulated for control. For frozen cargo the temperature is generally regulated at the air return (Smale, 2004). Precise temperature regulation is needed when operating in chilled mode and this is particularly relevant for the transport of chilled fish at -1 to 0 °C. In chilled mode the circulating fans operate at high speed in order to homogenize the temperature distribution around the cargo and the cooling compressor runs constantly. Supply and return air temperature differences regulate the fan to control air flow inside the container. In chilled mode the air circulation rate is typically 60-120 reefer volumes per hour during initial cooling and 30-60 per hour once the system is stable at the desired product temperature (IIR, 1995). Increased air velocities will generally reduce temperature variability but greater fan power will also introduce more heat to the system and increase power consumption (Smale, 2004).

Below a supply air temperature of approximately +10°C, the air cooler is defrosted at regular intervals, since at this temperature, the air cooler surface temperature can be below 0 °C. During defrosting, the reefer´s circulating fans and the cooling circuit are stopped. The air cooler and a drip tray are electrically heated. Since hot air rises slowly in the refrigeration unit, the return air temperature sensor always shows relatively high temperatures during defrosting. The beginning of the defrosting period is generally time-controlled, i.e. it occurs every 6, 8, 12 or 24 hours. The end of the duration of the defrosting process is normally determined when an end temperature is reached at the defrost end sensor above the air cooler. At the same time, however, a maximum defrosting period is also specified. If this is exceeded, the defrosting process is also ended. Some controllers are able to carry out defrosting as and when required. In this case, defrosting is triggered if the supply air temperature is not reached over a specific time period or if the temperature differential between the supply air and the return air is too high. Both criteria can indicate an insufficient air flow, which could in turn be caused by ice formation on the air cooler. However, other causes are also possible, making it difficult to carry out defrosting automatically as required (Wild, 2011).

3.4 Measured reefers

The measured reefers were all 40 ft. high cube RF45 type boxes with integral refrigeration units and a T-bar floor. The reefers were chosen in collaboration with the shipping company, emphasizing reefer types that are most commonly used for export of chilled fresh fish. The container boxes are similar in size and build with regard to material and insulation specifications, manufactured by Maersk Container Industry (MCI) and CIMC Containers (CIMC). Table 3.3 shows the main sizes and characteristics of the RF45 container boxes. The dimensions listed are the inside measures of a container box.

Table 3.3: Characteristics of a RF45 container

Lenght	Width	Height	Own weight	Capacity	Volume
11.6 m	2.3 m	2.5 m	4,950 kg	29,000 kg	67 m^3

The reefers are equipped with refrigeration units from different manufactures listed in Table 3.4. The tables month/year column refers to dates when the container was first used. The units have similar operating ranges and capacities, with cooling capacity ranging from 11.7 kW (Carrier, 2010) to 12.3 kW (Thermo King, 2007) when maintaining temperature around 2 °C inside the reefer with 38 °C ambient conditions. Heating capacities of the units range from 5.25 kW (Thermo King, 2007) to 5.6 kW (Carrier, 2010). In all experiments the refrigeration unit temperature was set at 0 °C, ventilation closed and the RU operation set to chilled mode, in which the evaporator fans run at high speed (up to 3,450 rpm). Figure 3.5 shows reefer refrigeration units and T-bar floor gratings viewed from the door-end. The height of the T-bars is 6 cm.

Table 3.4: Measured containers´ properties.

Reefer	**Box type**	**RU type**	**Month/Year**	**Refrigerant**
Experiment 1	MCI	Thermo King Magnum	02/2010	R404a
Exp. 2, Reefer A	MCI	Thermo King Magnum	02/2010	R404a
Exp. 2, Reefer B	MCI	Carrier 69 nt40-541	05/2007	R134a
Exp. 2, Reefer C	CIMC	Thermo King CRR40	04/2006	R134a
Exp. 2, Reefer D	MCI	Carrier 69 nt40-511	02/2009	R134a
Experiment 3	MCI	Thermo King Magnum	02/2010	R404a
Experiment 4	MCI	Thermo King Magnum	02/2010	R404a

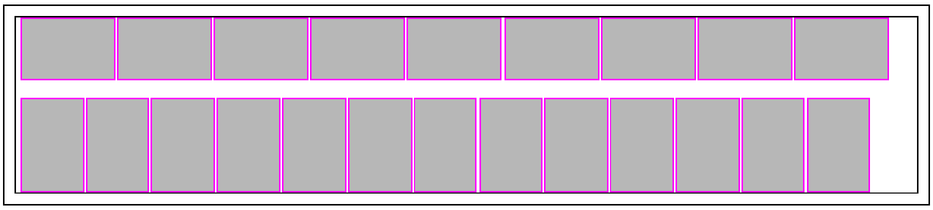
a) *b)*

Figure 3.5: a) T-bar floor gratings and b) measured reefers´ RU-end.

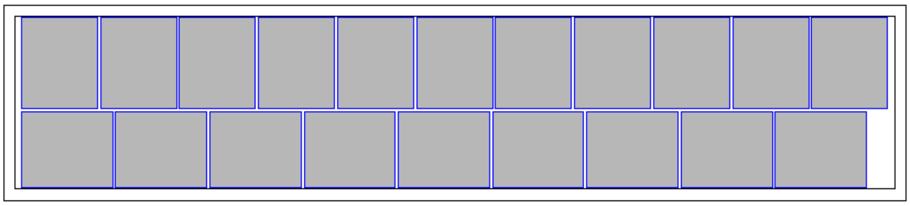
3.5 Experimental setup

In all experiments, reefers with a set point temperature of 0 °C were used. At least two sensors were placed outside the reefers in order to measure the ambient temperature.

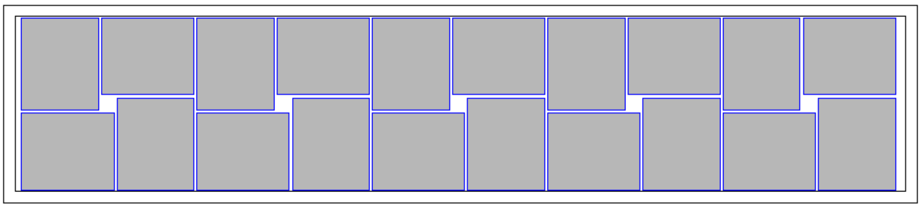
The choice of pallet stowage pattern in the reefers depends on the pallet sizes. The stowage patterns are chosen mostly with the aim of maximizing the number of pallets in the reefer and to balance the internal load (Sigurðsson, 2010). Common pallet types are the Euro pallet (800x1200 mm) and the industrial pallet (1000x1200 mm), both of which are used in this study. For those pallets the most common stowage patterns used are Europallet stowage and Zigzag stowage, shown in Figure 3.6. The Europallet stowage pattern refers to the layout of pallets and is not restricted to the Euro pallet as it is also used for industrial pallets, as in Figure 3.6 b). However the most common stowage for industrial pallets used by the shipper is the Zigzag pattern, shown in Figure 3.6 c). The Zigzag pattern for Euro pallets is much less common and rarely used by the shipper.



a) Europallet stowage pattern with Euro pallets, used in experiment 4.



b) Europallet stowage pattern with industrial pallets, used in experiment 1.



c) Zigzag stowage pattern with industrial pallets, used in experiments 1, 2 and 3.

Figure 3.6: Different pallet stowage patterns in a 40 ft. reefer.

With the Europallet stowage pattern, shown in Figure 3.6 a) and b), there is a longitudinal gap formed between the pallets. Due to the asymmetry of the stowage the gap is more to one side of the reefer centerline. With pallets pressed against the reefer walls this gap can be around 8 cm using industrial pallets and around 28 cm using Euro pallets. The industrial pallets fill most of the width of the reefer but for Euro pallets, air filled bags are blown up between pallets to ensure stability and minimize pallet movement within the reefer during transport. Figure 3.7 shows containerised EPS boxes on Euro pallets with an air bag in position. With the Zigzag stowage pattern, shown in Figure 3.6 c), vertical chimney shaped gaps are formed in the middle of each four-pallet cluster. With pallets pressed against the walls, the dimensions of these gaps can be 20x28 cm, in addition to the 8 cm longitudinal gap between pallets.

Figure 3.7: Stowage of Euro pallets. Air bags are used between the pallets to stabilize the cargo.

For all experiments a three dimensional grid was defined for the measurement points. Figure 3.8 a) shows 9 measurement points in a vertical cross section of a reefer. Left and right sides are viewed from the reefer door-end. In all experiments temperature loggers were placed in three horizontal levels; bottom, middle and top level, as presented in Figure 3.8 b). The largest measurement grid used in the experiments comprises 7 vertical sections from the reefer RU-end to the door-end, as shown in Figure 3.8 d).

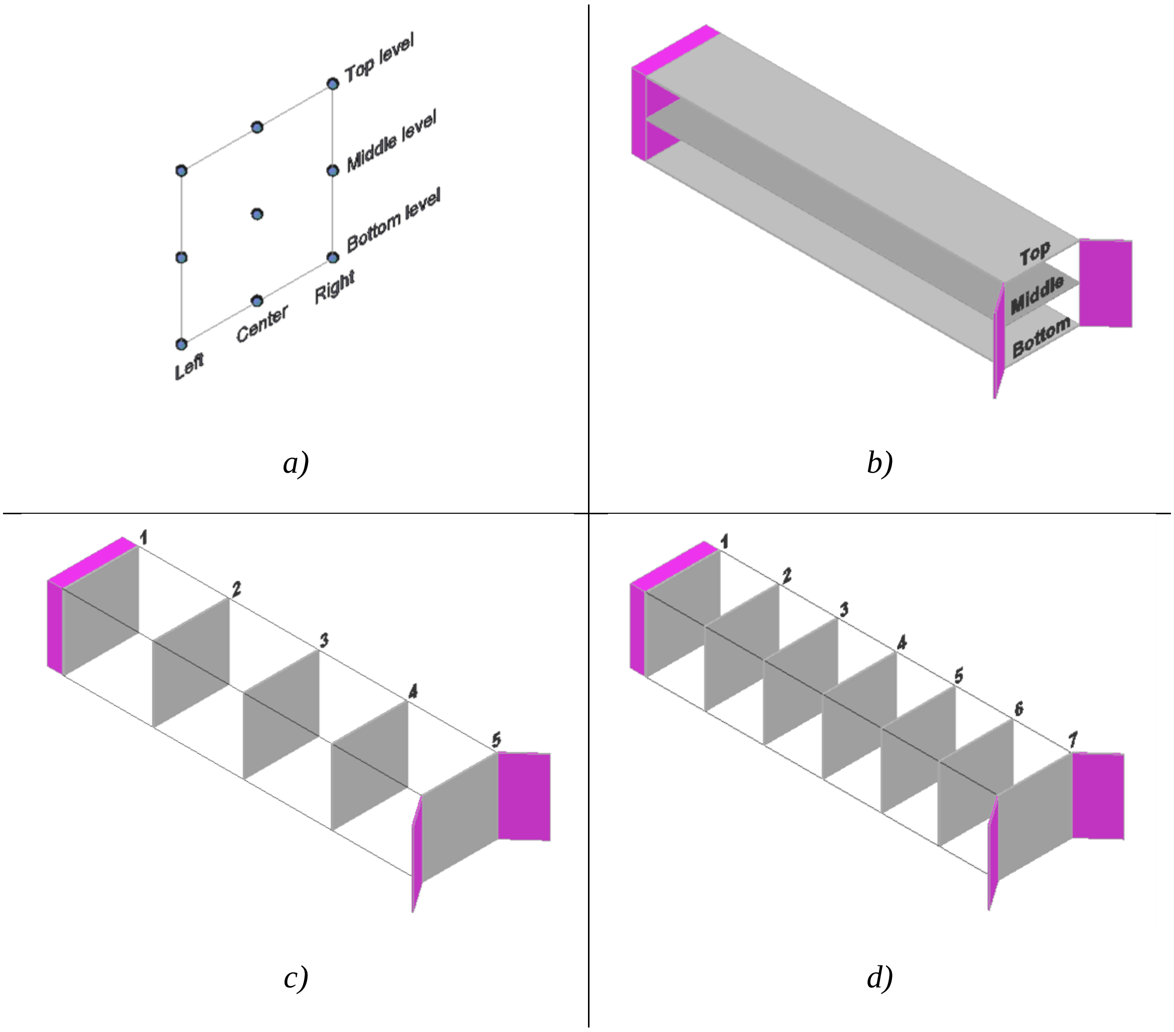


Figure 3.8: a) Logger placements in a vertical cross section, b) Definition of bottom, middle and top levels, c) Definition of vertical cross sections for experiments 3 & 4, d) Definition of vertical cross sections for experiment 1.

The sensor side of the temperature loggers inside the reefer pointed to the inside air while the back side faced the pallets, the reefer walls or the ceiling. Temperature loggers at the bottom level were placed at the pallets´ bottom. The height of the middle level varied between experiments. In experiments 1, 2 and 3, the loggers at the middle level were positioned on top of the pallet stacks and in experiment 4 they were positioned at the middle of the pallet stack. At the top level the loggers were fastened to the reefer walls by the ceiling and in the center line they were fastened to the ceiling itself.

3.5.1 Experiment 1: Variable pallet patterns

Experiment 1 was carried out in an outside, stationary environment at a container terminal in Reykjavik. Measurements on a reefer, listed in Table 3.4, took place over a period from July 23rd to August 3rd 2010, where the stowage pattern of pallets was changed from Europallet to Zigzag halfway through the period, on July 29th. In this experiment the same reefer was used during the whole period. The reefer was loaded with 20 industrial bacalao pallets from a chilled store and restacked using the same pallets. A measurement grid with 7 horizontal sections was used, as shown in Figure 3.8 d), with 63 measurement points in total. Two temperature loggers were placed at both ends outside the reefer, to measure the ambient temperature. Three humidity sensors were placed in the middle level center line; at the RU-end, in the middle and at the door-end. The middle level was on top of the bacalao pallets, 0.8 m above the bottom level. The distance between temperature loggers inside the reefer was 1.9 m in length and 1.1 m in width. Temperature and humidity were logged at 5 minute intervals throughout the experiment period.

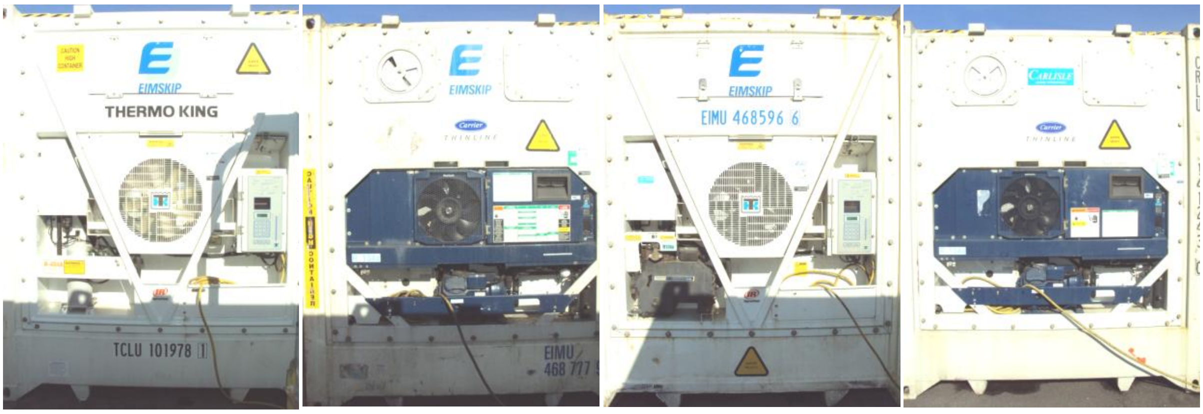
Figure 3.9 a) and b) show containerised pallets for each stowage pattern during the experiment. At the beginning of the experiment the temperature of the bacalao was measured between 8.5 and 9 °C when taken out from the cold store and loaded into the reefer. Halfway through the experiment, when pallets were restacked, the temperature in the bacalao measured 1.5 °C at the reefer RU-end and 2.5 °C at the door-end. At the end of the experiment the temperature measured was 1.0 °C in pallets at the RU-end and 1.8 °C at the door-end.

a) *b)*

Figure 3.9: Bacalao pallets in experiment 1; a) Europallet stowage pattern and b) Zigzag stowage pattern.

