



Heat Treatment of Internal Surfaces in Sea Containers

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Executive Summary

Treatment of shipping containers may be required for quarantine and pre-shipment purposes. At present, this is generally carried out by fumigating with methyl bromide, which is poisonous and an ozone depleting substance. International effort is now being devoted to finding alternatives. One such alternative treatment, known as ISPM15, is available for timber products. This involves exposing the products to temperatures in excess of 56°C for at least 30 minutes. This project investigates the feasibility of using this approach for treating the internal surfaces of containers and the surfaces of any cargo contained in them. The project also investigates the use of heat pumps to supply the necessary heat.

The project was carried out in three stages. The first stage was designed to investigate the factors affecting heat loss from naked containers. To do this, a container was placed on open ground in the premises of Applied Research Services, Nelson, and a network of sensors was installed to measure internal air and wall temperatures while heat was supplied and ambient meteorological conditions varied. The results confirmed that the dominant factors controlling heat loss were the ambient temperature and incoming solar radiation.

The second stage of the project was an investigation of heat transfer to simulated cargo items in the laboratory. Heat transfer to a high heat absorbing load (a pail of water) and a low heat absorbing load (a cardboard carton with paper packaging) was investigated. The high heat absorbing load rapidly absorbed large amounts of heat and so heated slowly. The low heat absorbing load absorbed less heat less rapidly. As a result, the surfaces of the low heat absorbing load were able to be raised rapidly into the desired range. By contrast, with the high heat absorbing load, significant heating of the whole mass to almost reach equilibrium was required for the surfaces to reach the desired temperature range.

The third stage of the project involved heat treatment of a simulated load of low heat absorbing cardboard cartons packed as palletised cargo in the above container. Large variations in temperature occurred when the bare container walls were left exposed to ambient conditions. Placement of insulation around the outside of the container resulted in more even heating and reduced variation in temperatures. This was further enhanced by the use of an auxiliary fan to jet air between the cartons. The use of insulation and forced air circulation in combination improved the probability of treatment conditions being met, and proof of concept was demonstrated in one of the trials.

A computer model was developed and validated that allowed heating times, temperatures and energy costs to be predicted. While the model assumed uniform air circulation and predicted air temperature, and could not predict wall surface temperatures, it demonstrated that cost effective treatment of empty containers and containers filled with palletised low heat absorbing cargo is feasible.

Overall, the results indicate that for empty containers and containers loaded with low heat absorbing cargoes, a treatment meeting the requirements of ISPM15 could be achieved in an acceptable time frame. This was particularly evident when the container was insulated and high velocity jets were used to supply hot air. High heat absorbing cargo may be amenable to this form of treatment given that decisions on appropriateness are likely to be required based on tolerance of the cargo to heat and suitable ambient conditions such as warm sunny days. The method is not likely to be useful where loads are crammed into containers and circulation is severely restricted.

A review of currently available technology indicated that the necessary heat could be supplied using an industrial heat pump.

1 Introduction

The Ministry for Primary Industries (MPI) requires suitable biosecurity treatments for the insides of containers to deal with surface-inhabiting hitchhiker pests such as ants and spiders. The research reported below explores the feasibility of using heat as an alternative to methyl bromide for this purpose. Methyl bromide has growing limitations on its use because of its toxicity (ERMA 2005) and environmental impacts as an ozone depleting substance (UNEP 2009). The research was conducted to determine:

1. the likely heat load required to treat the exposed surfaces inside shipping containers;
2. the feasibility of delivering the air temperature required to provide adequate surface treatment to the internals of the container, wooden pallets and packaging, and the exposed surfaces of cargo items; and
3. the feasibility of using heat pumps for this application.

The internationally accepted standard ISPM 15 for treatment of wood specifies heat treatment to raise core wood temperature to a minimum of 56 °C for 30 minutes as an alternative to methyl bromide fumigation (FAO 2009). This study examined the feasibility of extending this approach to surface treat the insides of containers and their cargo, by exploring the heat input required to reach this treatment threshold throughout the container when both empty and loaded. This was a preliminary study to explore proof of concept, to evaluate required heat inputs and delivery parameters in order to support further decision making on operational deployment.

Heat for treatment can be generated electrically or by combustion, typically using oil or gas. Application of heat pump technology is particularly appealing, as it offers the ability to substantially reduce energy costs through using low grade heat from adjacent air, water, earth or process streams.

In this research, experimental work was undertaken to establish a baseline data set. These data informed the development and calibration of a computer model, which was used to determine the likely behaviour of containers and cargoes when heat treated under a variety of conditions. These conditions included the impact of changing weather, time of day, addition of insulation and forced air circulation.

The data set and outputs from the model were used to explore proof of concept for empty and loaded containers, and where loaded, under conditions where the load had low and high heat absorbance. In order for heat to provide an effective biosecurity treatment, the heat must reach most, if not all, of the internal container and cargo surfaces. This presents particular challenges where a container is fully loaded and the load obstructs the free flow of heated air.

For quarantine and pre-shipment (QPS) treatment of sea containers, the doors must remain shut during the treatment to prevent possible escape of mobile pests, so a temporary ‘ducted door’ with internal hot air injection would be required for heating.

While heat has been used to treat fresh fruit, grain, timber and other commodities, treatment of cargoes and determination of temperature-time mortality relationships for target pests was outside the scope of this research.

2 Background

2.1 GENERAL

The following summarises relevant background literature to cover application of heat with a view to using it as a QPS treatment for internal container surfaces.

2.2 SHIPPING CONTAINERS

Shipping containers are formally described as intermodal shipping containers, and are generally manufactured according to dimensions specified by the International Standards Organisation (ISO) and hence also may be referred to as ISO Containers. There are over 30 ISO standards covering specifications, handling, coding and testing of intermodal containers (International Standards Organisation 2006). A typical container has doors fitted at one end, and is constructed of corrugated 3mm Corten steel. Containers are generally 8 feet (2.44 m) wide by 8 feet (2.44 m) high, and either a nominal 20 feet (6.10 m) or 40 feet (12.19 m) long, although variations exist. Dimensions of typical general purpose containers are summarised in Table 2.1. A 20 foot 'high cube' container was used for this project.

Table 2.1: Dimensions of typical general purpose containers (CMA, 2006)

| Category | | 20 foot | 20 foot 'high cube' | 40 foot |
|---------------------|--------|---------------------|---------------------|---------------------|
| External dimensions | length | 6.096 m | 6.096 m | 12.192 m |
| | width | 2.438 m | 2.438 m | 2.438 m |
| | height | 2.591 m | 2.890 m | 2.591 m |
| Interior dimensions | length | 5.758 m | 5.758 m | 12.032 m |
| | width | 2.352 m | 2.352 m | 2.352 m |
| | height | 2.385 m | 2.650 m | 2.385 m |
| Door aperture | width | 2.343 m | 2.343 m | 2.343 m |
| | height | 2.280 m | 2.560 m | 2.280 m |
| Volume | | 33.1 m ³ | 37.1 m ³ | 67.5 m ³ |
| Max gross mass | | 30,400 kg | 30,400 kg | 30,400 kg |
| Empty mass | | 2,200 kg | 2,400 kg | 3,800 kg |
| Net load | | 28,200 kg | 28,000 kg | 26,600 kg |

2.3 HEAT TREATMENT REGIME

The present project involved the use of forced heated air to treat the internal surfaces of containers and the surfaces of their contents. The treatment regime was based on the ISPM15 Standard (FAO 2009), with some additional constraints. For ISPM15 specifications to be met, all surfaces must be heat treated to a minimum of 56 °C for 30 minutes. A maximum temperature of 60 °C was also arbitrarily set, in recognition of the need to minimise any heat damage to contents. In addition, to minimise impacts on commerce, heat treatment had to be completed within 24 hours, with a preferred target treatment time of 12 hours or less.

2.4 HEAT GAIN AND LOSS FROM SHIPPING CONTAINERS

Weiskircher (2008) noted that the temperature inside a container can vary from -21 °C to 57 °C, depending on external conditions, and that direct sunlight can heat the roof to temperatures of up to 70 °C and can cause the upper part of the inside of the container to be more than 15 °C warmer than the outside.

2.5 HEAT TREATMENT USING FORCED AIR TO OPTIMISE HEAT DISTRIBUTION

Various aspects of forced air heat treatment of stone and tropical fruit have been investigated, including airflow and temperature distribution among boxes of fruit. Obenland and Neven (2008) achieved rapid heating of boxes of stone fruit within four hours at a chamber temperature of 46 °C. When controlling for humidity to maintain a dew point of at least 2 °C, Mangan and Ingle (1992) similarly achieved rapid heating of boxes of mangoes within 101 to 213 minutes using an air speed of approximately 0.4 m³/s.

A study of heat penetration into bales of alfalfa/ brome grass hay found that increasing the air velocity and temperature reduced heating times (Opuku et al 2001). Pre-heated air was delivered to the bales using a variable speed centrifugal fan capable of delivering air at up to 0.41 m³/s at a static pressure of 4.49 kPa

Prior research has also demonstrated that the use of internal fans to aid heat distribution facilitates treatment of wooden pallets by maintaining an average internal air temperature of 60 °C for a minimum of 30 minutes (Hoch et al 1998).

In forced air ovens, air flows are optimised by placement of fans and nozzles at suitable locations within the oven (Stigter et al 2001; Heldman 2003). This indicates that the ability of air from a heating system to penetrate evenly throughout a container depends on the configuration of the outlet nozzles supplying the heated air. The velocity profile and its decay with distance, the intensity of turbulence and the rate of entrainment of surrounding air all affect the performance of the jet (Niessen 2002). Nozzle geometry affects the velocity profile and amount of turbulence, and hence the degree of heat transfer (Mujumdar 2006). Nozzles that generate higher turbulence create enhanced mixing between the jet flows and the surrounding fluid (Khan 2007). Air circulation within shipping containers has been improved by fan placement within a container (Hoch et al 1998).