3.5.2 Experiment 2: Variable reefer types

Experiment 2 was carried out in an outside, stationary environment at a container terminal in Reykjavik. Measurements on four different reefers, listed in Table 3.4, took place over a period from August 24th to September 6th 2010. The four reefers were running simultaneously from August 26th to September 1st. The reefers were lined up side by side, with reefers A and D at each end as shown in Figure 3.10.



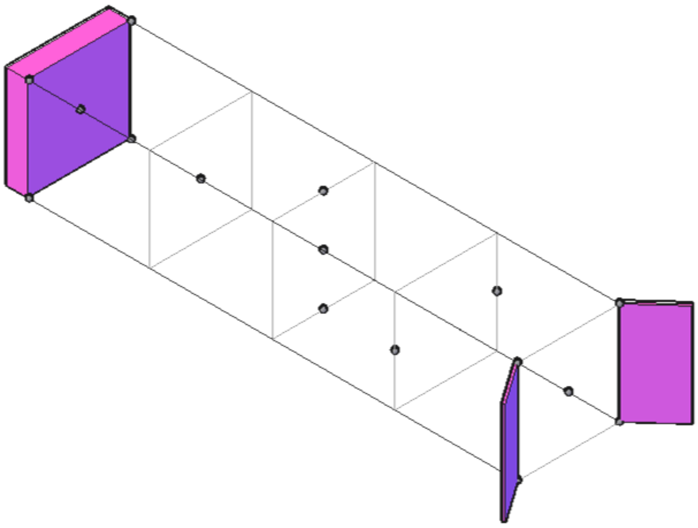
Reefer A *Reefer B* *Reefer C* *Reefer D*

Figure 3.10: Measured reefers in experiment 2.

Each reefer was loaded with 40 bacalao stacks on industrial pallets from a chilled store, identical to the pallets used in experiment 1. The temperature of the salt fish measured between 5 to 6 °C when taken out from the chilled store. The pallets were double stacked to a total height of 1.6 m above the bottom level, as shown in Figure 3.11 a). The stowage pattern used in all reefers was Zigzag, as it is more commonly used by the shipping company (Sigurðsson, 2010).

The measurement grid used in experiment 2 is shown in Figure 3.11 b), where 5 temperature loggers are placed at each end cross section of the reefer along with a few loggers in cross sections 2, 3 and 4. A total of 16 temperature loggers were placed inside each reefer. The middle level was positioned on top of the bacalao pallets, 1.6 m above the bottom level. The distance between temperature loggers inside the reefer was 2.9 m in length and 1.1 m in width. Temperature was logged with 5 minute intervals throughout the experiment period.

a)



b)

Figure 3.11: a) Stacked bacalao pallets and b) Logger setup for experiment 2.

3.5.3 Experiment 3: Winter experiment

Experiment 3 was carried out in an outside, stationary environment at a container terminal in Reykjavik. Measurements on a reefer, shown in Figure 3.12, took place over a period from March 10th to March 21st 2011. On March 17th two bacalao pallets were unloaded and replaced by pallets from the chilled store. The reefer was loaded with 20 industrial pallet of bacalao, 1.4 m in height, using Zigzag stowage pattern. The pallets were loaded from a chilled store at a mean temperature of 0.8 °C.

Figure 3.12: Bacalao pallets in the reefer in experiment 3.

The measurement grid used in the experiment is shown in Figure 3.8 c). The middle level of the measurement grid was positioned on top of the bacalao pallets, 1.4 m above the bottom level. The distance between temperature loggers inside the reefer was 2.9 m in length and 1.1 m in width. Humidity sensors were placed at the middle level center line, at the RU-end and the door-end. Temperature and humidity were logged with 5 minute intervals throughout the experiment period.

3.5.4 Experiment 4: Shipping field test

Experiment 4 was a field test measuring temperature distribution inside a reefer during transport from Iceland to France. The experiment was a blind test as the shipper was not informed a priori. The experiment took place from April 14th to April 19th 2011 and measured temperature profiles during transportation of fresh cod loins in a reefer from a processor in Dalvík, Iceland (DVK) to Boulogne Sur Mer, France (BSM). The sea freight was from Reyðarfjörður, Iceland (REY) to Rotterdam, in the Netherlands (RTM). The measurement grid used was the same as in experiment 3, measuring temperature at 5 vertical cross sections with 45 measuring points in total. In addition to measuring temperatures inside the reefer, 5 loggers were placed outside the reefer for measuring ambient temperature and 28 loggers inside EPS boxes. Inside each EPS box a logger was placed in the middle between fish loins and another in the corner of the box, on top of a loin, as can be seen in Figure 3.13.

Figure 3.13: Cod loins in an EPS box in experiment 4. iButton logger is placed in top left corner, and in the middle between loins.

The fresh fish loins were packed in EPS boxes on Euro pallets. The pallets were loaded in a Europallet stowage pattern inside the container. Air filled bags were blown up between pallets in the reefer centerline, as shown in Figure 3.14 a). The middle level of the measurement grid was positioned 1.1 m above the bottom level, and the placement of temperature loggers as seen in Figure 3.14 b). Bottom and top levels were positioned at the pallets´ bottom and the reefer ceiling, respectively. Temperature and humidity were logged with 3 minute intervals throughout the experiment period.

a) *b)*

Figure 3.14: a) Europallet stowage pattern b) Middle level logger in experiment 4.

Humidity loggers were also placed inside the reefer, two at the RU-end at the top and middle levels. One by pallet 2, shown in Figure 3.15, at the middle level and one by the door-end, at the top level. Four pallets in the reefer contained EPS boxes being monitored. Figure 3.15 shows the placement of monitored pallets. Red marks represent the position of the monitored top and bottom corner boxes. Each of the measured pallets also had one monitored EPS box in the middle of the pallet stack.

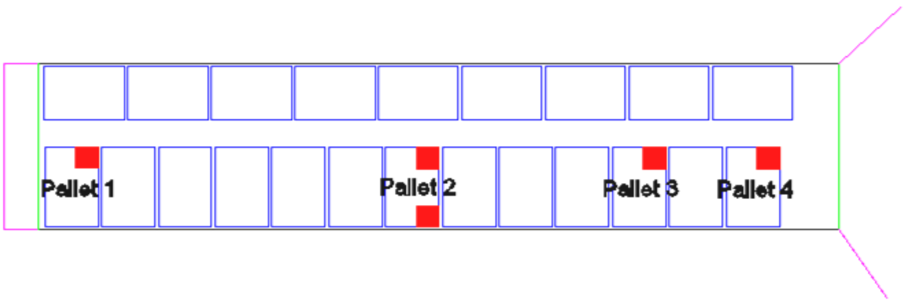


Figure 3.15: Placement of pallets with monitored EPS boxes in experiment 4.

4 Results

4.1 Experiment 1: Variable pallet patterns

Temperature mapping for two different loading patterns is presented over a period of 259 hours, starting when the reefer is closed with pallets stacked in a Europallet pattern. The reefer was opened and pallets restacked in a Zigzag pattern after 142 hours. Figure 4.1 shows the ambient temperature during the measurement period, which fluctuates fairly evenly around an average temperature of 14.5 °C. The figure also shows the average air temperature inside the reefer for each stowage pattern during the whole period. Because of defrosting, spikes are seen in the reefer average temperature, which occurs every nine hours throughout the period. During defrosting, air temperature in the reefer rises sharply for 10 to 15 minutes after which it takes around 15 to 30 minutes to reach a steady state.

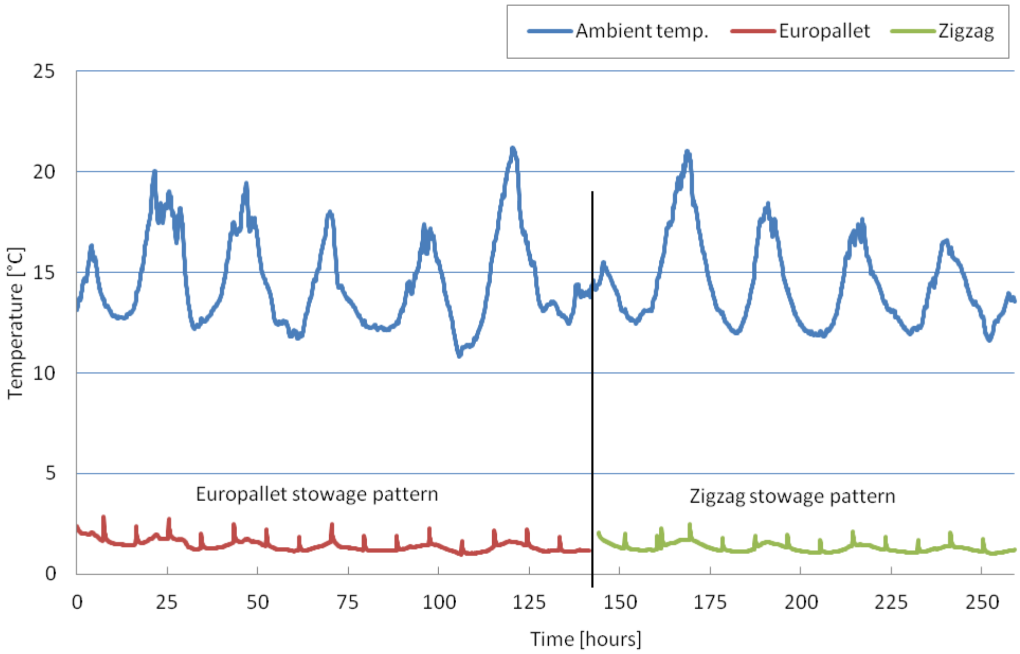


Figure 4.1: Ambient and reefer average air temperatures during experiment 1.

The effects of defrosting are greatest close at the RU-end and lesser near the reefer door-end, as seen in Figure 4.2.

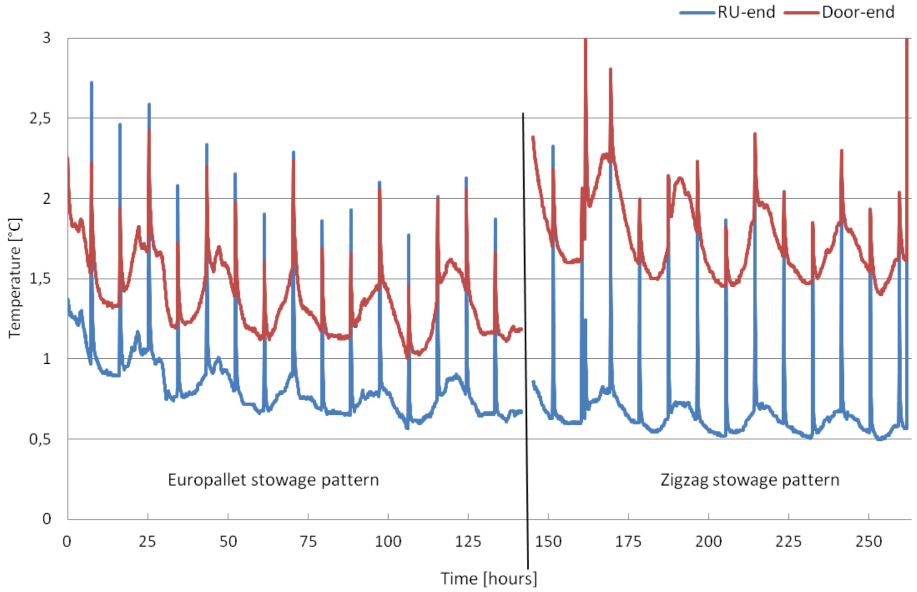


Figure 4.2: Average temperature at the RU-end and the door-end with defrosting effects.

The defrosting process also affects the reefer ceiling area more than the floor area, as seen in Figure 4.3.

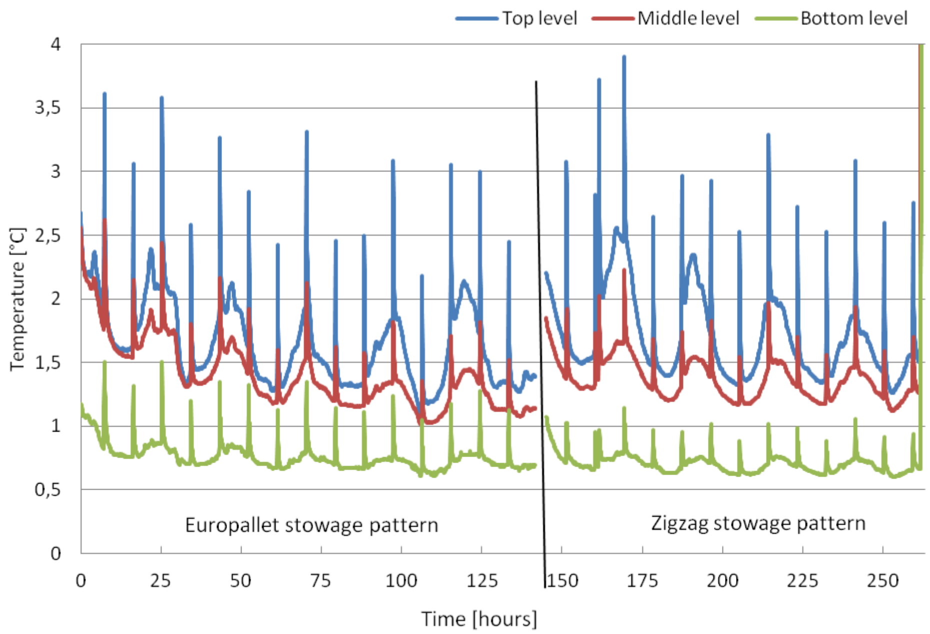


Figure 4.3: Average temperature at top, middle and bottom level with defrosting effects.

The average air temperature inside the reefer is shown in Figure 4.4, neglecting the effects of defrosting for a smoother curve. As the reefer was loaded with bacalao at around 8.5 °C above the set temperature of 0 °C, it takes the reefer up to 3 days to reach a reasonably steady state in terms of average temperature. A 72 hour time period is chosen for each stowage pattern, shown in Figure 4.4, to compare temperature distribution between the patterns. The ambient temperature fluctuations are similar over each of the chosen periods and the average temperature inside the reefer has reached a reasonably balanced state.