2.6 THE ANALYSIS OF HEAT FLOWS

The analysis of heat flows is well established and there are numerous text books which cover the subject (for example Welty 1978; Rogers and Mayhew 1967; ASHRAE 2009; Lienhard and Lienhard 2012). In general, heat transfer through any system is comprised of convective, conductive and radiative heat flows and the analysis of a given system involves identifying which flows are significant and quantifying these. This includes heat flows in buildings (e.g. ASHRAE 2009) accompanied by extensive tabulations of the heat transfer coefficients and heat capacities that are required to calculate heat flows in given situations. A sea container is also similar to structures such as greenhouses for which heat flows have been analysed (Suhardiyanto and Romdanah 2008), and this included most of the parameters that would be needed for this research.

A container and its contents provide a relatively complex system from a heat flow perspective. Heat sources include energy from the sun, and energy from the heating source. Heat will be lost through the walls of the container under cool conditions without sun and gained during hot sunny weather.

Heat transfer through walls is well covered in the engineering literature relating to air to air heat exchange (Welty 1978; Rogers and Mayhew 1967) and involves primarily convective heat transfer to the hot side of the wall, conduction through the wall, and convective heat transfer of heat away from the cool side of the wall. Matlas (1968) sets out a scheme for walls and roofs that takes these factors into account and also considers heat transfer at a wet surface (such as that wet by rain).

Heat transfer to solid objects, such as load items in a sea container, involves convective heat transfer to the object and conduction of heat from the surface of the body to its interior. This is also well covered in standard engineering texts on heat transfer. (Welty 1978; Rogers and Mayhew 1967).

When sunlight falls on a surface, such as the roof or walls of a sea container, part of the energy is reflected and the rest is absorbed by the surface. The proportion of energy that is absorbed depends on the colour and finish of the surface. Articles by Suerhrcke, Peterson and Selby (2008) and Parker et al (2007) consider the absorption of solar radiation by building structures and give the proportion of radiation that is absorbed by various surfaces.

Apart from the effect of sunlight, radiation does not contribute significantly to heat flows until temperatures become significantly hotter than those anticipated during the treatment of sea containers. For example, radiation is not usually considered in analysis of heat exchangers until temperatures exceed 500 °C (Bell and Mueller 2012).

2.7 MODELLING OF HEAT FLOWS

Modelling procedures are widely used in engineering in order to assist with understanding system behaviour and predicting response to changing inputs (e.g. load and heat). The processes for developing and validating such models are well established, and the National Institute of Standards and Technology Guide to Process Modelling (NIST 2012) provides an overview of the steps involved in model construction, validation and interpretation of simulation results.

Engineering models of heat flow use the information described in section 2.7 to predict heat flows in a particular system. The models generally involve the use of numerical methods, such as the finite difference method, to solve the heat flow equations. (Rogers and Mayhew 1967; Welty 1978; Thirumaleshwar 2006).

The use of computer modelling to predict temperature distributions and air flows across a wide range of related applications is well established. For example, the generation of numerical approximations to the solution of mathematical models of fluid flow and heat transfer, known as Computational Fluid Dynamics (CFD), has been used to predict convective heat flows during sterilisation of liquids in bottles and cans (Heldman 2003; Alvarez-Vasquez and Martinez 1999; Kumar et al 2006) and to model the development of fire inside a 40 foot shipping container (Povel et al 2008). Computer modelling has also been used to develop optimal heating strategies for convection ovens, which use forced air to raise the temperature

of their contents (Stitger et al 2001). Computer models have further predicted variations in temperature, velocity and turbulence within these systems (Heldman 2003).

Finite element methods obtain approximate solutions to engineering problems by dividing up an area of interest into numerous connected sub-regions or elements in which approximate functions are used to represent the unknown quantity. Finite element methods have been employed in computer modelling approaches to predict uniformity of heat distribution of forced air heat treatment of tomatoes (Lu et al 2009) and papayas (Gaffney and Armstrong 1990).

2.8 REDUCING HEAT LOSS FROM CONTAINERS

A variety of methods have been used to insulate bare shipping containers. For example, woven reflective liners reduce temperature fluctuations during shipping of wine and other temperature sensitive goods (JMP Holdings 2008; Weiskircher 2008). Where shipping containers are converted for human occupation, insulation is typically applied as a spray or foam to the exterior of the container (Shipping Container Homes 2009). While these would not be suitable for the present application, they demonstrate that effective insulation is possible.

Insulating tarpaulins could be used to further reduce heat losses. The use of tarpaulins to reduce heat losses from greenhouses has been modelled (Tiwari and Dhiman 2003). There are a variety of thermal insulating tarpaulins available that can incorporate air cells or foam (to reduce conduction), and a foil layer to reduce radiative heat transfer (Inland Plastics 2006; ETP 2005). An insulating tarpaulin has been developed to protect shellfish in transit (Covertex 2005) and similar products are used to provide insulation under concrete slabs during building construction (Insul-Tarp 2010).

In this study, experiments were carried out with a container covered with standard tarpaulins and with a layer of expanded polystyrene foam panels. The latter allows the effect of a relatively well defined insulation layer to be investigated to explore the possible impact of using insulating tarpaulins.

2.9 THE USE OF HEAT PUMPS IN INDUSTRIAL APPLICATIONS

Heat pumps are a potential source of heat for the heat treatment of containers. Heat pumps extract energy from one medium at a lower temperature and deliver it to another medium at a higher temperature. In contrast, other forms of heating require energy from a fuel source to directly heat the air.

Heat Pumps are used in both heating and cooling applications and range in size from small (e.g. a domestic refrigerator) to extremely large (e.g. industrial scale heat pumps). They have many and varied applications, typically extracting energy from air, water, earth or one process stream and delivering it to air, water or another process stream (Silberstein 2002).

There are two main types of heat pump: mechanical and absorption. In mechanical systems, the heat transferred by a working fluid is absorbed when it evaporates and is released when it condenses. Absorption heat pumps compress the working fluid thermally, rather than mechanically (US-DOE 2009). Industrial systems are typically sized from 20 KW up (US-DOE 2009). Mechanical heat pumps used in industrial applications are typically driven by

electric or diesel motors. When a diesel motor is used to drive the compressor, the heat from the engine can be captured by the heat pump. Efficiency can be improved by the use of economisers or intercoolers. Multistage systems can be used to increase the temperature lift (Soroka 2007) as can enhanced vapour injection (Bruderer and Hohl 2010).

Heat pumps typically use working fluids such as hydrofluorocarbons (HFCs), carbon dioxide (CO₂) (Thermea 2010) or ammonia. Ammonia systems are used in large scale heating applications in Norway where heat is drawn from the ground (Stene 2008).

Heat pumps are widely used in drying applications in the timber and paper industries. In dehumidification drying, a heat pump is used to recycle heat that is typically lost to the atmosphere during normal drying. Extensive work has been done in timber drying applications, and this has been found to be efficient for temperatures between 65 and 70 °C (Fernandez-Golfin Seco 2004).

Lower temperature drying (up to 50 °C) has been applied to a wide range of fruit and vegetables (Colak and Hepbasli 2009) and a small scale system is commercially available in New Zealand (Bay Refrigeration 2010). Energy flows within similar heat treatment systems have been analysed (Ceylan 2009). The use of heat pumps to dry grain has also been investigated (FEC 1987) and the drying of herbs has been computer simulated (Phoungchandang 2009).

There is a range of commercially available heat pump systems designed to deliver temperatures up to 80 °C. Typically these are designed to produce hot water rather than hot air, although the addition of a heat exchanger and fan would allow the production of hot air.

The present study proposes that a heat pump could be used to heat the air used for heat treatment of shipping containers. If the treatment system needs to be portable, it is likely that air would be the most likely heat source for the heat pump. In situations where containers can be moved to a particular location for treatment, other heat source options may be available such as sea water, ground or waste heat from nearby industry.

The performance of an electric compression heat pump is typically described using its coefficient of performance (COP). This is defined as the ratio of heat delivered by the heat pump to the electricity supplied to the compressor. The COP typically ranges between 2.5 and 5 depending on the characteristics of the device and the required temperature lift (IEA 2010). The COP drops as the required temperature lift increases. The efficiency of air source heat pumps drops as ambient temperature decreases, and this would need to be taken into account for application to container heat treatment.

3 Methods

3.1 OVERVIEW

Demonstration of feasibility required evidence that an operational heat treatment system could deliver sufficient energy to raise container and cargo surfaces to the required temperature for the required time at acceptable cost. To achieve this, the system would have to deliver sufficient energy to heat air and surfaces throughout loads and offset losses through the walls. It would need to do this for a range of container types, meteorological conditions and cargoes,

In order to compile the evidence needed to explore feasibility and draw robust conclusions, a programme involving computer simulation and experimental testing was undertaken. Using established equations, a computer model was constructed and a series of initial tests were used to define key parameters in the model and to test its output. At this early stage, the model was used to assist planning of further tests designed to enable its validation and explore various aspects of the heat treatment process. Data from these further tests were used for model validation by comparing fit of simulated outputs with observations. Most of these tests were initially conducted in an empty container over a ten day time span and a broad range of conditions, and for final validation, against a test which provided experimental evidence about feasibility. In this test, the same container was filled with a low heat absorbing load and with insulation and application of heat.

Once validated, the model could be used with confidence to predict the type of system most likely to meet treatment objectives and also to predict likely limitations that are likely to be encountered.

Following the above scheme, a rudimentary simulation model was constructed and used as a tool to assist planning experimental work, and as a platform for further development. The project developed as follows:

1. Field tests were conducted on an empty 20 foot container to obtain base measurements and understand heat flows between the inside and outside of the container, including establishing the relative contribution of factors affecting heat flows and identifying the important ones to include in the model;
2. Heat flow into simulated cargoes was explored, and included imitation but representative items of low and high thermal capacity;
3. Field tests were conducted on the 20 foot container filled with a low heat absorbing load to measure temperature profiles and distribution and explore feasibility of heat treatment under various ambient weather conditions with adjustments to heating arrangements and insulation;
4. In parallel with the above, the simulation model was developed and validated;
5. Computer simulations were run using the validated model to predict feasibility of treatment under a range of conditions.

3.2 THE SHIPPING CONTAINER

A 20 foot high cube shipping container was used for the project and was located on open ground at the premises of Applied Research Services Ltd., Nelson. The container had an ISO

code of 25G1 with corrugated steel sides, a wooden floor and vents in the upper part of the cargo space (Fig. 3.1). Dimensions were the same as those provided for high cube containers in Table 2.1.



Figure 3.1: Shipping container used for ambient heat loss tests.

3.3 TEMPERATURE MONITORING

Temperatures were monitored using 64 Type K thermocouples interfaced via four Advantech PCLD-788 Multiplexer Boards to an Advantech PCI-1710 HG multifunction interface. The PCI-1710 HG provided sixteen twelve bit high gain analog inputs. The multiplexers connected each thermocouple in turn to channel 1 of the interface with a 200 ms delay between readings to allow the switching relays to settle. All thermocouples were read within 13 seconds. Data were recorded at 5 minute intervals, except where noted, which allowed changes in temperature to be tracked and data volumes to be managed.

The cold junction temperature of the thermocouples was monitored using a semiconductor temperature sensor ($24.4 \text{ mV}/^\circ\text{C}$) located on the PCLD-788 boards. A fan installed in the cabinet ensured all the cold junctions were at the same temperature. The cold junction sensor was monitored continuously via Channel 0 of the interface. Thermocouple calibration was confirmed using ice point and boiling point (hypsometer) measurements.

Fourteen channels remained unused and were available for other monitoring purposes.

Information from thermocouples and analog inputs was recorded and monitored using software that was purpose written in Microsoft Visual Basic 6.0 Professional and Advantech

ActiveDAQ controls. The software controlled the selection of individual thermocouples inputs via the multiplexers and converted voltages and other analog inputs into the correct units based on the calibration data.

3.4 WEATHER MONITORING

A commercial weather station (Jaycar XC0348) was used to monitor ambient temperature, wind speed, wind direction, rainfall, relative humidity and barometric pressure. The sensors for this station were located on the roof of the container (Figure 3.2). Data from the sensors were relayed back to a base station located in the adjacent building via a radio link and passed to the monitoring computer via a RS232 link. Software supplied with the weather station was used to monitor and record the weather data.

In addition to commercial weather data, the level of sunshine was monitored using a multi-directional 5 channel pyranometer (Fig. 3.3). The pyranometer was constructed using PDB-C139 silicon photodiode sensors from Advanced Photonix Incorporated covered with Teflon film to minimise cosine error. The sensors were calibrated by comparison with a calibrated Middleton SK08 pyranometer and the current delivered by each diode to a 470 Ω resistor was monitored (Fig 3.4). Five diodes were embedded into the faces of a cube and the cube was oriented in the same way as the container so that the response from each sensor gave a measure of the solar radiation falling on the corresponding wall of the container.



Figure 3.2: Weather sensors located on the container roof.

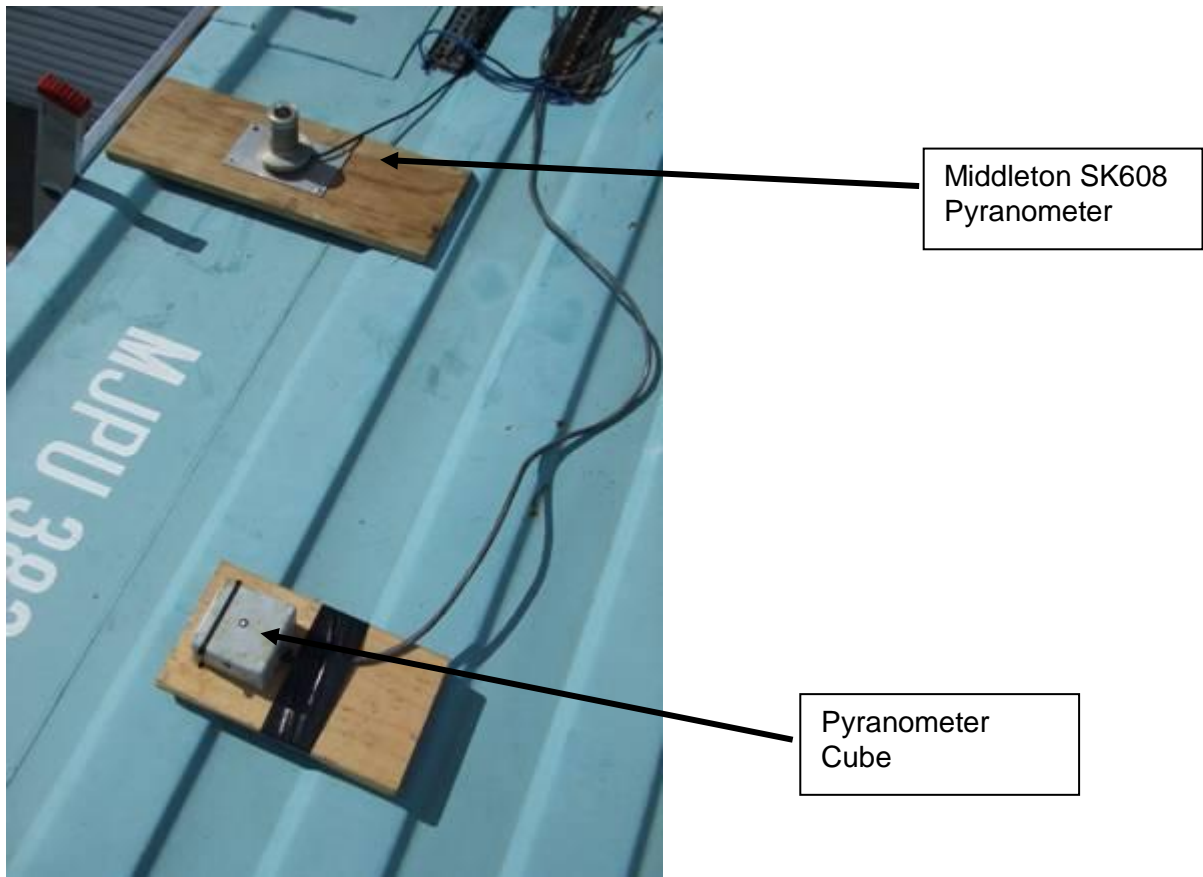


Figure 3.3: Measurement of solar radiation.

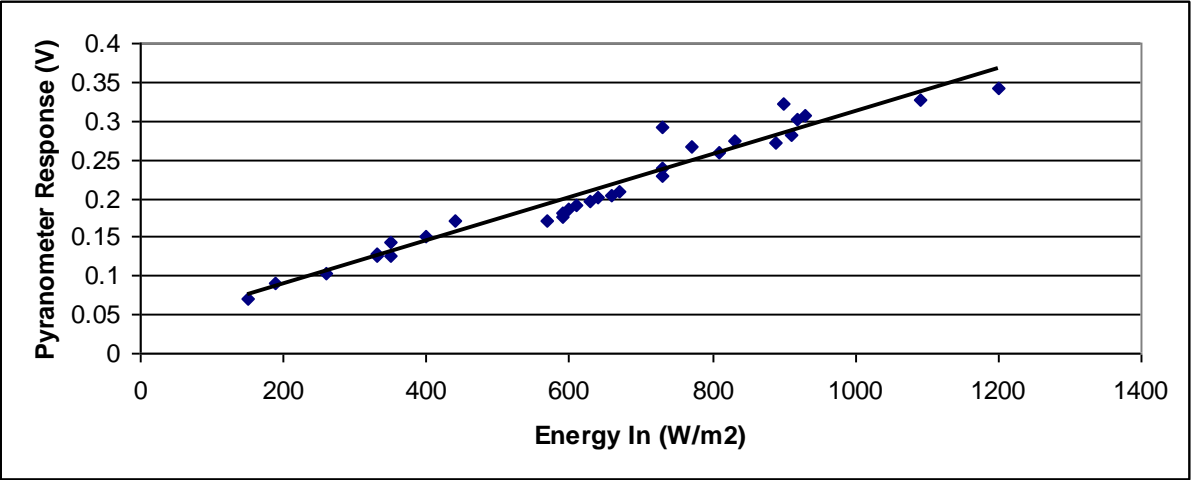


Figure 3.4: Pyranometer calibration curve.

3.5 POWER INPUT MONITORING

The power input to the heater and fan placed in the container was monitored using a calibrated Email 5196B single phase Watt Hour meter with a pulsed output (1000 impulses per kWhr). The impulses were passed to the counter input of the PCI-1710HG interface and the counter input was read using the monitoring program. The power to the 21 kW heater used in the full load trials was monitored using a Ferranti FMmX50 Watt hour meter.

3.6 EMPTY CONTAINER TESTS

Tests were carried out on the empty uncovered container to measure the rate and uniformity of heating, the effect of weather conditions and the effect of heating and cooling on the temperature of air inside the container and its internal wall temperatures, and to provide data to calibrate and validate the model.

Thermocouples were attached to the centre of the walls and ceiling of the container by sticking them to the surface with self adhesive tape. Thermocouples were also suspended in the internal air using plastic bands. A fan was used to mix the air within the container and a heater was used to provide heat input. The configuration of these components is shown in Figure 3.5.

A 6 kW heater was used, which gave an adequate temperature rise and sufficient measurements to calibrate the model. The model was then used to predict the heat input needed to achieve the required treatment, which was valuable for planning further tests.