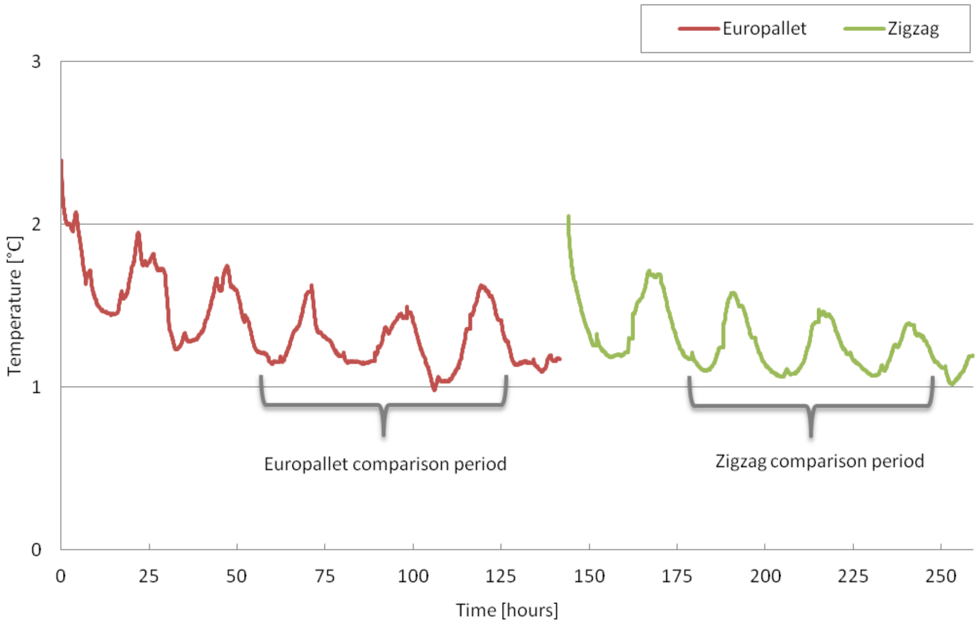


Figure 4.4: Reefer average temperature with defrosting effects removed from the results.

Ambient temperature fluctuations clearly affect the temperature inside the reefer, as a change in ambient temperature of 8 to 9 °C results in a change of approximately 0.5 °C in the average air temperature inside the reefer. The effects of the ambient temperature fluctuations inside the reefer are relatively small close to the RU-end and down by the container floor, as seen in Figure 4.3. However they are more noticeable farther from the RU-end and by the door-end ceiling the daily ambient temperature changes result in temperature fluctuations of 1 to 1.5 °C inside the reefer (Appendix vi). The average air temperature measured for each stowage pattern over the comparison period is similar, around 1.3 °C (Appendix vii). The defrosting has little effect on the average temperatures over the whole period due to their short impact time.

Figure 4.5 shows the relative frequency distribution for all 90,000 measurement observations collected during both comparison period, hours 56-128 and 176-248. Values between 1 and 2 °C occur most frequently during the observation periods.

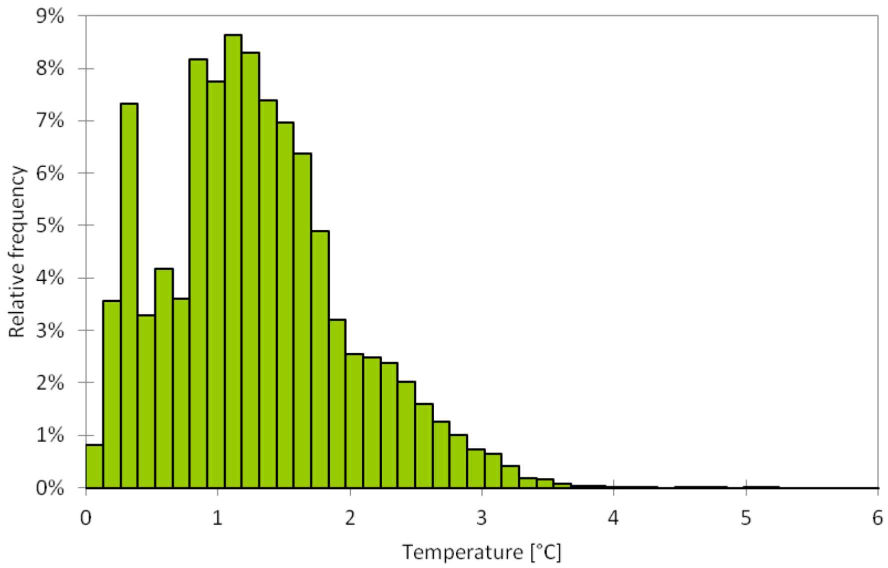


Figure 4.5: Relative frequency distribution for all indivitual temperature measurements inside the reefer during comparison periods in experiment 1.

Differences are found in the temperature distribution between the stowage patterns over the comparison period. Figure 4.6 shows contour plots of the average temperature for the bottom, middle and top levels for each stowage pattern over the comparison periods. The temperature results in Figure 4.6 are interpolated with a spline function. Black dots mark the positions of temperature loggers used in the experiment.

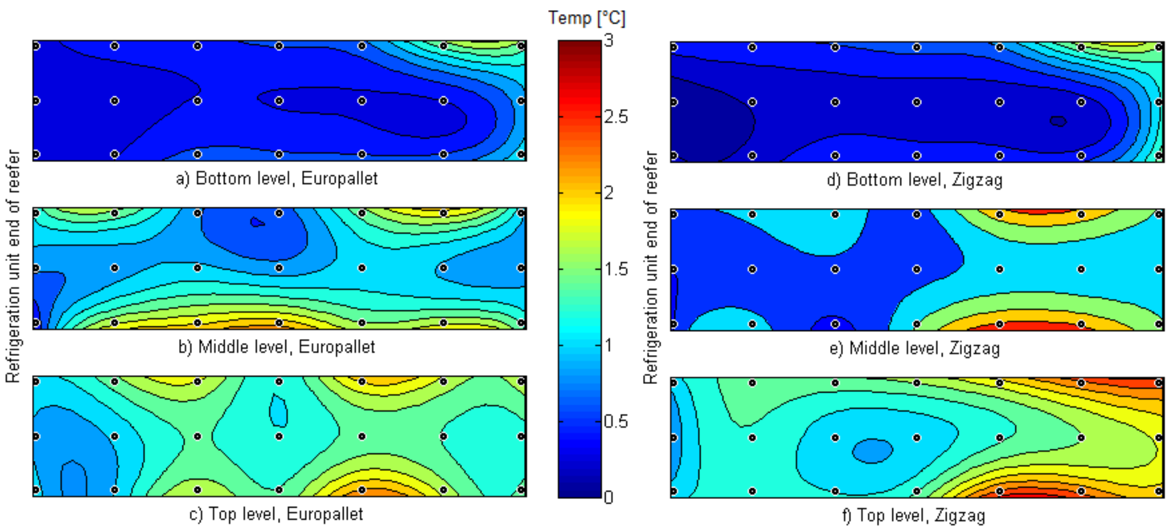


Figure 4.6: Average temperature distribution for Europallet (hours 56 to 128) and Zigzag (hours 176 to 248) patterns.

Average air temperatures at the bottom level are similar for both stowage patterns; temperatures are low at the RU-end and to the vertical cross section 6 near the door-end. At the bottom level door-end cold air is drawn more to the reefer´s left side (viewed from the reefer door-end). At the middle level in the Zigzag pattern the average air temperature is lower at the RU half-end of the reefer than at the door half-end. At the door half-end temperatures are higher, especially towards the sides. Average air temperature distribution is more homogenous through the middle level in the Europallet pattern, with higher temperature at the reefer´s right side. The temperature distribution at the top level is also more homogenous for the Europallet pattern compared to the Zigzag. At the top level side in both setups, average temperatures above 2 °C are measured but in the Zigzag pattern average temperatures are higher by the door-end, reaching up to 3 °C by the door-end right side.

Table 4.1 shows the average air temperature for each vertical cross section from the RU-end to the door-end. Neither stowage pattern measures the highest average temperatures at the door-end section. The average temperature distribution is more homogenous throughout the reefer vertical cross sections with the Europallet pattern whereas with the Zigzag pattern temperatures are lower at the RU-end and higher at the door-end. The difference between the highest and the lowest temperatures is greater in the Zigzag pattern compared to the Europallet. The average temperature is around 0.5 °C higher at the reefer left and right sides (viewed from the door-end) compared to the vertical centerline for both setups.

Table 4.1: Average temperature over vertical cross sections for each stowage pattern [°C]

Stowage pattern	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7
Europallet	0.7	1.1	1.2	1.1	1.4	1.4	1.3
Zigzag	0.6	0.9	0.9	1.0	1.6	1.8	1.7

Figure 4.7 shows the measured average relative humidity content of the air inside the reefer over the period. The difference in average relative humidity is not large between stowage patterns but measures around 1 to 1.5 % higher for the Zigzag pattern period. When the reefer was opened after 142 hours and pallets restacked the relative humidity rises and it takes 12 to 24 hours to reach a balanced state.

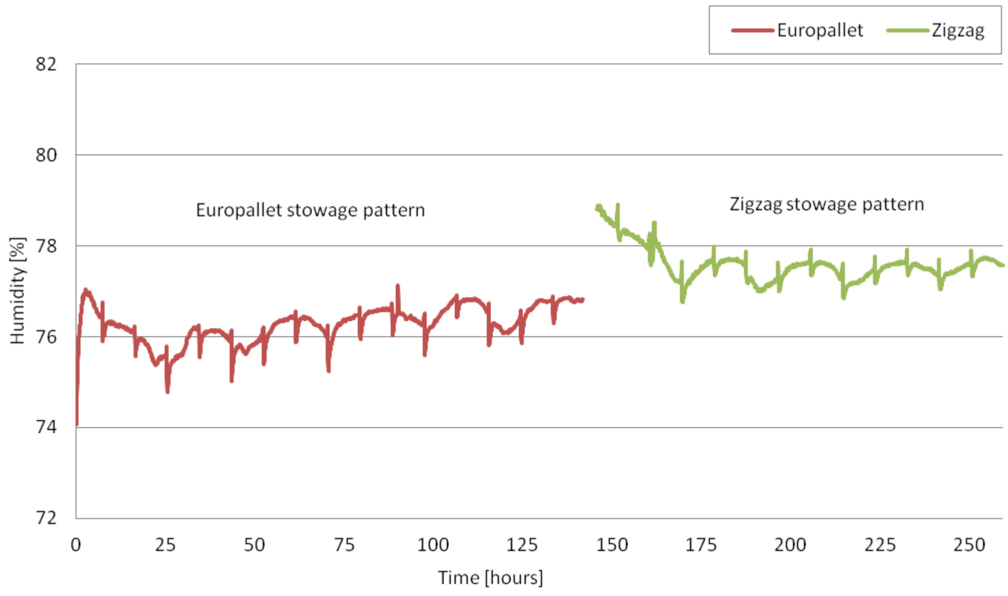


Figure 4.7: Average relative humidity in experiment 1.

Figure 4.8 shows the difference between the average relative humidity and each of the sensors, placed at the reefer door-end, in the middle and at the RU-end. Relative humidity was measures highest, around 1.5 % above average, at the RU-end where refrigerated air is circulated. Humidity in the middle of the reefer is around 1 % above average but by the door-end it is considerably lower, i.e. more than 2 % below average.

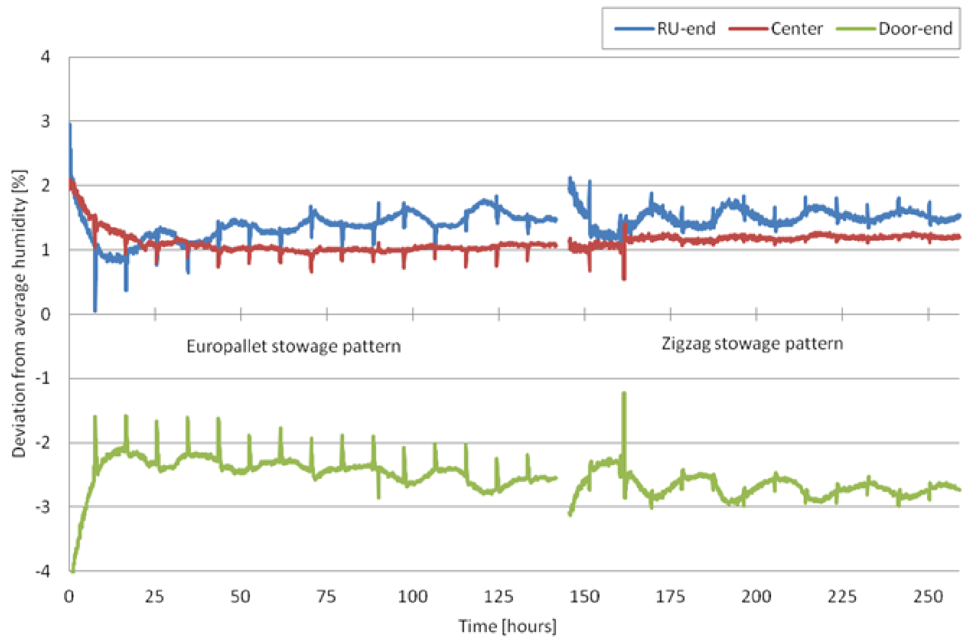


Figure 4.8: Deviation between average relative humidity and each logger during experiment 1.

4.2 Experiment 2: Variable reefer types

A temperature mapping from experiment 2 is shown in Figure 4.9 during a period of 138 hours where all measured reefers were running simultaneously, starting from when reefers C and D were loaded. Reefers A and B were loaded the day before and therefore reached a steady state sooner.

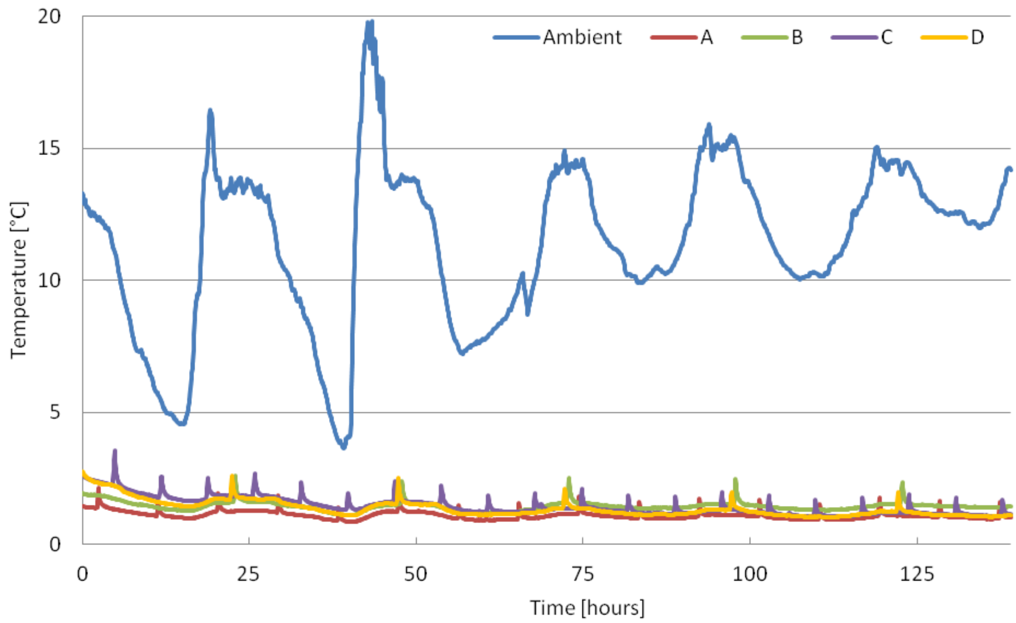


Figure 4.9: Ambient and average reefer temperature in experiment 2 (with defrost pulses).

Ambient temperature fluctuations influence the average air temperature of all the reefers to a similar degree. Considerable fluctuations in the ambient temperature during the first part of the period cause a change of around 0.5 °C in average air temperature inside the reefer. With less fluctuation in ambient temperature later in the period the average reefer temperature fluctuations are reduced but still noticeable. Reefer A defrosts every 9 hours and reefer C every 7 hours, with effects of temperature spikes lasting 45 to 60 minutes from start to finish. Reefers B and D defrost every 25 hours with effects on temperature lasting from 60 to 80 minutes. Table 4.2 shows average temperatures in all reefers between hours 60 to 135 of the experiment period (with defrosting). The effects of defrosting pulses were found to raise the average temperature inside the reefer by 0.1 °C at most.