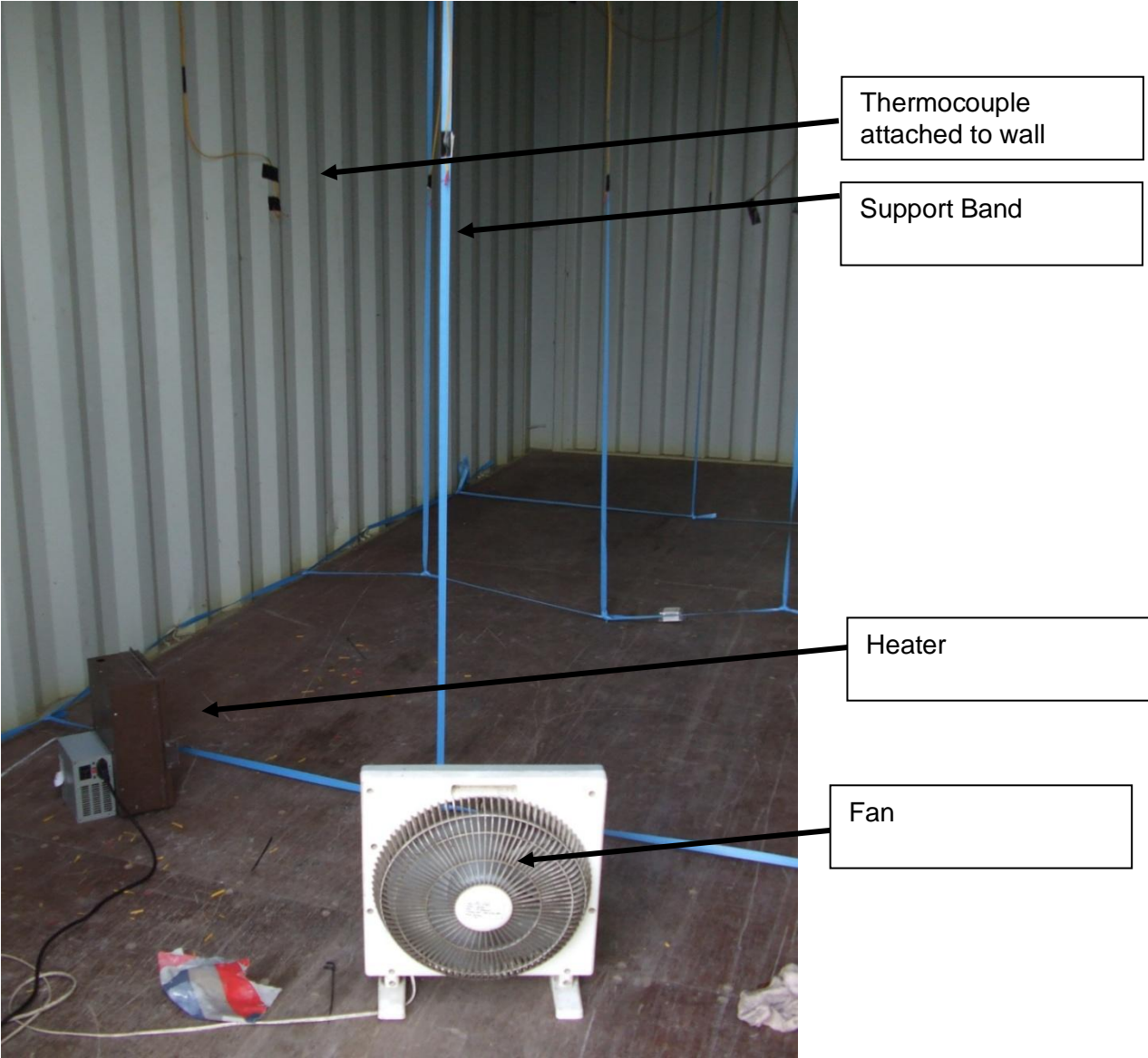


Figure 3.5: Arrangement used for heat loss measurements.

3.7 TESTS ON SIMULATED CARGO ITEMS

In order to understand the impact of cargo loads on heat treatment application, it was necessary to determine heat flows into low heat absorbing (low heat capacity) and high heat absorbing (high heat capacity) items of simulated cargo. This information was required for the model to predict the temperature time profiles and rate of energy input needed to heat the surfaces of each cargo type until they reached the designated treatment temperature.

3.7.1 Tests with a Pail of Water (High Heat Capacity Load)

A pail of water was used to simulate a high capacity heat load. Tests were conducted in an enclosure of medium density fibreboard 1800 (high) x 1500 x 1500 mm. The enclosure was supplied with 3kW of heating controlled to a maximum temperature of 60 °C using a Fuji PXR4 digital temperature controller and a fan to ensure the air temperature was relatively uniform. A single 20 litre HDPE pail filled with water and fitted with a close-fitting lid was placed on a wooden pallet inside the enclosure.

Air temperatures were measured with 8 thermocouples. These were located at mid points on each wall projecting 100mm into the interior and in the roof midpoint centre projecting down 100 mm. Additional sensors were placed:

- 50 mm off the floor in the air space inside the pallet;
- beside the pail 50 mm and 250 mm above the pallet;
- 50 mm above the top of the pail.

The pail contained 20 litres (± 0.1 litres) of water. Pail surface temperatures were measured using 3 thermocouples held to the surface with black self adhesive tape to ensure that they were in good mechanical contact with the surface. These were placed at the following locations:

- centre top of pail;
- midpoint side of pail;
- centre of base at a point where the pail was in contact with the pallet.

The temperature of the water in the pail was measured with three thermocouples located as follows:

- near the top surface (upper);
- in the middle;
- near the base of the pail (lower).

3.7.2 Tests with a Single Carton (Low Heat Capacity Load)

The same arrangement of test enclosure and air temperature measuring thermocouples described in Section 3.7.1 was used for this test. A low heat capacity load was simulated by placing a corrugated cardboard carton (450 mm high x 750 long x 450 wide) inside the test enclosure instead of the pail. The carton contained a small 'inner' box (300 mm x 150 mm x 50 mm). The carton was filled with long sausage bubble wrap. Thermocouples were placed on the outer surface of the carton and at various locations inside the carton. The temperature was controlled at 58 °C for this test.

3.8 TRIALS WITH THE CONTAINER WITH A LOW HEAT ABSORBING LOAD

3.8.1 Overview

These tests were conducted in the shipping container with a low heat absorbing load to determine the required heat input and delivery configurations needed to achieve treatment temperature. This included measuring the uniformity of heating with various methods of air distribution and the effect of adding insulation.

3.8.2 Low heat absorbing load

A cargo of low heat absorbing materials was prepared by filling cardboard boxes with crumpled newsprint. Two sizes of standard cardboard cartons were used for this test (Table 3.2).

Table 3.2: Cardboard cartons and filled weights.

| Size | Dimensions (mm) | Total Number in Load | Filled Weight (kg/ carton) |
|-------|-----------------|----------------------|----------------------------|
| Large | 500 x 500 x 450 | 175 | 1.52 |
| Small | 250 x 250 x 570 | 103 | 0.58 |

The cartons were stacked in two tiers, with two layers of large cartons to each tier on 16 standard wooden pallets (1200 x 1000 x 140 mm). The small cartons were used to fill up the head space on the upper tier, leaving a gap of approximately 50 mm to the roof (Fig 3.6). Table 3.3 gives the air spaces between the blocks of cargo and between the cargo and the container walls.

Table 3.3: Air gaps around the carton stacks.

| | Approx distance (mm) |
|------------------------------|----------------------|
| Container end to cartons | 60 |
| Container side to cartons | 100 |
| Container roof to cartons | 50 |
| Gap between each pallet load | 50 |



Fig. 3.6: Stacking pallets and placing thermocouples, and the arrangement of the load on pallets.

3.8.3 Thermocouple placements

Sixty four thermocouples were placed in three vertical transects running longitudinally down the container. The first transect ran down the left hand side, the second down the centre and the third down the right hand side (Fig 3.7). Thermocouples were either attached to the load surface or placed in the air adjacent to the load. Some thermocouples malfunctioned and behaved erratically during tests, and the information they generated was removed from temperature plots.

No detectable difference in temperature was observed between thermocouples placed adjacent to each other on the load surface or in air. This indicated that the temperature of the load surface and the adjacent air were the same.

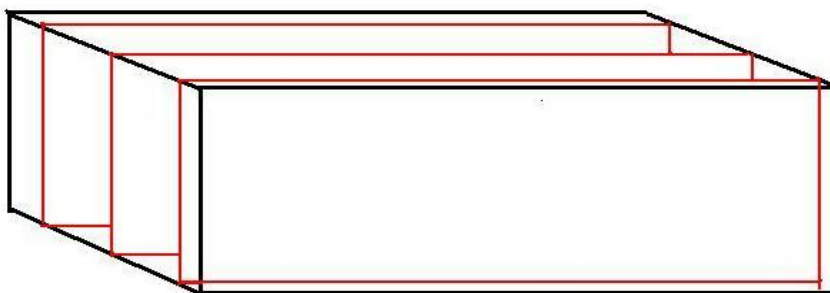


Figure 3.7: Transects along which thermocouples were placed (red outlines) within the container (black outline).

3.8.4 Heat Treatment Unit

A plywood panel was fitted to cover the doorway of the container and a heating unit was attached to this to deliver hot air to the container (Fig. 3.8). Heat was provided by a 21 kW electric heater with adjustable output via seven individually switchable 3 kW elements in a 350 mm duct with an integral fan. The rectangular inlet and outlet had 620 x 480 mm apertures. A number of configurations were tried, including delivering hot air to either the top or bottom of the container and use of an auxiliary fan and flexible ducting to improve air flow and mixing.

Nine evenly spaced measurements of air flow through the system were made across the duct in a 3 x 3 grid pattern. The measured velocities varied between 1.0 and 5.2 m/s with an average of 2.9 m/s and a standard deviation of 1.1 m/s. This corresponded to a volumetric flow rate of 0.87 m³/s.



Figure 3.8: The heating unit fitted to the container door way.

3.8.5 Impact of covering and insulation

Initial tests were carried out without covering the container. Standard polyethylene weave tarpaulins were used for one test, which also trapped a layer of still air between the tarpaulin and the container, adding to the insulating effect (Fig 3.9). For remaining tests, panels of 40 mm thick EXPOL ThermaSlab S expanded polystyrene insulation were strapped to the outside surfaces of the roof and walls. Manufacturer's data for this product indicated a density of 16 kg/m³ and an R value of 1.05 m²K/W. The same material was used where additional insulation was strapped on to the doors.



Figure 3.9: Tarpaulins used to cover the container.

3.8.6 Impact of airflow

Some experiments were carried out with an auxiliary fan (Brooks Crompton Betts Model 61S146-02, 600W, 1360 RPM centrifugal type) attached to the exit duct of the heater to increase air flow and velocity (Fig. 3.10). The unit took up space inside the container and it was necessary to remove some cartons to accommodate it. Air from the fan's 200 mm diameter exit was directed through a cone with a 105 mm outlet. Nine air flow measurements were made across two perpendicular axes of the 200 mm diameter section of exit duct. The measured velocity varied between 7.5 and 10.2 m/s with an average of 9.2 m/s and a standard deviation of 0.95 ms. An average velocity of 9.2 m/s corresponds to a volumetric flow rate of 0.28 m³/min and an exit velocity of 32 m/s through the 105 mm diameter outlet. The air outlet was pointed between pallet loads of cartons in the centre of the container about 300 mm above the floor.



Fig. 3.10: The auxiliary fan fitted with outlet cone.

For some tests, air from the outlet of the heating unit was captured using the arrangement shown in Fig. 3.10 and directed via the auxiliary fan to three 100 mm diameter flexible ducts.

(Fig 3.11). During one experiment the flexible ducts were placed in the container to direct air along the roof of the container, while in another experiment they were placed to direct air at floor level.

Based on a volumetric flow rate of $0.28 \text{ m}^3/\text{min}$ measured for the auxiliary fan and a combined outlet area of 0.024 m^2 for the three flexible ducts the exit velocity from the flexible ducts was calculated to be 11.9 m/s .



Fig. 3.11: The auxiliary fan fitted with three outlet hoses.

3.8.7 Examination of temperature data

The data from these tests were examined using real time plots and a spatial presentation to enable hot and cold spots to be identified.

For real time plots, outputs from thermocouples was graphed together against time, along with prevailing weather as represented by ambient air temperature, radiation, wind speed and rainfall. This provided an immediately accessible summary of system performance and enabled conclusions about performance to be drawn in relation to heat delivery and insulation.

A purpose written Visual Basic program called MAFanimate enabled visual depiction of changes in temperature distribution as time elapsed. The data collected from thermocouples was displayed in a pictorial colour coded representation of the three transects, where each thermocouple was depicted by a single square and temperature was represented by a colour code (Figure 3.12). A black circle appeared in the centre of each square to show when the thermocouple for that square was in the specified treatment range of between 56 and $60 \text{ }^\circ\text{C}$. While the programme allowed temperature changes to be viewed as time elapsed, presentations in this report are from single snapshots taken during each test.

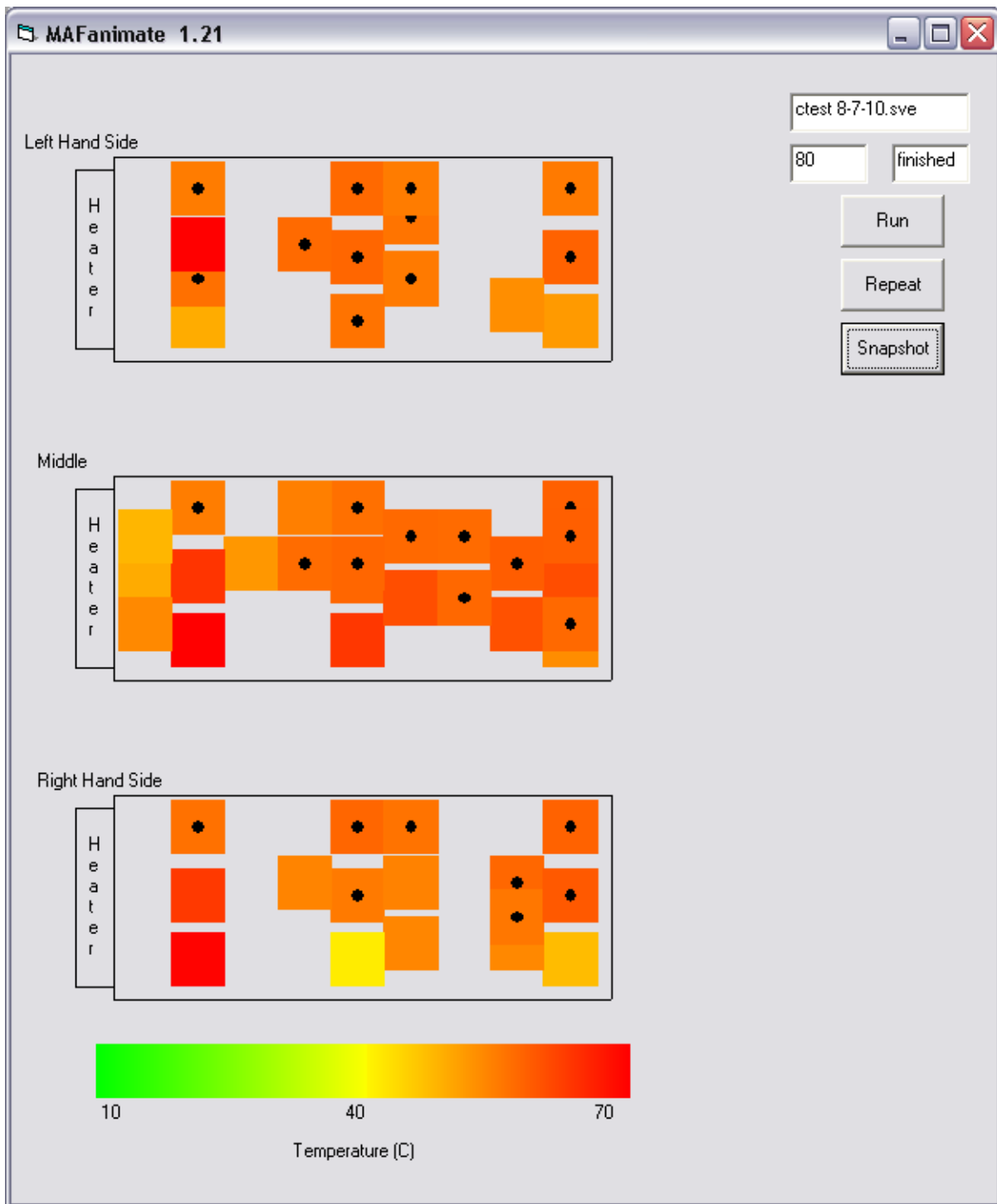


Figure 3.12: MAFanimate depictions of temperature distributions during a heat treatment test.

3.9 EXTERNAL THERMOCOUPLE PLACEMENT TEST

It may be practical to attach sensors to the outside of the container at the opposite end to the heater to assess penetration of heat into this area, provided these are adequately insulated from the outside air. This would enable temperature to be monitored without disturbing the load. A test was carried out on the bare container where a sheet of 40 mm ThermaSlab S expanded polystyrene was used to insulate an externally attached thermocouple (Fig. 3.13). In this test, temperature differences between the exterior insulated thermocouple and an internally located counterpart were compared.

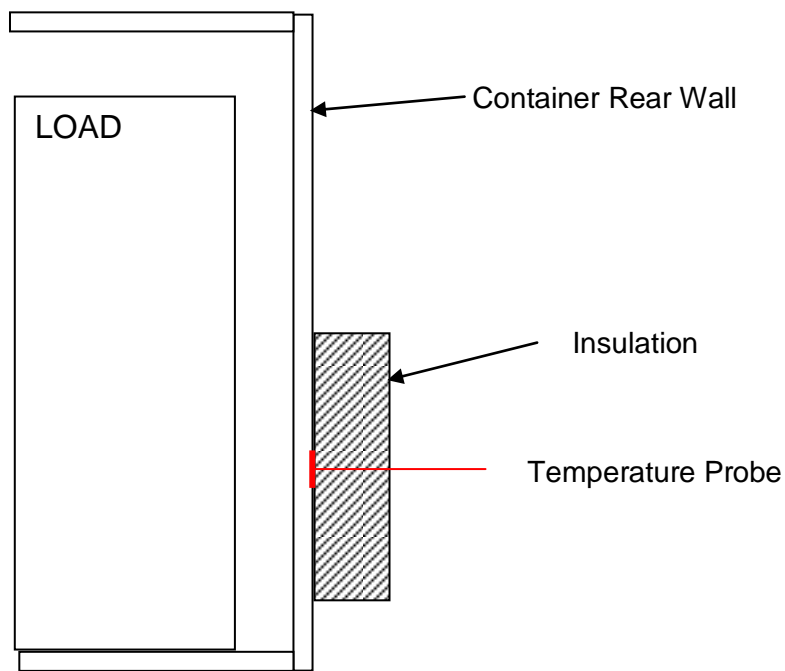


Figure 3.13: Placement of insulated thermocouple on rear wall of container.

4 Tests on the empty container

4.1 INTRODUCTION

To obtain information on the flow of heat between the inside and outside of the container and heating and cooling, a series of tests were run with the 20 foot container between 26 February and 7 April 2010, using the experimental arrangement described in Section 3.6. As well as providing background information on the container's response to heat input and meteorological conditions, these data sets provided the basis for developing, calibrating and validating the computer model so that it could be used to explore proof of concept and likely feasibility of adopting this approach.

4.2 RESULTS

The first test was started on 26 February 2010 and was run over three days during a period of fine weather. As an early exploration of possible control options, thermostatic control of 1.8 kW heat input was included. While the outdoor ambient temperature varied between 13 - 25 °C, the temperature in the container varied between 16 - 35 °C. As expected, the hottest temperature occurred in the middle of the day, and the heater only made a small contribution to raising night-time temperatures (Fig. 4.1). All the internal thermocouples tracked temperatures that were within 1 °C of each other, demonstrating that the internal air temperature was adequately mixed for the purpose of this series of tests.

A second test was started on 2 March 2010 at 14:34 and ran for 17 hours. This test also included variable heat input up to a maximum of 1.8 kW. While there were some differences in weather regarding radiation input and the occurrence of a small amount of rain, similar results were obtained to the first test with respect to internal temperature and response to heat (Fig. 4.2). The heater behaved slightly differently to Test 1, with continuous heat input being provided during the whole test, but this declined to between 600 - 800 kW during the warmest part of the day. Internal air temperature reached a maximum of 32 °C and the heater could only raise internal air temperature 2 - 4 °C above the external ambient temperature.

A further series of tests was conducted between 19 - 31 March. As a result, a comprehensive data set was obtained covering a range of weather conditions and the response of internal air temperature within the container with and without heat. Heat inputs of 2.5 kW, 6 kW and 12 kW were tested.

In the third and fourth tests (Figs. 4.3 and 4.4), heat input was raised to 2.5 kW and thermostatic control was removed. The third test started on 19 March and ran for almost four days. The fourth test started on 23 March and ran for almost two days. The weather during these tests covered a range of conditions from hot day time temperatures to cool night time temperatures which fell to 10 °C, and included a period of rainfall. Heat input into the container raised internal temperatures 5 - 18 °C above the external ambient temperature, with a maximum of 45 °C reached on the hottest day when a maximum external air temperature of 30 °C was recorded. This still represented a substantial shortfall in reaching the target treatment temperature.