Table 4.2: Average temperatures during the comparison period between hours 60 and 135

	Reefer A	Reefer B	Reefer C	Reefer D
Average temperature [°C]	1.1	1.4	1.2	1.2

The average temperatures during the comparison period are shown in Figure 4.10, where reefer average temperatures are shown without the effects of defrosting pulses, giving smoother curves for visualisation. Temperatures of reefers C and D appear to be descending during the comparison period, while reefers A and B are more stable.

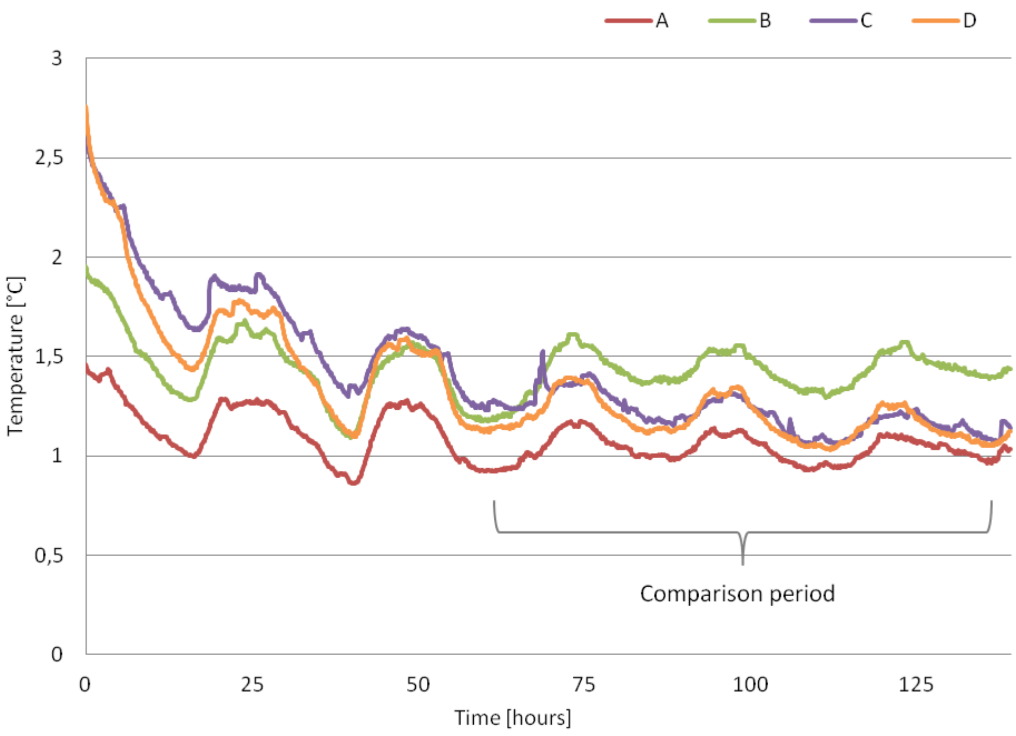


Figure 4.10: Average reefer temperature with defrosting effects removed.

Figure 4.11 shows four graphs, one for each reefer. The graphs show deviations of the average temperature of the cross sections at each end of the reefer from the overall average temperature in the reefer, shown in Figure 4.10. During the comparison period the difference in average temperature at the RU-end and the door-end is the greatest for reefer C, i.e. around 0.8 °C. For reefers A, B and D this difference is from 0.4 to 0.6 °C. During the comparison period the average temperature at the door-end measures highest in reefer B, from 1.6 to 1.9 °C (Appendix xi). Individual loggers in that section measure the highest temperatures at the reefer ceiling. Effects of ambient temperature fluctuations appear to be less at the RU-end during the comparison period, especially for reefers A and B. The effects of defrosting pulses, however, are less at the reefers door-end (Appendix xi).

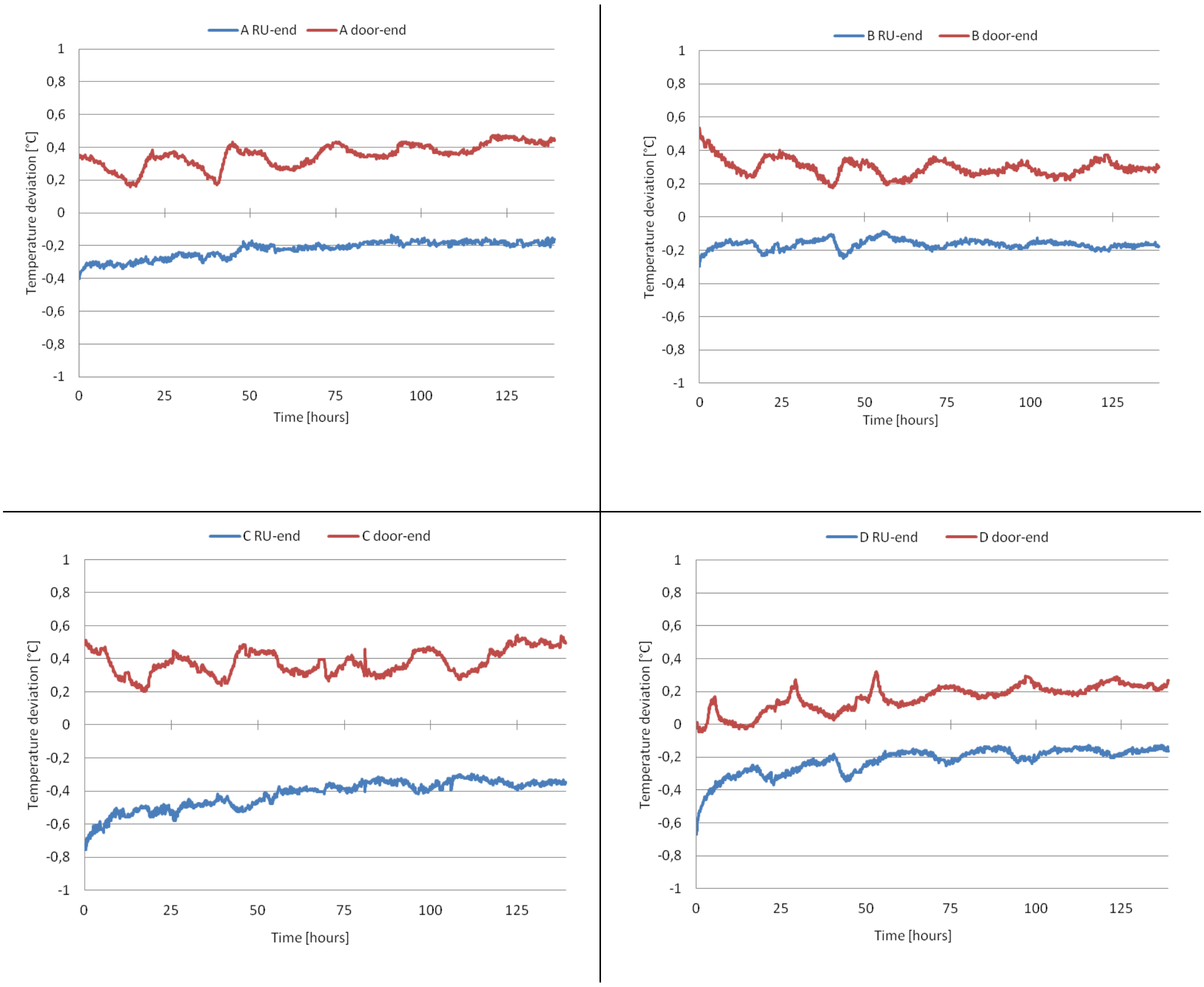


Figure 4.11: Deviations from average temperature in reefers A, B, C and D in experiment 2 (neglecting defrosting effects).

4.3 Experiment 3: Winter experiment

Temperature mapping in experiment 3 was carried out over a period of 260 hours where ambient temperatures range from -12 °C to 10 °C, with an average value of -1.5 °C. Figure 4.12 shows the ambient temperature and the average reefer air temperature during the period. Air temperature inside the reefer is fairly stable around an average value of 0.2 °C. The effects of variable ambient temperature are noticeable within the reefer, especially when ambient temperatures are higher than around 5 °C or lower than around -5 °C. The average temperature fluctuates less at the reefer RU-end and effects of ambient temperature are greater by the door-end.

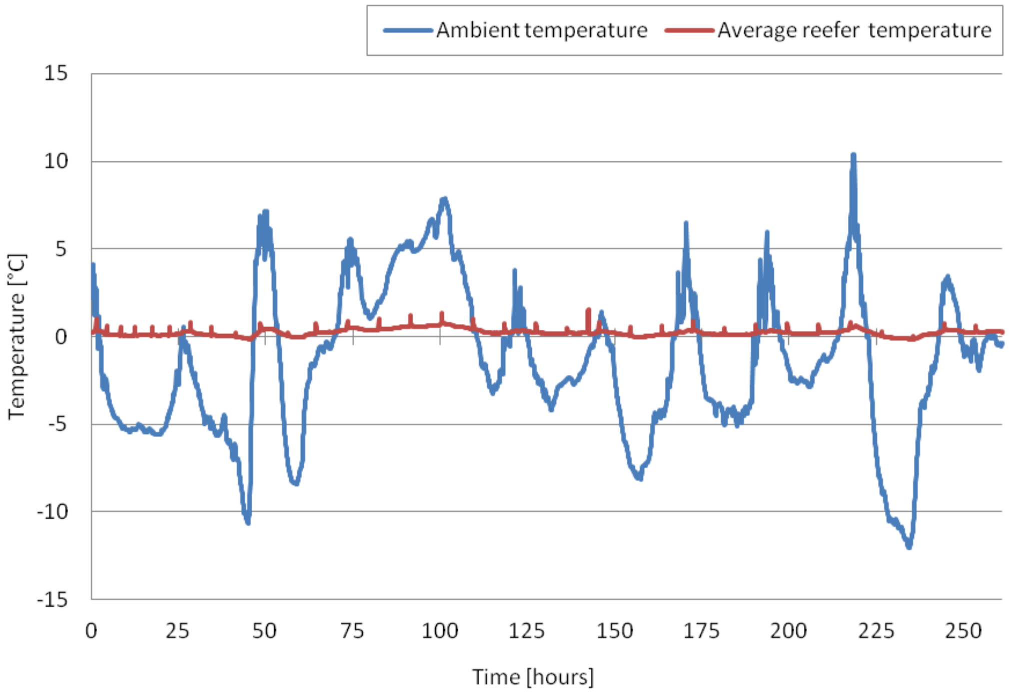


Figure 4.12: Ambient and average reefer air temperature during experiment 3.

Defrosting takes place at 3 to 8 hour intervals up until hour 64 of the time period, after which the refrigeration unit defrosts regularly every 9 hours. Defrosting effects are greatest in cross section 1, at the RU-end and close to the ceiling, as seen in Figure 4.13.

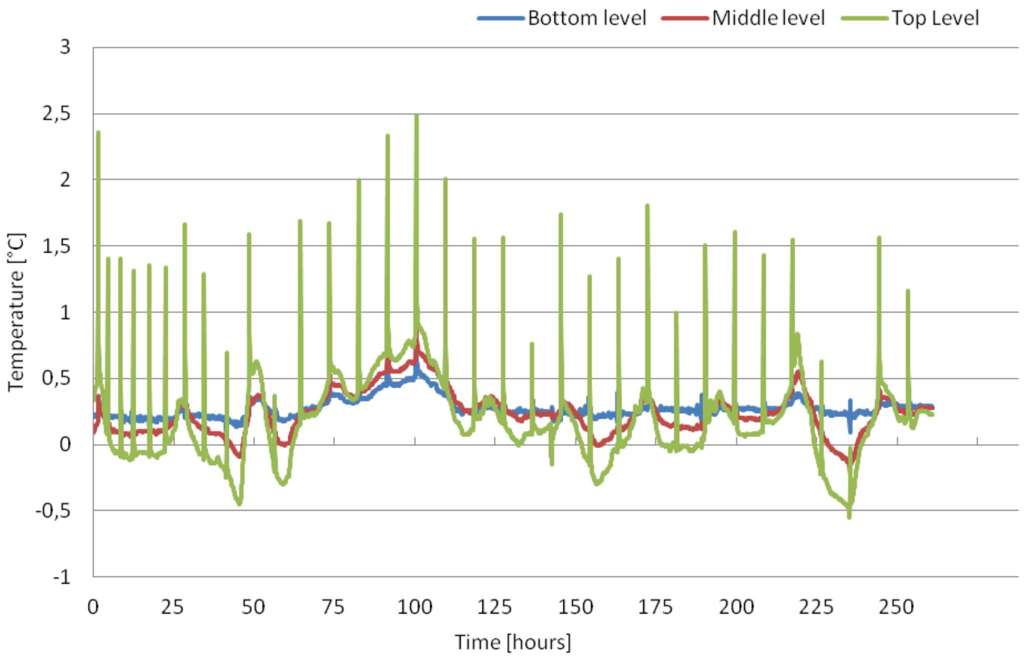


Figure 4.13: Average temperature at top, middle and bottom levels with defrosting effects.

Table 4.3 shows the average temperature of vertical cross sections in the reefer with defrosting effects.

Table 4.3: Average temperature of the vertical cross sections

	Section 1	Section 2	Section 3	Section 4	Section 5
Average temperature [°C]	0.3	0.3	0.2	0.2	0.1

Figure 4.14 shows the relative frequency distribution for all 130,000 measurement observations collected during the period. Values between 0 and 0.5 °C occur most frequently during the observation period.

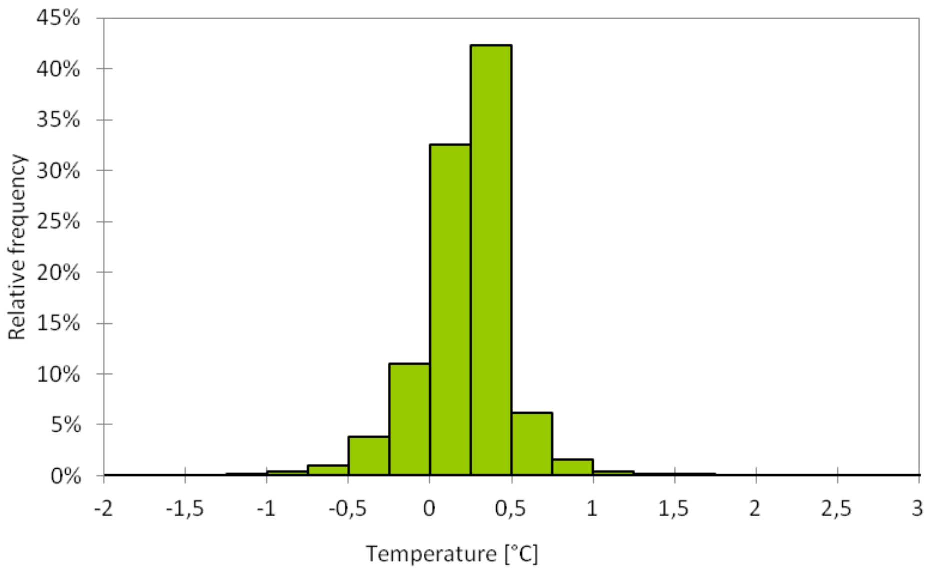


Figure 4.14: Relative frequency distribution for all indivitual temperature measurements inside the reefer during experiment 3.