On 25 March, heat input was raised to 12 kW in the fifth test. The opportunity was also taken in the sixth test to obtain records of cool down times once heat was turned off and to obtain observations on internal temperatures without heat input. The fifth test was started at 10.46 h

and continued for five hours over the middle of the day during a period of sunshine in the morning with varying radiation inputs in the afternoon. It was found that 12 kW heat input drove an increase in internal air temperature of between 28 to 30 °C above external ambient temperature, and that the required treatment temperature was being approached (Fig 4.5). It was also noted that initial warming occurred quite rapidly over a 30 minute period. In the sixth test, once the container had cooled down and solar input had ceased, internal container temperature followed external ambient (Fig 4.6).

On 26 March, the above process was followed for the seventh and eighth tests with 6 kW heat input. The seventh test was run from 10:25 h to 13:10 h, after which the system was left for a further 2.7 days to obtain additional information about behaviour with solar input and no additional heat (the eighth test). It was again found that initial warming up took about 30 minutes, and 6 kW was able to sustain a temperature differential of between 12 - 17 °C above an external mid-day ambient temperature of 25 °C (Fig 4.7). With no additional heat, solar input was able to sustain an increase in internal temperature of between 4 - 8 °C (Fig 4.8).

A final two runs were conducted without heat input to obtain more complete information on heat transfer over a broad time period. The ninth test was run over two days from 09:08 h on 29 March 2010, and the tenth for 7.5 days starting at 10:04 h on 31 March 2010. These tests further indicated that solar heating can make a contribution, when differences between external and internal temperatures of 10 °C were recorded (Figs. 4.9 and 4.10).

4.3 DISCUSSION AND CONCLUSIONS

These tests provided baseline information on which to base model development and to plan further experimental work.

A comprehensive data set was obtained, which enabled the basic heat flows in the container to be established, and together with information on likely behaviour of palletted cargo, estimate the likely heat input that would be needed to heat the internal air and surfaces.

While the required treatment temperatures were not reached during this work, the baseline information that was obtained enabled development of the simulation model. This enabled tests on heat treating the container with a load to be planned and conducted, which in turn enabled the model to be refined and validated so that it could be used to predict the heat that would be required to achieve treatment temperatures. It was anticipated that the feasibility of practically applying this method for treating containers would be amply explored through a combination of measurements from tests conducted in a real system and through predictive simulation using a robust model.

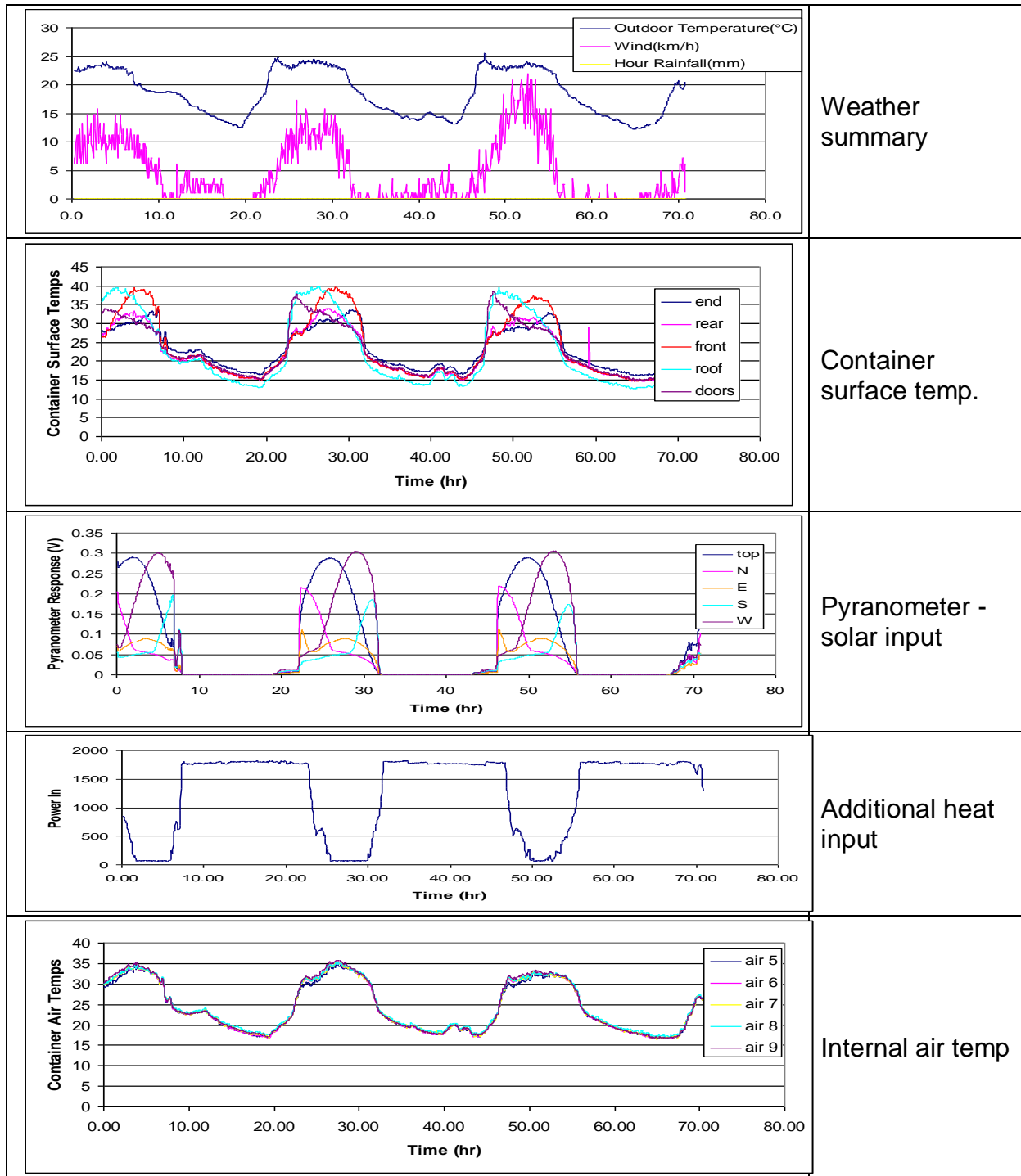


Fig 4.1: Empty container Test 1: Plots of external variables, heat input and internal air temperature. The test started at 12:07 h on 26 February 2010, and finished at 10:57 h on 1 March 2010.

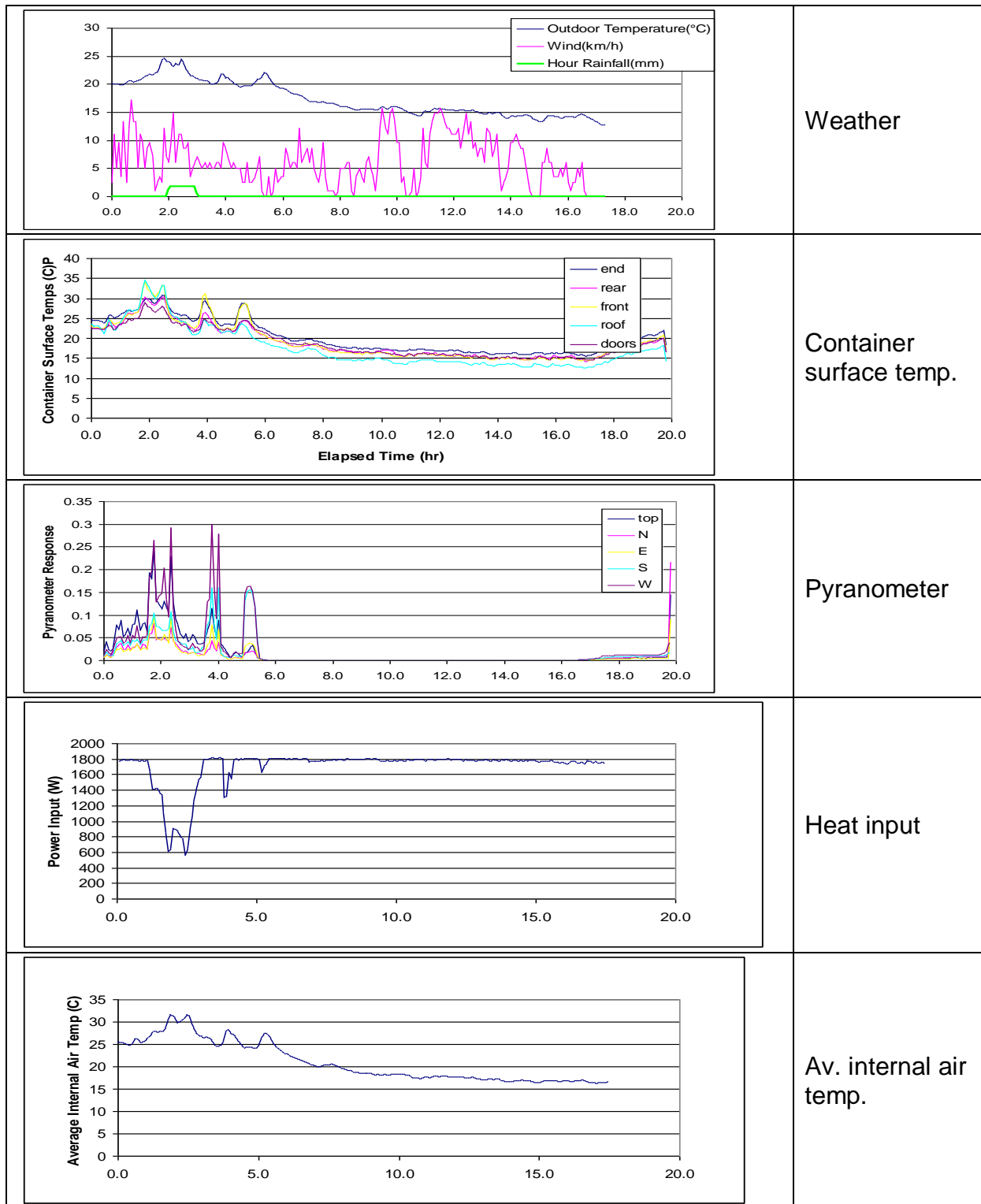


Fig 4.2: Empty container Test 2: Plots of external variables, heat input and internal air temperature. The test started at 14:34 h on 2 March 2010, and finished at 10:23 h on 3 March 2010.