Figure 4.15 shows contour plots of the average air temperature during the period for the bottom, middle and top levels with a temperature scale from 0 to 0.5 °C. The temperature results in Figure 4.15 are interpolated with a spline function. Black dots mark the positions of temperature loggers used in the experiment. The supply air from the RU cools down as it reaches the reefer door-end and at the top level door-end the average air temperature is close to 0 °C.

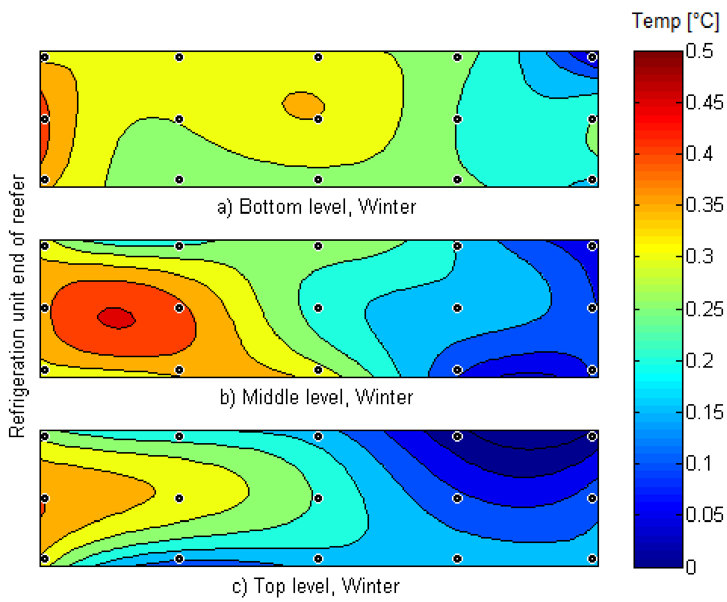


Figure 4.15: Contour plots of average air temperature inside the reefer in experiment 3 for a) Bottom, b) Middle and c) Top levels.

Figure 4.16 shows deviations of average temperature in vertical cross sections from the reefer overall average temperature. The temperature is closest to the reefer average at the RU-end and cross section temperatures fluctuates more with changes in the ambient temperature near the reefer door-end. When ambient temperatures are below -10 °C, the average temperature at cross section 5, at the door-end, decreases to -0.8 °C below the reefer average, while at section 1 the temperature is close to the reefer average. Ambient temperature changes are also found to have more effect at the reefer ceiling and less at the floor area, as seen in Figure 4.13.

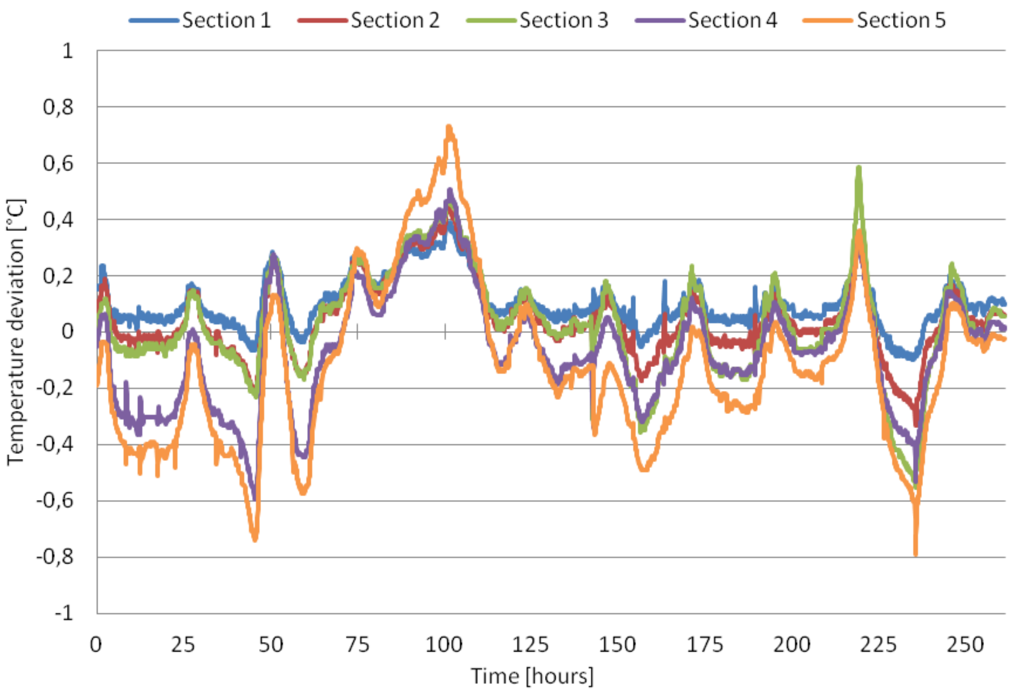


Figure 4.16: Section temperature deviations from reefer average temperature in experiment 3.

Figure 4.17 shows relative air humidity inside the reefer at the RU-end and the door-end. Effects of defrosting on relative humidity are smaller at the reefer door-end. With lower relative humidity outside the reefer the humidity rises at the beginning of the period and measures 79 to 83 % when reaching a balanced state. At hour 143, eight pallets from the door-end were unloaded and replaced with pallets from the chilled store. After this the relative air humidity fluctuates more at the door-end.

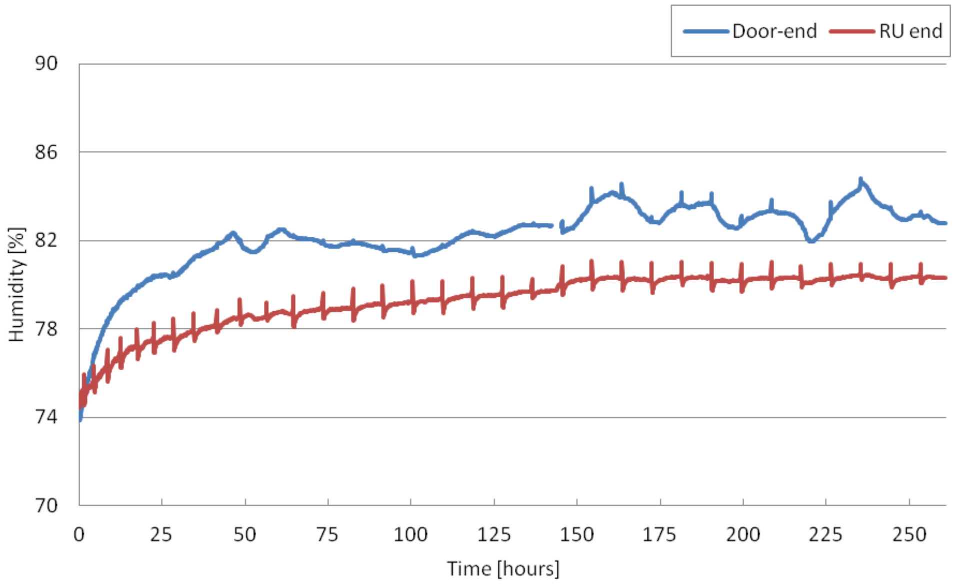


Figure 4.17: Relative air humidity measured at each end of the reefer during experiment 3.

4.4 Experiment 4: Shipping field test

The field test temperature mapping was performed over a period of 116 hours, from April 14th to April 19th 2011. Temperature was measured in the ambient outside the reefer, in the air inside the reefer and in the EPS boxes containing fish loins. Figure 4.18 shows the average temperatures measured during transport of the reefer from the processor in DVK to the final destination in BSM. Sea freight takes place from the shipping port in REY to RTM.

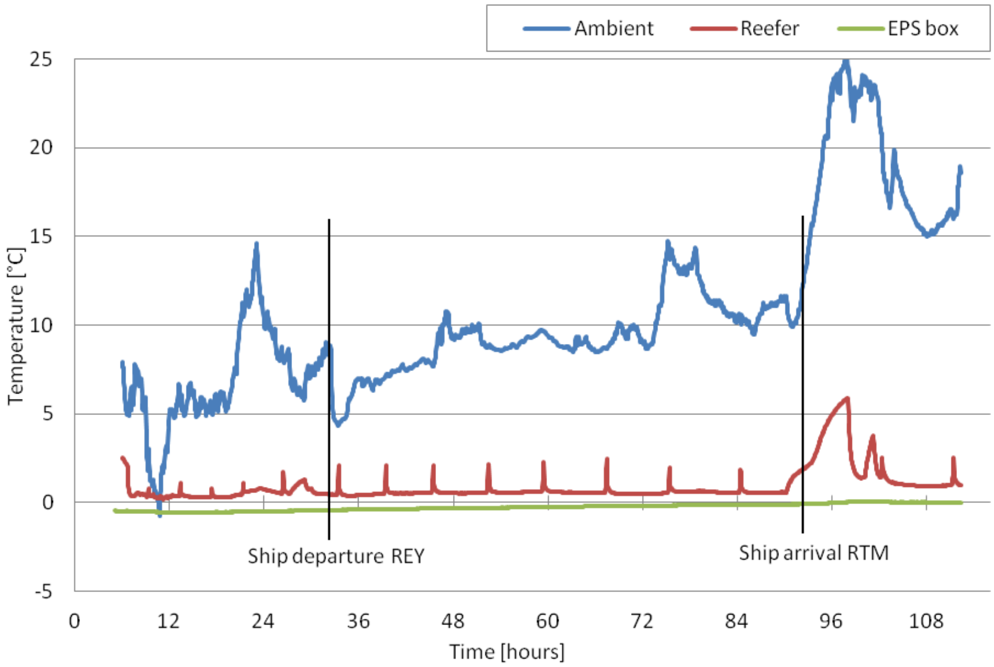


Figure 4.18: Temperature profiles in experiment 4, from the processor (Iceland) to the final destination (France).

The field test timeline and descriptions of the time intervals are shown in Table 4.4. The temperature in the reefer rises slightly when it is disconnected from a power supply before loading onto the ship. The average air temperature inside the reefer throughout most of the shipping is 0.6 °C, before it is unplugged again when preparing for arrival at the port in RTM. There it remains unplugged for approximately 8 hours causing the average air temperature inside the reefer to rise above 6 °C, as shown in Figure 4.18.

Table 4.4: Field test timeline

Time periods [hours]	Description of time intervals
0 – 7	Cod loins production, storage at producer and reefer loading
7 - 31	Land transport from DVK to REY and storage at REY container terminal
31 - 92	Shipping from REY to RTM
92 - 112	Storage at RTM, land transport from RTM to BSM, holding time in BSM
112 - 116	Delivery of pallets 4, 3, 2 and 1 (in chronological order)

Figure 4.19 shows the relative frequency distribution for all 93,000 measurement observations collected during the period. Values between 0 and 1 °C occur most frequently during the observation period.

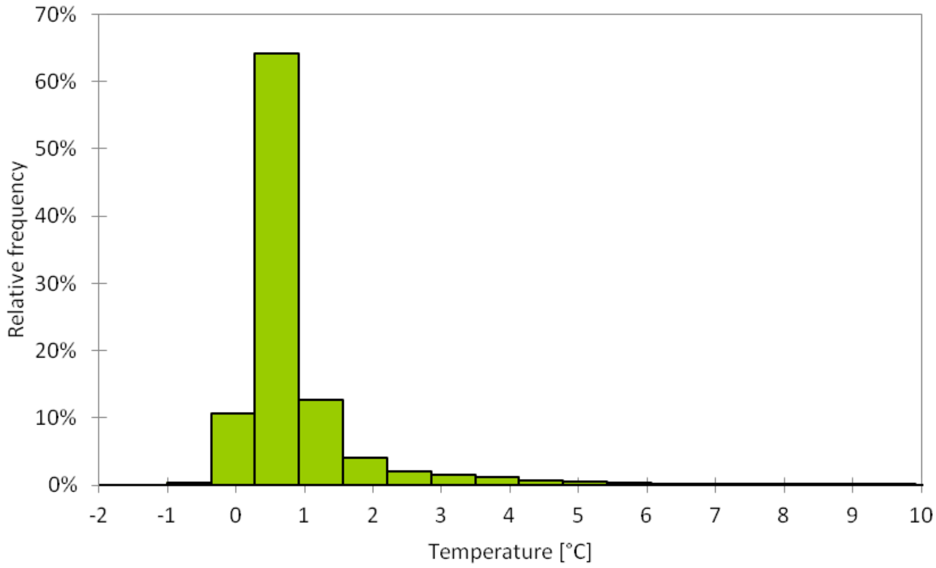


Figure 4.19: Relative frequency distribution for all indivitual temperature measurements inside the reefer during experiment 4.

Figure 4.20 shows the ambient temperature around pallet 1 from packaging to reefer loading. The pallet is stored in a freezer storage after processing and then moved to a loading area before being containerised. While in the freezer storage the temperature in the pallet top corner box lowered but a temperature change was not noticeable in the middle and bottom corner boxes (Appendix xviii).

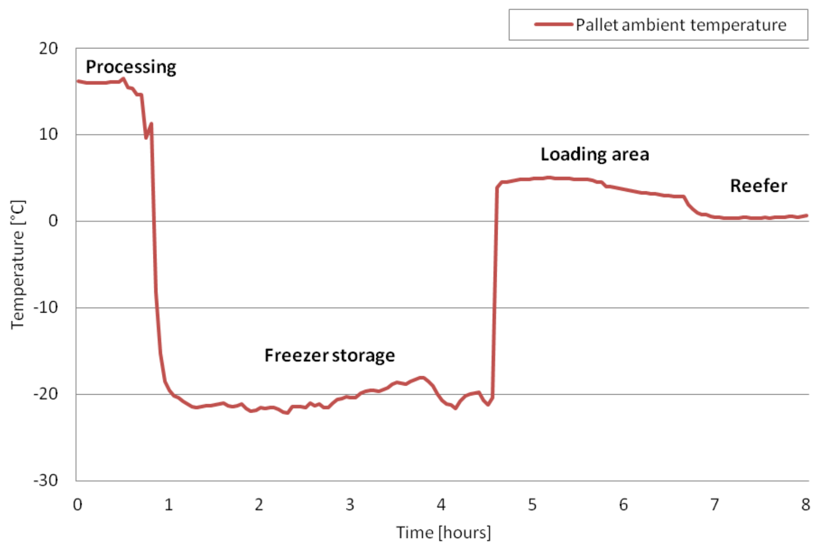


Figure 4.20: Temperature from production to container loading.

Figure 4.21 shows the contour plot temperature distribution in the bottom, the middle and the top levels of the reefer for; I) the whole journey (hours 7 to 112), II) during a steady state part of the sea freight (hours 35 to 85) and III) when the reefer is unplugged at arrival in RTM (hours 90 to 105). Effects of defrosting are included in the contour plots but they were found to have little effect on the average temperature due to the short impact time. The temperature results in Figure 4.21 are interpolated with a spline function. Black dots mark the positions of temperature loggers used in the experiment. All the plots have a common "cold spot" at the middle level and a "hot spot" at the top level at the reefer left door-end side. Figure 4.21 I) and II) share the same temperature scale of 0 to 2 °C. Temperature distribution plots for the whole journey, shown in Figure 4.21 I), show high temperatures at the door-end by the ceiling. The high average temperature in the middle level, at cross section 2, on the right side of the reefer is mainly caused by a high temporary thermal load between hours 19 and 27, when the reefer is located at the shipping port in REY. The sea freight temperature distribution, in Figure 4.21 II), shows the most stable part of the journey in terms of the reefer´s average temperature. Figure 4.21 III) has a temperature scale of 0 to 5 °C, showing the reefer unplugged in high ambient temperature conditions in RTM. During this period the reefer is plugged to a power supply for a short time before being disconnected again. With the refrigeration unit shut off the top level shows thermal load effect from all external walls. Average temperatures reach up to 5 °C during the period but individual loggers recorded temperatures over 10 °C by the ceiling door-end corners.

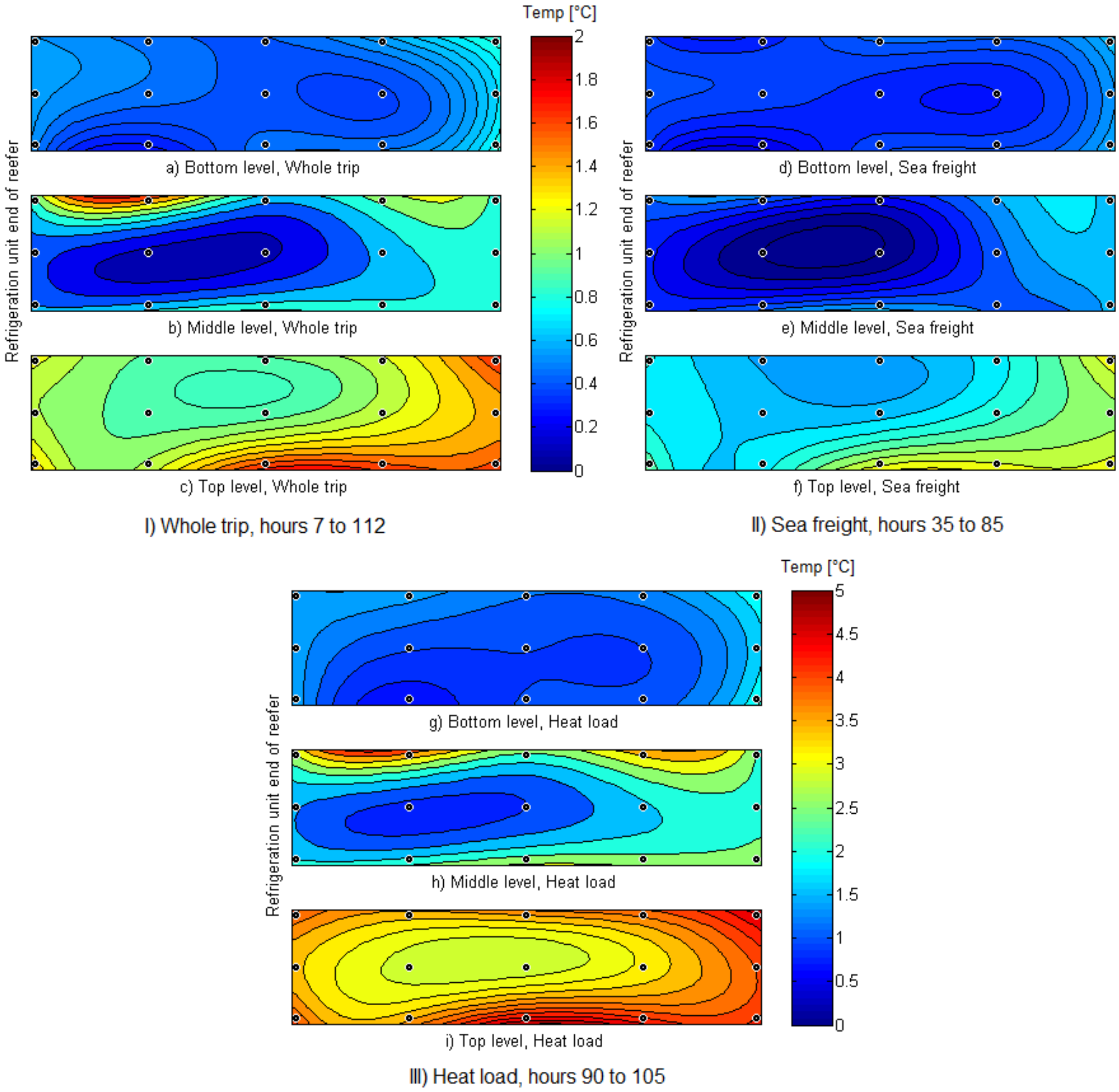


Figure 4.21: Temperature distribution in the reefer during experiment 4, I) Average temperature through hours 7 to 112, II) Average temperature during sea freight hours 35 to 85, III) Average temperature during heat load hours 90 to 105.

Figure 4.22 shows the average temperature of loggers inside EPS boxes in contact with fish loins, from the reefer loading in DVK to delivery in BSM. The average temperature of pallet 4, located by the reefer doors, rises more rapidly than in the other pallets. A temperature rise inside all EPS corner boxes is noticeable when the reefer is unplugged during arrival in RTM. Top corner boxes on pallets are subject to the greatest temperature rise through the journey. Boxes in bottom corners of pallets suffer less thermal load and boxes located in the middle of pallets are not affected, except on pallet 4 (Appendix xxiii).

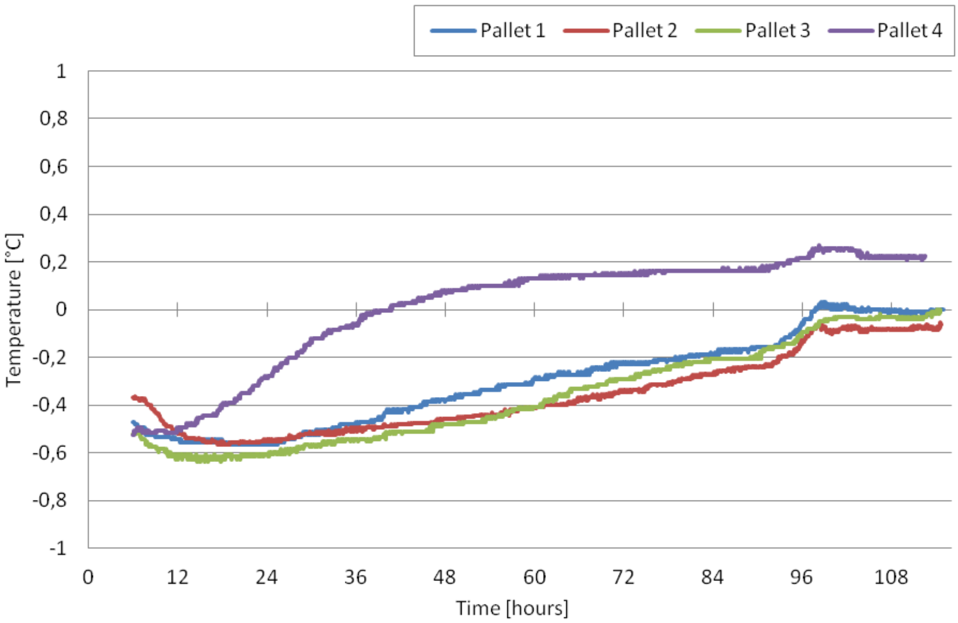


Figure 4.22: Average temperature of EPS boxes from reefer loading to delivery in experiment 4.

Figure 4.23 shows the relative air humidity inside the reefer throughout the period. The relative humidity continues to rise through the journey and then decreases when the reefer is unplugged and unloaded from the ship. The humidity loggers did not give a conclusive result, probably due to poor placement by the pallets plastics wrapping, possibly blocking some sensors. The effects of defrosting are more noticeable at the reefer ceiling and RU-end.

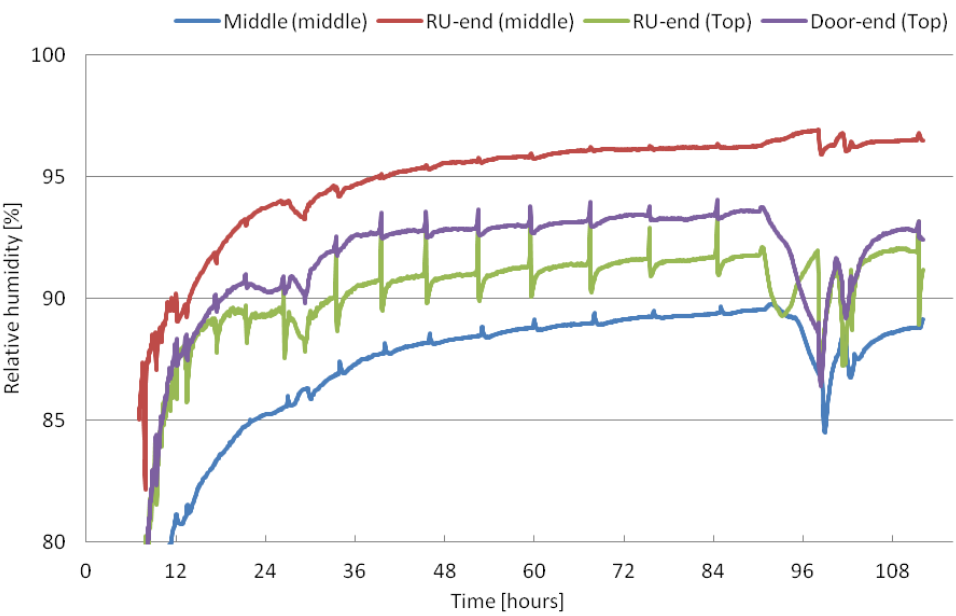


Figure 4.23: Relative air humidity in experiment 4.

5 Discussion

Results of reefer temperature mappings show that high temperatures are generally found at the reefer walls, ceiling and the door-end quadrant. This is in good agreement with results by Moureh et al. (2004), who found high temperatures by the walls and insufficient air flow to the door-end. By modelling the container space and using forced air circulation, directing cool air towards the door-end, they were able to predict better temperature distribution throughout the container space. The results from the field test and summertime experiments also indicate that by pressing the pallets up to the reefer walls, air flow is blocked from where it is needed, to counteract heat gain from the ambience. Smale (2004) conducted air flow and heat transfer simulations of containers where the load was spaced from the walls and found that reducing the space between pallets and the wall caused significant in-package temperature increases.

Measurements of different pallet stowage patterns results in similar average overall temperatures but the temperature distribution is found to be more homogenous using a Europallet stowage pattern, while the Zigzag pattern results show that cold air is circulated excessively before reaching the reefer door-end. Montsma et al. (2011) performed a comparison with similar stowage setups and did not measure a significant difference between pallet patterns; however their results also showed less air flow to the reefer door-end. With covering the first 6 m of the T-bar floor by the RU-end they found that the air flow at the door-end could be improved. The difference obtained between stowage patterns could be caused by larger gaps between pallets in the Zigzag setup resulting in reduced air flow to the door-end. This leads to the assumption that with the Europallet asymmetry, creating a longitudinal gap between pallets closer to one side of the reefer wall, air flow could be directed more to one side of reefer. Using industrial size pallets this gap is at most 8 cm wide but can be 28 cm wide using Euro pallets. The results of the field test show higher temperatures towards the opposite side of the longitudinal gap; however this is not a conclusive result as other external influence factors could have caused more heat gain to one side during the field trip journey, as it did while at the container terminal in Reyðarfjörður before shipping. A study by Tanner et al. (2003) on a Europallet setup found the right side to be warmer than the left side, probably because of differential defrosting of that particular reefer design. In the experiments performed, a difference in defrosting effects on either side is not found to be significant but their main influence area is measured above the middle level by the RU-end. Rodriguez et al. (2006) found that current control strategies for on/off control refrigeration in reefers are insufficient for maintaining industry recommendations of a set point ± 0.5 °C.

Comparison of different reefer types shows that the newer reefers perform slightly better than the older types. The service life of reefers at an Icelandic shipping company is generally estimated to be around 10 years (Sigurðsson, 2010) and many studies on insulated containers (IIR, 1995; Rand, 2007; Montsma et al., 2011) show an increasing deterioration rate with age. Taking into account the prolonged storage life of whitefish at optimal storage conditions, as shown by Lauzon et al. (2010), reefers older than 2-3 years should probably be used for less sensitive cargo than fresh fish.

Results from experiments where bacalao was loaded above the desired temperature stress the importance of pre-cooling the cargo to the desired storage temperature before containerising. With lower heat capacity and less water content bacalao will cool down more rapidly than fresh fish, yet after more than 4 days the bacalao was still cooling down. After a balanced temperature was reached the difference between bacalao pallets on either end of the container was approximately 1 °C. The time required to cool the bacalao, shown in Appendix viii, implies that around 20% of the RU specified cooling capacity is used to cool the cargo.

Studies by Margeirsson et al. (2010) and Mai et al. (2011) showed that the top corner boxes on pallets are in most danger of thermal loads during containerised sea freight. Those studies however did not monitor the exact locations of measured pallets within the reefer. The field test in the current study also found the top corner boxes suffering the most thermal load and that bottom corner boxes are also affected. Temperatures in boxes in the middle of pallets are found to be relatively constant throughout the journey; however temperatures in all boxes, including the middle one, on the pallet at the reefer door-end rises considerably faster compared to other pallet locations. A study by Punt (2005) on temperature variances in a reefer carrying plums also found the pallet closest to the doors to be subject to the least rapid cooling rate.

The influence of changes in ambient temperature is quite noticeable as air temperatures inside the reefers fluctuate accordingly in all four experiments in the current study. The reefer ceiling area and door-end are found to be more subject to changes in ambient temperatures, especially during the summertime. A set point temperature of 0 °C in summertime is found to be immoderate, with average reefer temperatures measuring 1 to 1.5 °C above the set point and generally higher temperatures are found near the door-end. A set point temperature of between -1.5 and -1 °C would be closer to achieving the desired reefer temperatures during summer. Under more favorable conditions during winter, with ambient temperatures around -5 to 5 °C, a mean air temperature of around 0 to 0.5 °C can be expected inside the reefer. This implies that in order not to risk excessive freezing of the fresh fish due to air temperature fluctuations, the set point temperature should not be set lower than around -1 °C during winter. During the field test pallet storage at around -20 °C for four hours was not found to have a significant effect on the temperature inside the EPS boxes. Mean ambient temperatures around fresh fish pallets during storage, handling and transport were mapped by Mai et al. (2011) with the main conclusion that temperature control in containerised sea transport is generally much better than in multimodal air transport chains. Compared to the sea freight mean temperatures mapped by Mai et al. (2011) the field test results in this study measure a higher mean temperature and a shorter total transportation time from the processor to the final destination. The higher mean temperature mapped in the field test implies that the cod loin’s storage life would be shorter than the 11-12 days estimated by Margeirsson et al. (2010) at optimal sea transportation conditions.

Results from temperature and relative humidity mapping during summer and winter experiments indicate a leakage of air by the reefer doors. The doors of a reefer constitute a weak point, as the wear of rubber gaskets or improper handling may result in the doors no longer closing correctly. The frame around the reefer doors can be slightly bent due to external forces, i.e. from container loading, fork-lifts or being set down on uneven ground (Sigurðsson, 2010). This can result in doors becoming less tight and more subject to outside air leaking in. During reefer pre-trip and check-up it is important to constantly monitor this factor and fix regularly if needed.

6 Conclusions

In conclusion the results of the study indicate that temperature control during containerised sea freight may be improved by changes in operation procedures and conditional temperature settings of the reefer. When transporting fresh fish, reefer set point temperatures should be set between -1.5 to -1 °C during summer and -1 to 0 °C during winter because of influences of variable season ambient conditions. Reefers older than 2-3 years should be used for less sensitive cargo than fresh fish as newer reefers were found to perform better. Loading cargo at temperatures above the desired transport conditions should be avoided and the loading should preferably take place in a temperature controlled environment or at least under a shelter during the summertime.