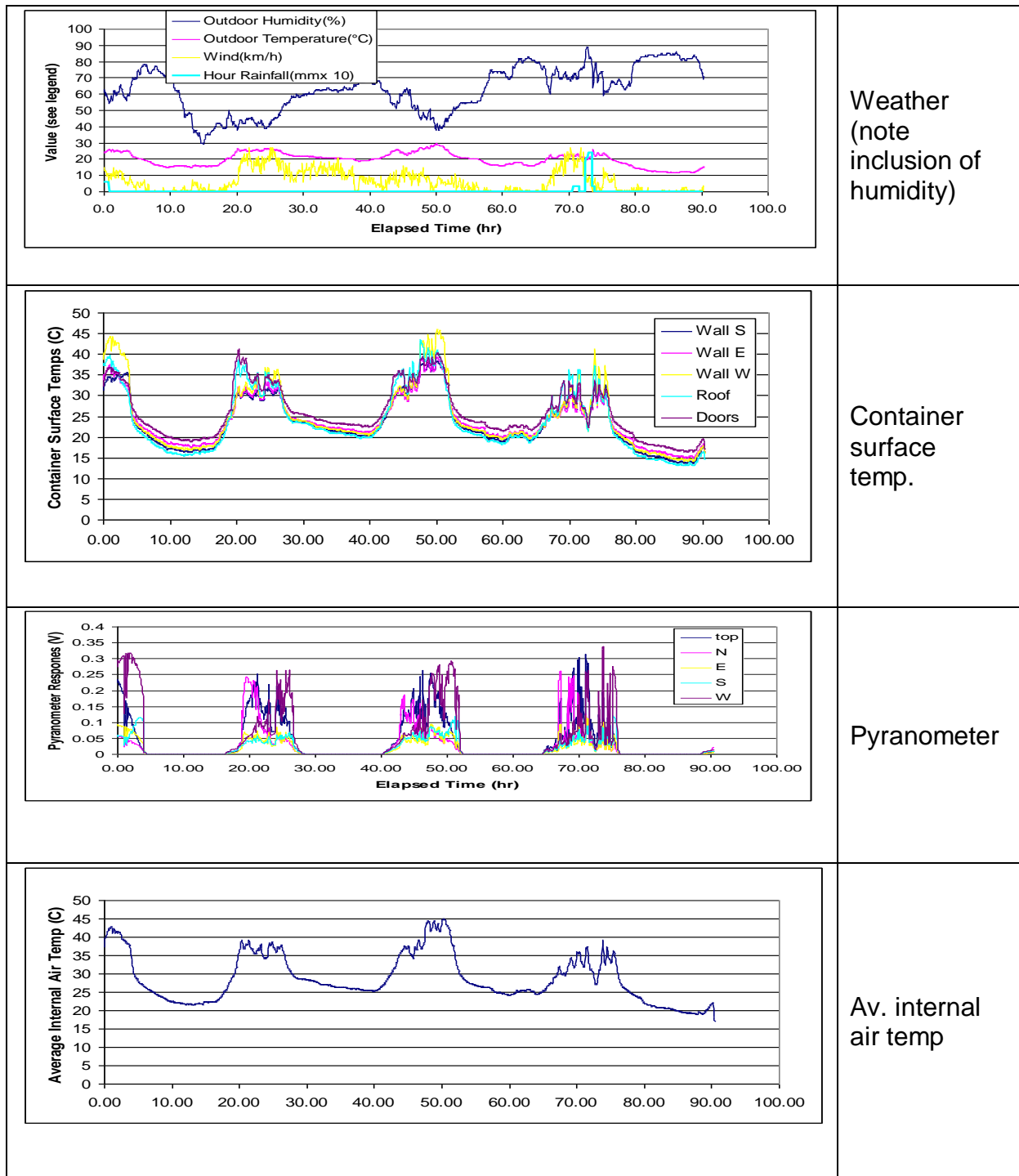


Fig 4.3: Empty container Test 3: Plots of external variables and internal air temperature. The test started at 15:19 on 19 March 2010, and finished at 9:46 h on 23 March 2010, and included 2.5 kW continuous heat input.

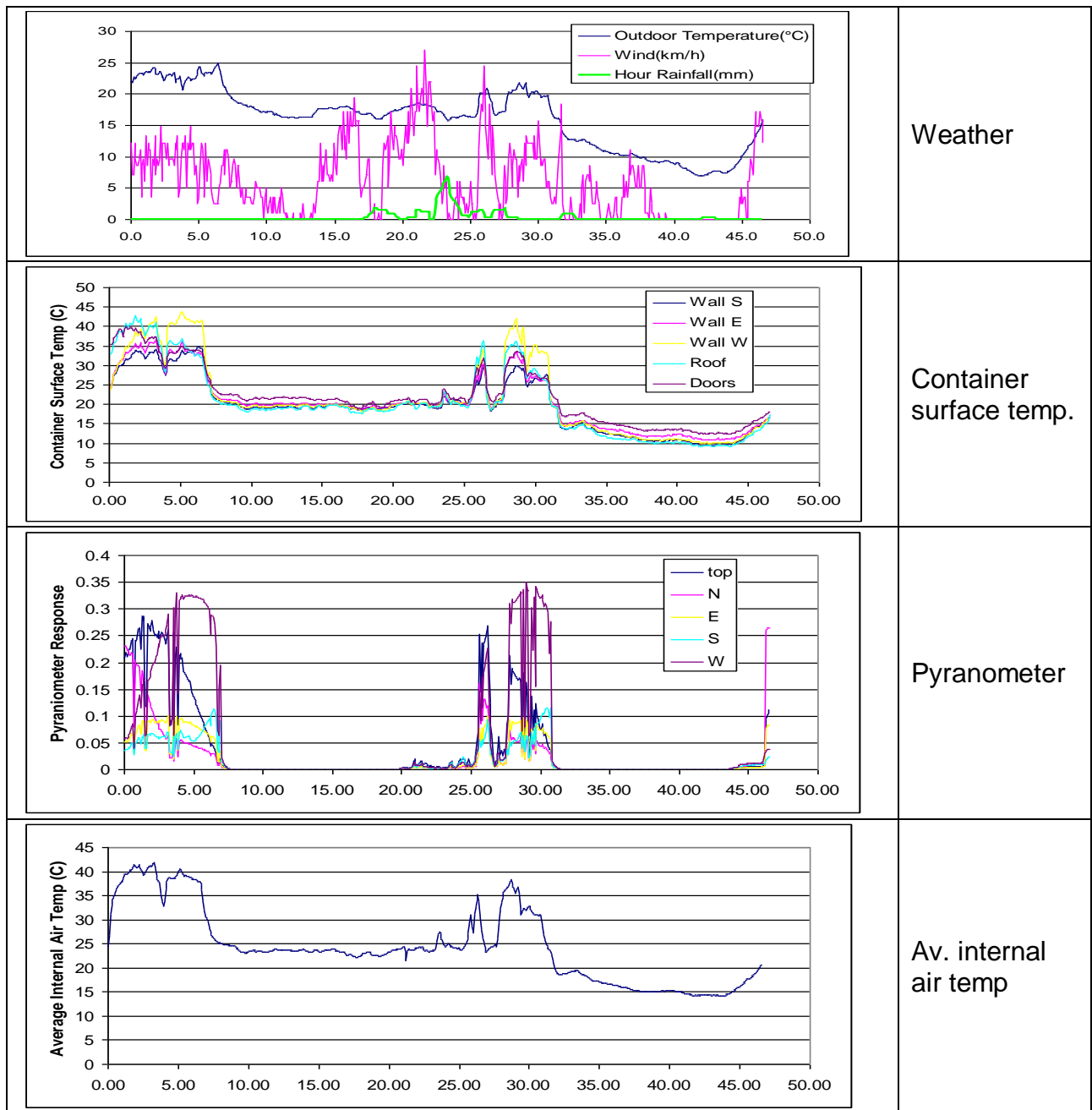


Fig 4.4: Empty container Test 4: Plots of external variables and internal air temperature. The test started at 11:56 h on 23 March 2010, and finished at 10:23 h on 3 March 2010, and included 2.5 kW continuous heat input.