Actions should be taken to force air flow to the reefer´s door-end area, where temperatures and temperature fluctuations were generally found to be the greatest. This could be done by blocking off the T-bar floor at the RU-end of the reefer. The cargo should also be spaced from the reefer walls to allow for air flow to counteract heat gain from the ambience. To achieve this, Euro pallets could be pressed together in the reefer centerline and air bags blown up on both sides between pallets and the walls. This method will however use twice as many air bags to stabilize the cargo compared to the conventional setup. Industrial pallets should be containerised using the Europallet stowage pattern, rather than Zigzag, to achieve a more uniform temperature distribution throughout the reefer.

As the doors of the reefer constitute a weak point regarding leakage, they must be regularly monitored and repaired. The highest temperatures were generally found by the door-end ceiling, so for optimal temperature control the refrigeration unit should be regulated from the temperature in that area in addition to the supply air temperature. Finally, the time reefers are unplugged during transport should be minimised. This is especially relevant prior to loading and unloading the reefer from container ships.

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Measurement devices

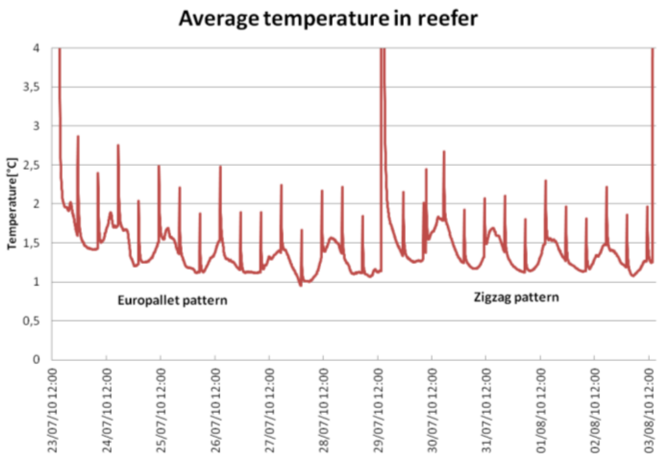
HOBO U12: http://www.onsetcomp.com/products/data-loggers/U12-data-loggers

Ibutton DS1922L: http://www.maxim-ic.com/quick_view2.cfm/qv_pk/4088

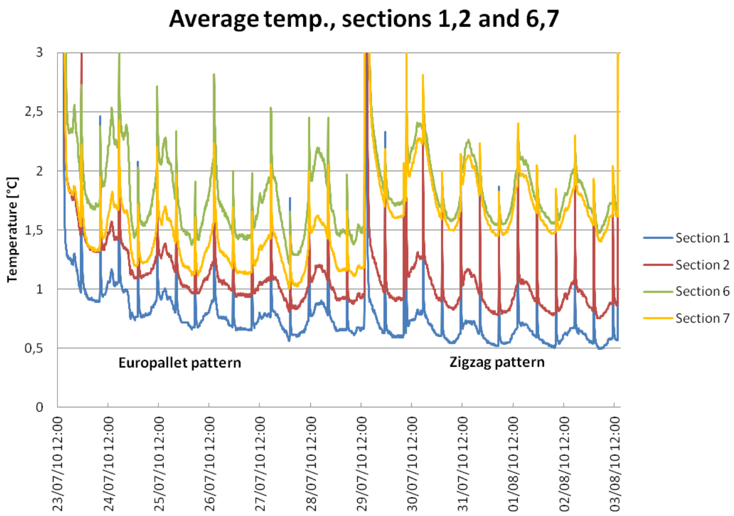
TidbiT v2: http://www.onsetcomp.com/products/data-loggers/utbi-001

Appendix

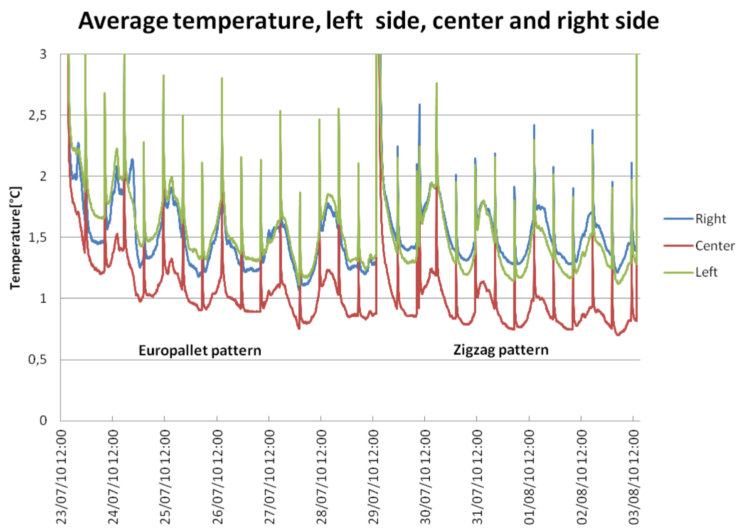
Experiment 1



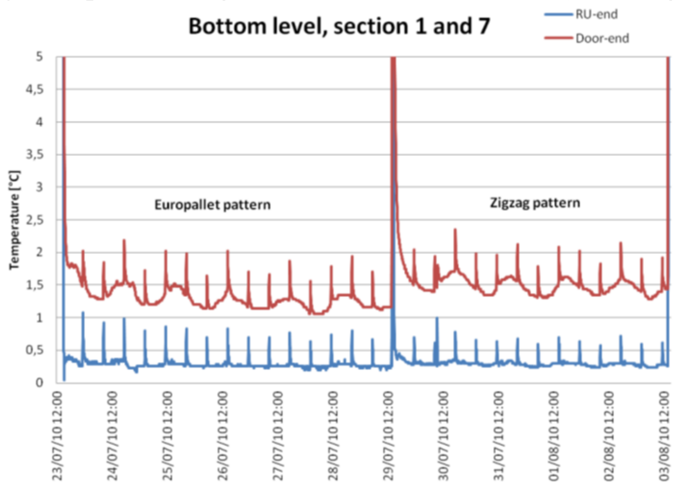
Appendix i: Average temperature of all data loggers in experiment 1.



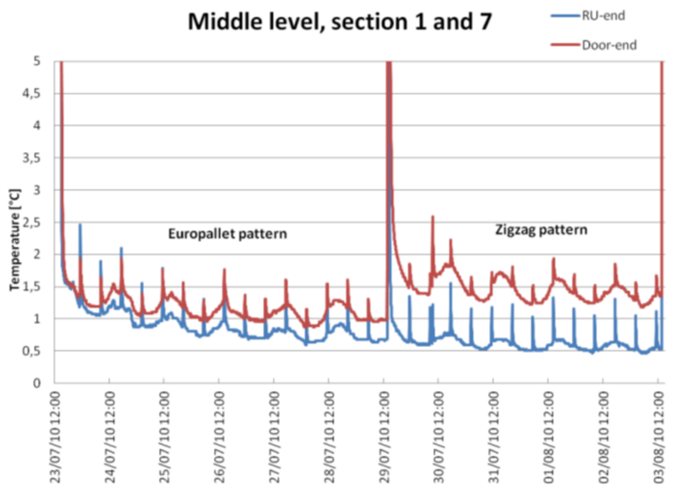
Appendix ii: Average temperature of vertical cross sections in experiment 1.



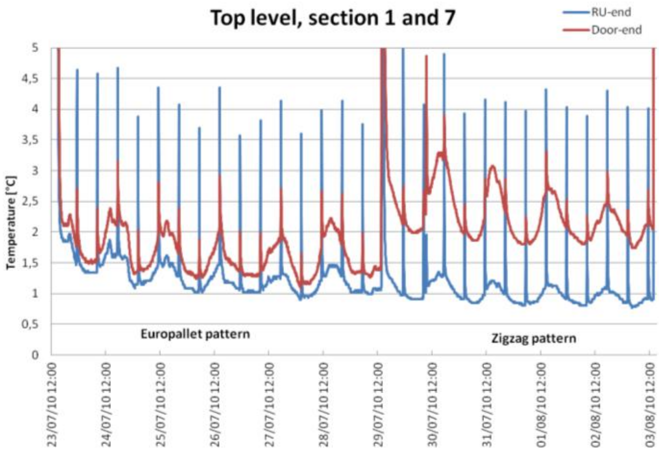
Appendix iii: Average temperature of vertical center and sides (viewed from the door-end).



Appendix iv: Average temperature at the RU-end (section 1) and the door-end (section 7) at the bottom level.



Appendix v: Average temperature of the RU-end (section 1) and the door-end (section 7) at the middle level.



Appendix vi: Average temperature of the RU-end (section 1) and the door-end (section 7) at the top level.

Appendix vii: The table shows the average temperature [°C] over a time period, standard deviation and a f-test comparison on variance in experiment 1.

Variable	Observations	Minimum	Maximum	Mean	Std. deviation
Europallet	864	0,982	2,496	1,313	0,197
Zigzag	864	1,062	2,144	1,265	0,168

F-test / Two-tailed test:

95% confidence interval on the ratio of variances:
] 1,199; 1,567 [

Ratio	1,371
F (Observed value)	1,371
F (Critical value)	1,143
DF1	863
DF2	863
p-value (Two-tailed)	< 0,0001
alpha	0,05

Test interpretation:
H0: The ratio between the variances is equal to 1.
Ha: The ratio between the variances is different from 1.
As the computed p-value is lower than the significance level alpha=0,05,the alternative hypothesis Ha is accepted.
The risk to reject the null hypothesis H0 while it is true is lower than 0,01%.

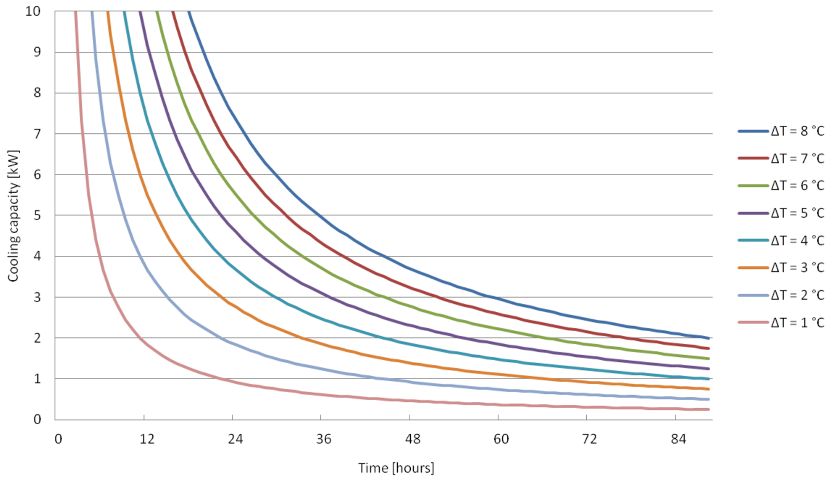
TOST (Equivalence test):

90% confidence interval on the difference between the means:
] 0,033; 0,062 [

Test	Value
Lower bound (TOST)	0,000
Lower bound (90 %)	0,033
Upper bound (90 %)	0,062
Upper bound (TOST)	0,000
Test interpretation	Not equivalent

TOST (Equivalence test) 2:

Test	Difference	t	t(Critical value)	DF	alpha	p-value
Upper	0,048	5,434	1,646	1684,790	0,050	< 0,0001
Lower	0,048	5,434	-1,646	1684,790	0,050	1,000
Total				1684,790	0,050	1,000



Appendix viii: Required cooling capacity for variable initial cargo temperature.

Shows the required cooling capacity for cooling cargo at variable initial temperature down to 0 °C.

$$Q = \frac{M \cdot C_p \cdot \Delta T}{t}$$

Where:

Q = Cooling capacity [kW]

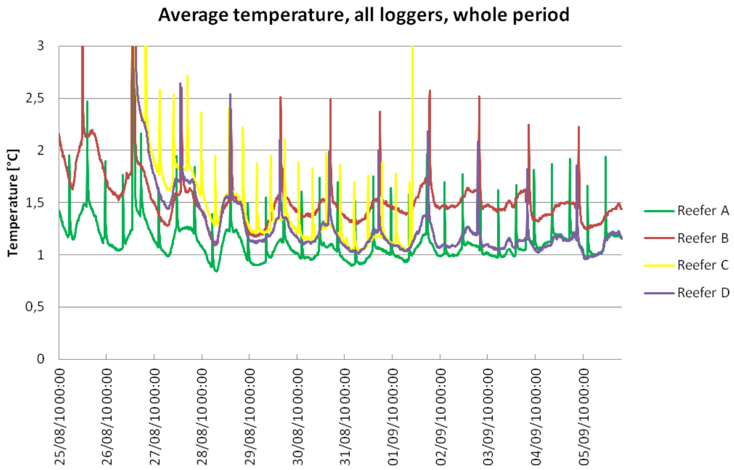
M = cargo mass [kg]

Cp = Cargo specific heat

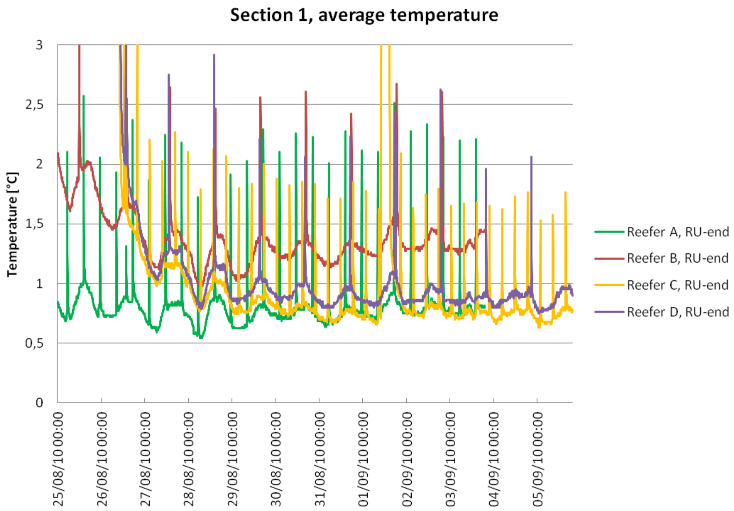
ΔT = Difference between cargo initial temperature and cooling temperature

t = cooling time

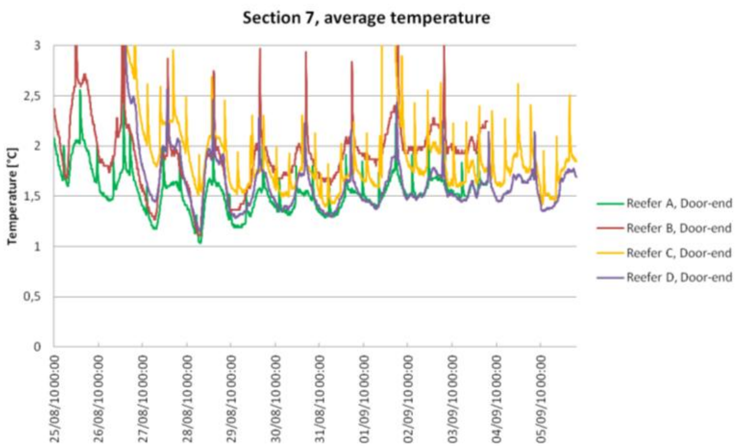
Experiment 2



Appendix ix: Average temperature of reefers A, B , C and D in experiment 2.



Appendix x: Average temperature by the RU-end (section 1).

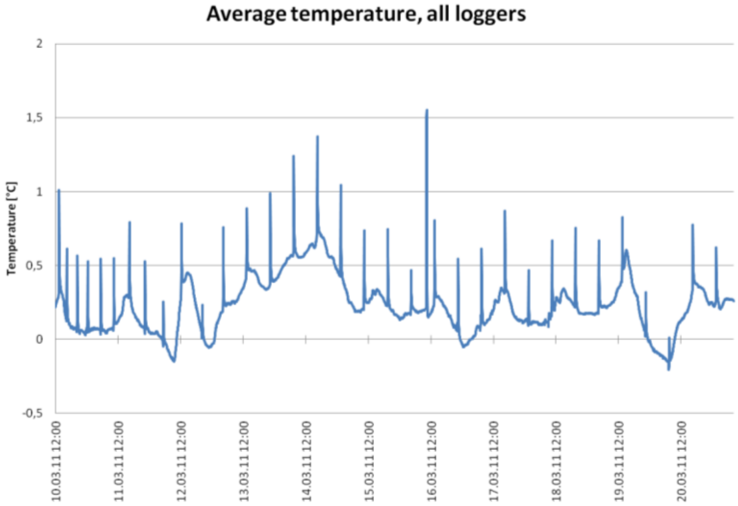


Appendix xi: Average temperature by the door-end (section 7).

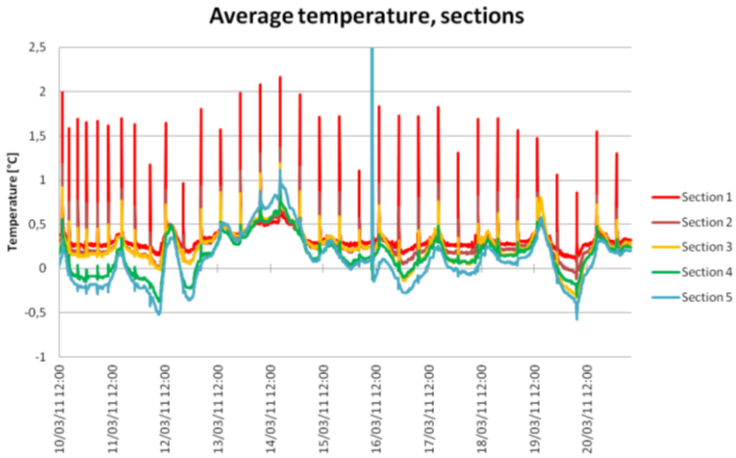
Appendix xii: The table shows the average temperature [°C] over a time period and the standard deviation of the average in experiment 2.

Variable	Observations	Minimum	Maximum	Mean	Std. deviation
Reefer A	901	0,922	1,836	1,053	0,108
Reefer B	901	1,173	2,514	1,436	0,143
Reefer C	901	1,054	2,090	1,247	0,139
Reefer D	901	1,030	2,102	1,197	0,131

Experiment 3

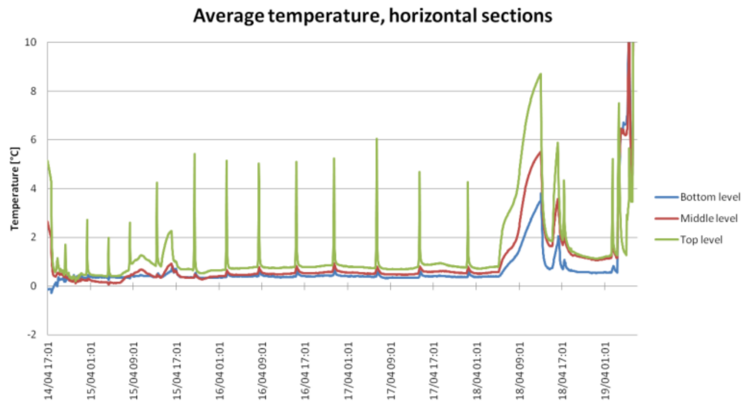


Appendix xiii: Average temperature of all data loggers in experiment 3.

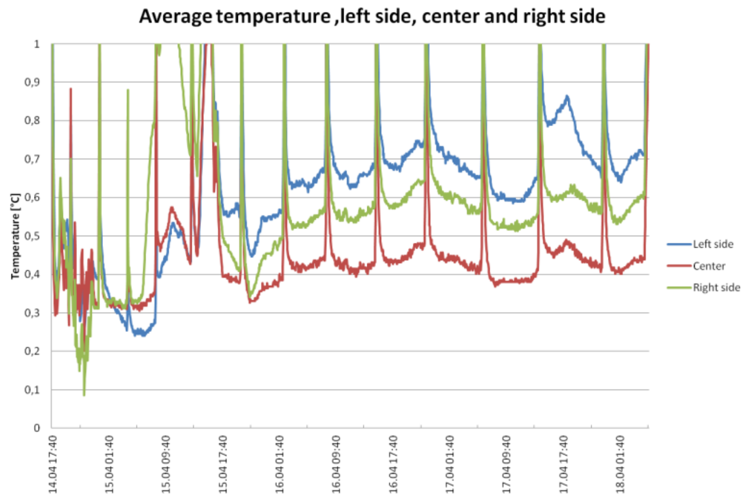


Appendix xiv: Average temperature of vertical cross sections in experiment 3.

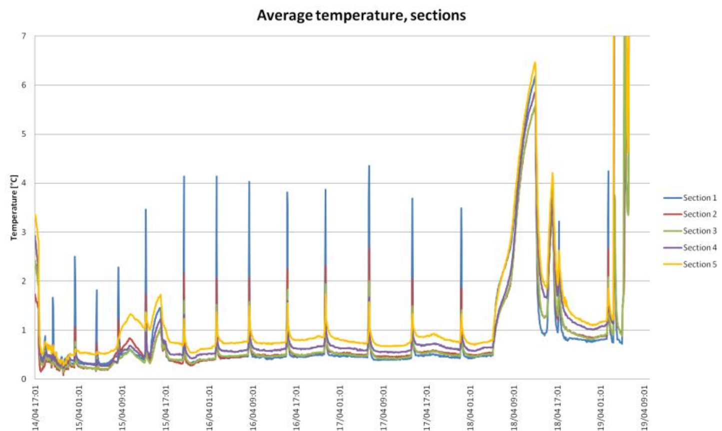
Experiment 4



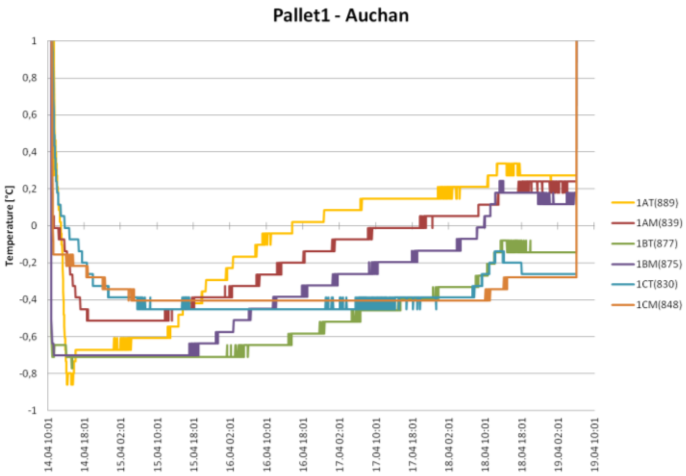
Appendix xv: Average temperature of horisontal levels in experiment 4.



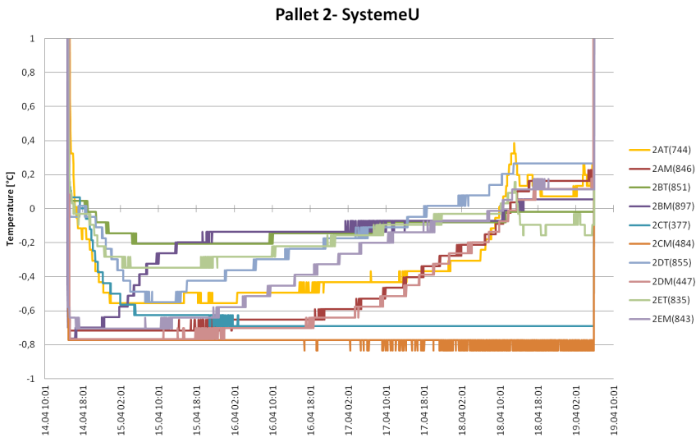
Appendix xvi: Average temperature of vertical center and sides (viewed from door-end).



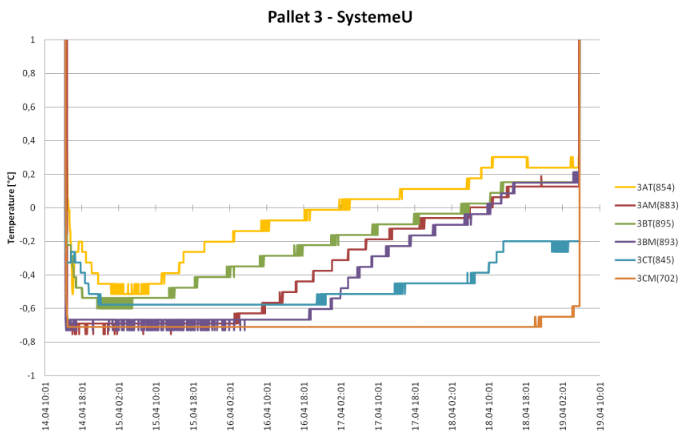
Appendix xvii: Average temperature of vertical cross sections in experiment 4.



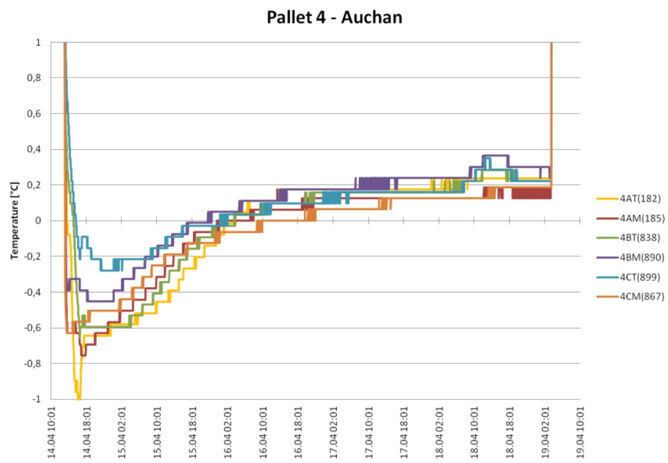
Appendix xviii: Temperature of data loggers in Pallet 1. Box A is the pallet top corner box. Box B is the pallet bottom corner box. Box C is the pallet middle box. T is a corner location of a data logger within a box. M is a the middle location of a data logger within a box.



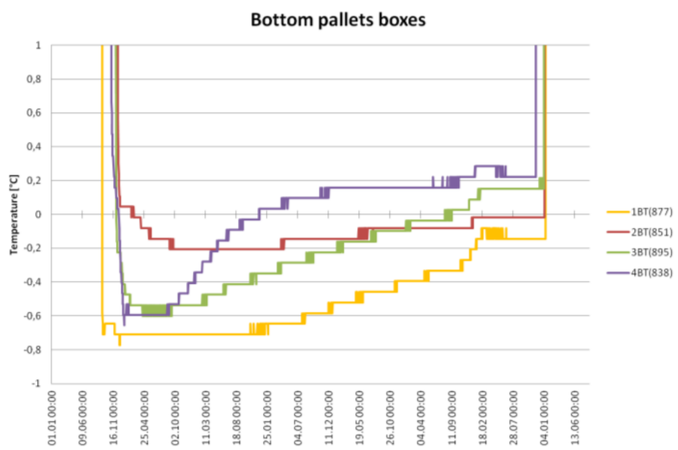
Appendix xix: Temperature of data loggers in Pallet 2. Boxes A and D are the pallet top corner boxes. Boxes B and E are the pallet bottom corner box. Box C is the pallet middle box. T is a corner location of a data logger within a box. M is a middle location of a data logger within a box.



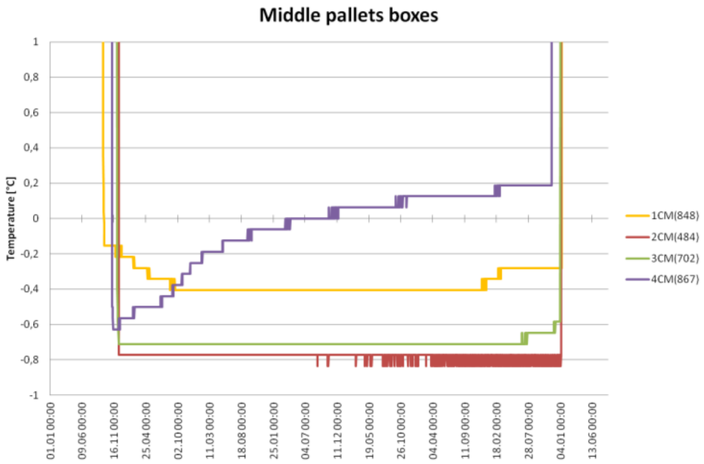
Appendix xx: Temperature of data loggers in Pallet 3. Box A is the pallet top corner box. Box B is the pallet bottom corner box. Box C is the pallet middle box. T is a corner location of a data logger within a box. M is a middle location of a data logger within a box.



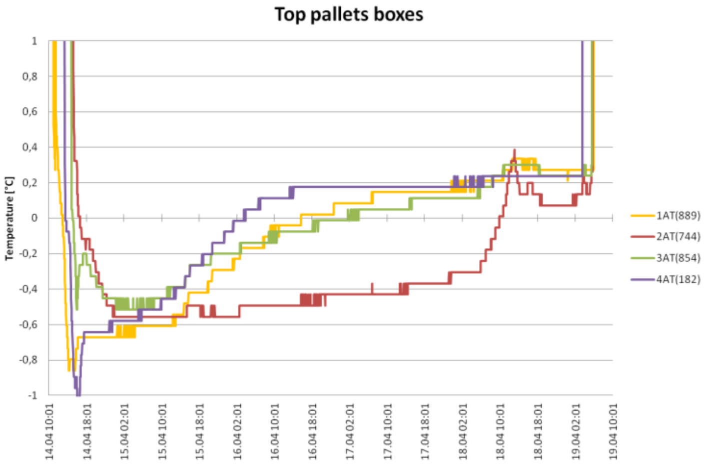
Appendix xxi: Temperature of data loggers in Pallet 4. Box A is the pallet top corner box. Box B is the pallet bottom corner box. Box C is the pallet middle box. T is a corner location of a data logger within a box. M is a middle location of a data logger within a box.



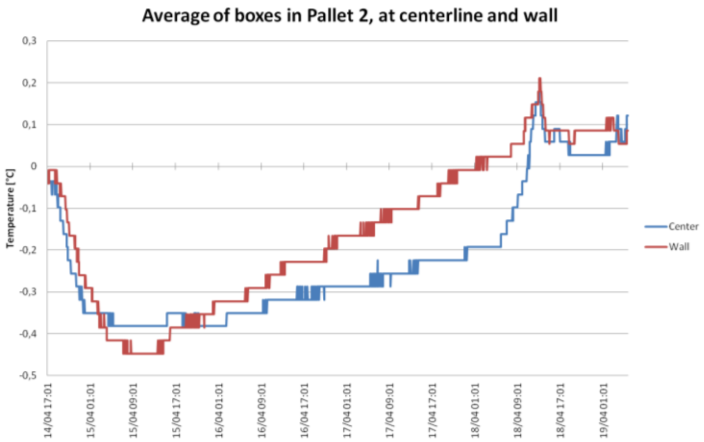
Appendix xxii: Loggers in pallets bottom corner boxes.



Appendix xxiii: Loggers in pallets middle boxes.



Appendix xxiv: Loggers in pallets top corner boxes.



Appendix xxv: Average temperature of boxes in Pallet 2. "Center" are top and bottom corner boxes by the reefer wall. "Wall" are top and bottom corner boxes by the reefer centerline.