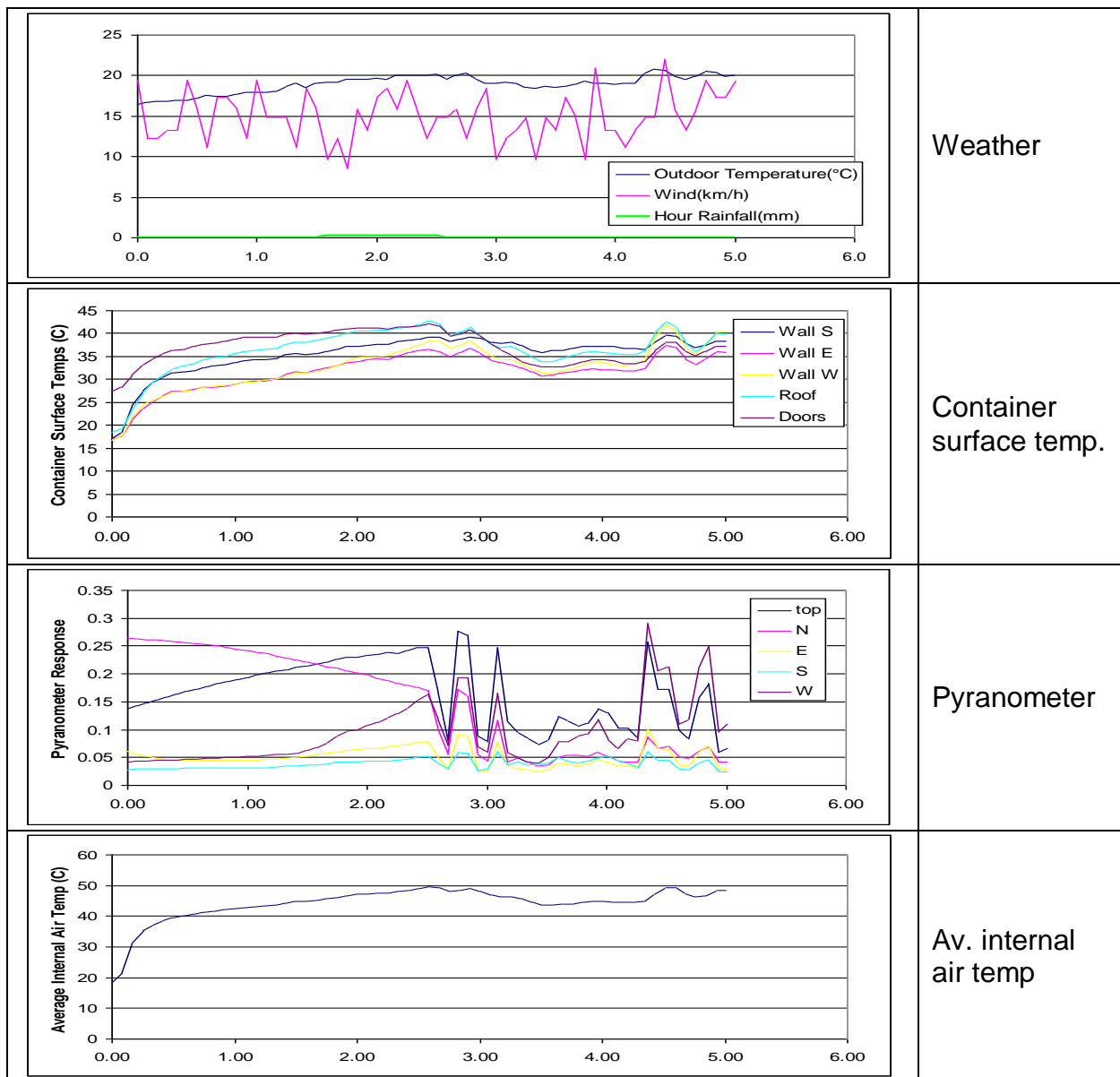


Fig 4.5: Empty container Test 5: Plots of external variables and internal air temperature. The test started at 10:46 h on 25 March 2010, and finished at 15:47 h on 25 March 2010. The test included 12 kW continuous heat input.

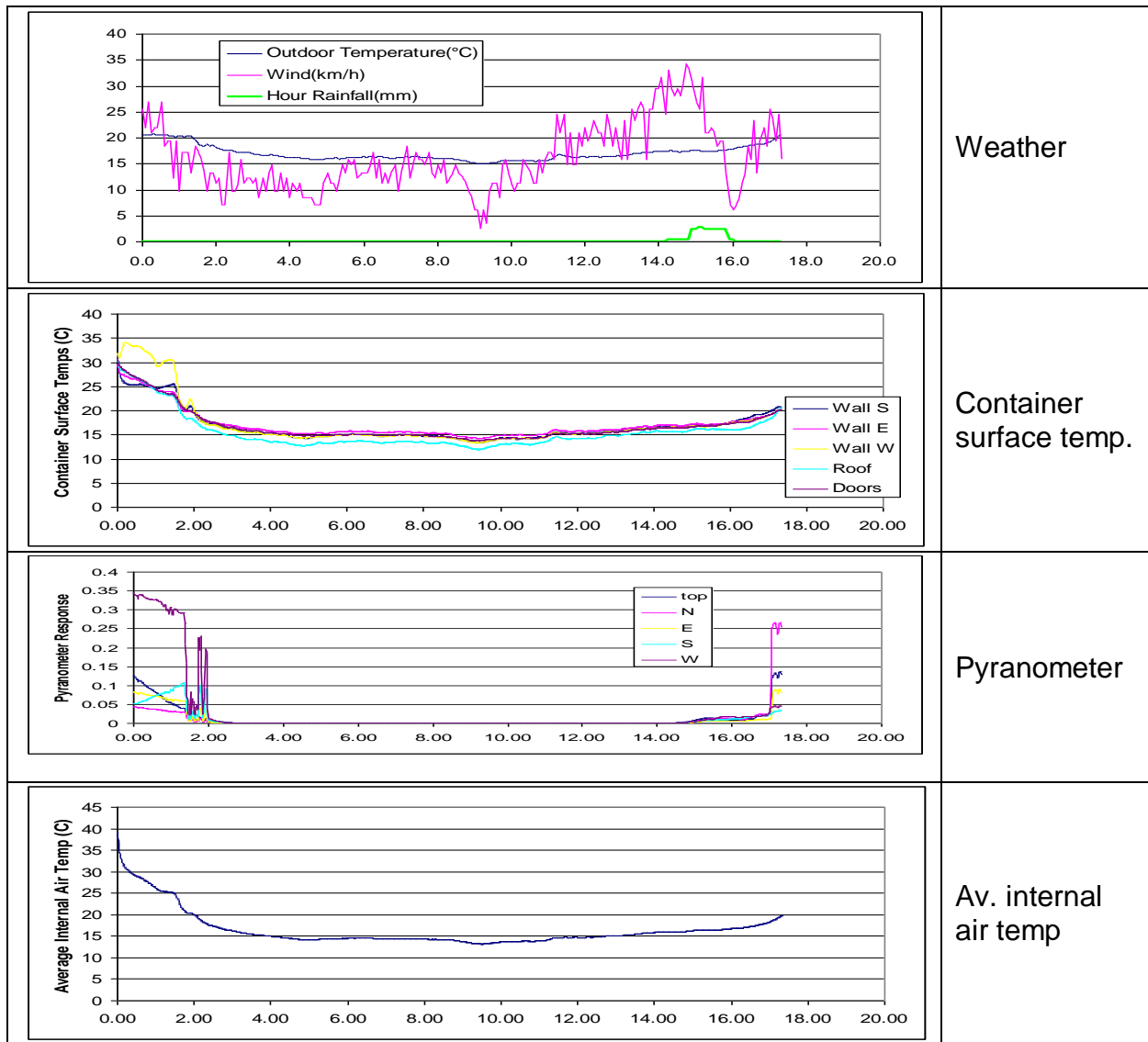


Fig 4.6: Empty container Test 6: Plots of external variables and internal air temperature. The test started at 17:04 h on 25 March 2010, and finished at 10:23 h on 26 March 2010. The test followed after Test 5 and included cool down after 12 kW heat input was switched off.

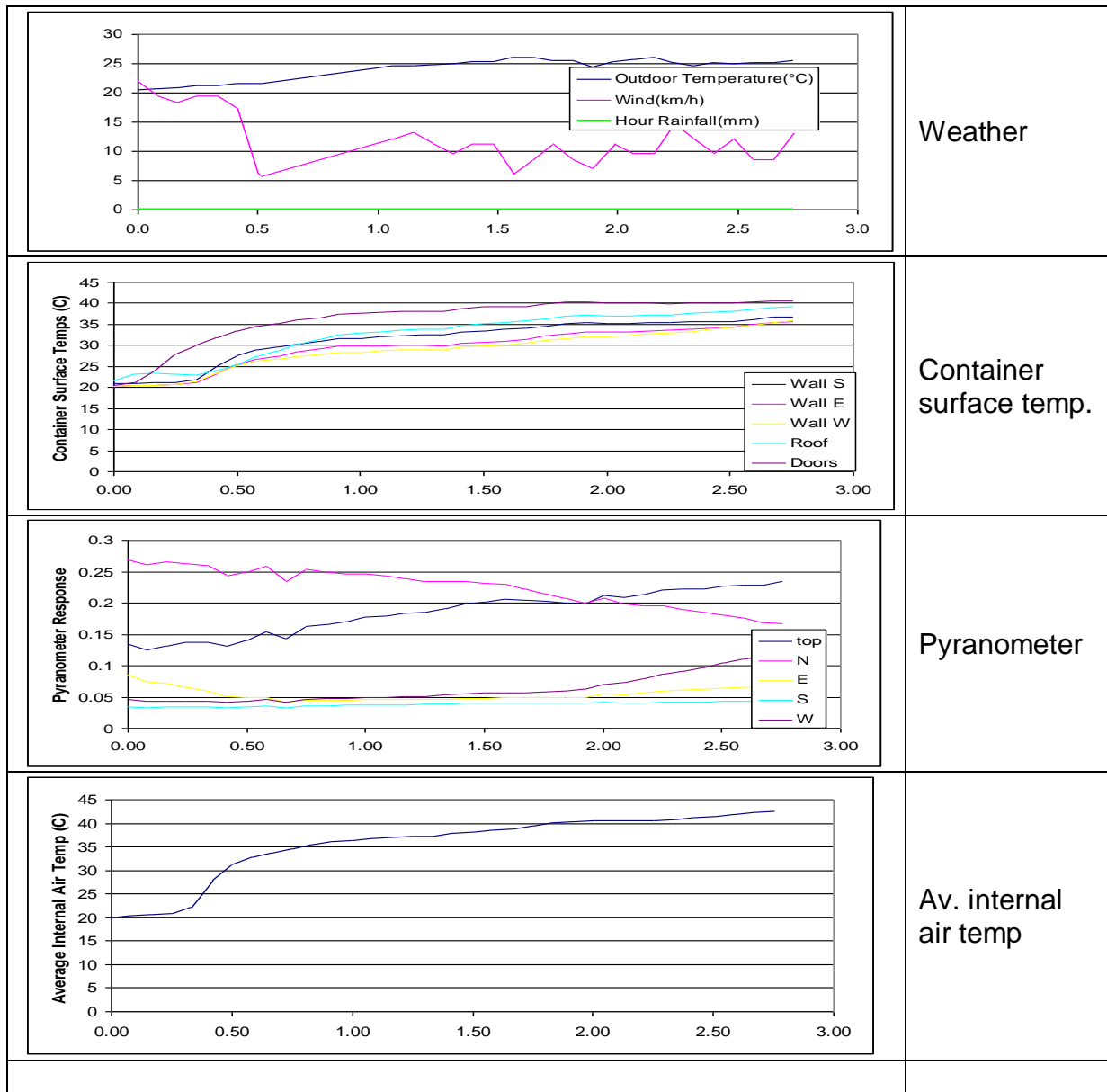


Fig 4.7: Empty container Test 7: Plots of external variables and internal air temperature. The test started at 10:25 h on 26 March 2010, and finished at 13:10 h on 26 March 2010, and covered a heating up period resulting from 6 kW heat input. Heat was turned on 16 minutes (0.27h) after the start.

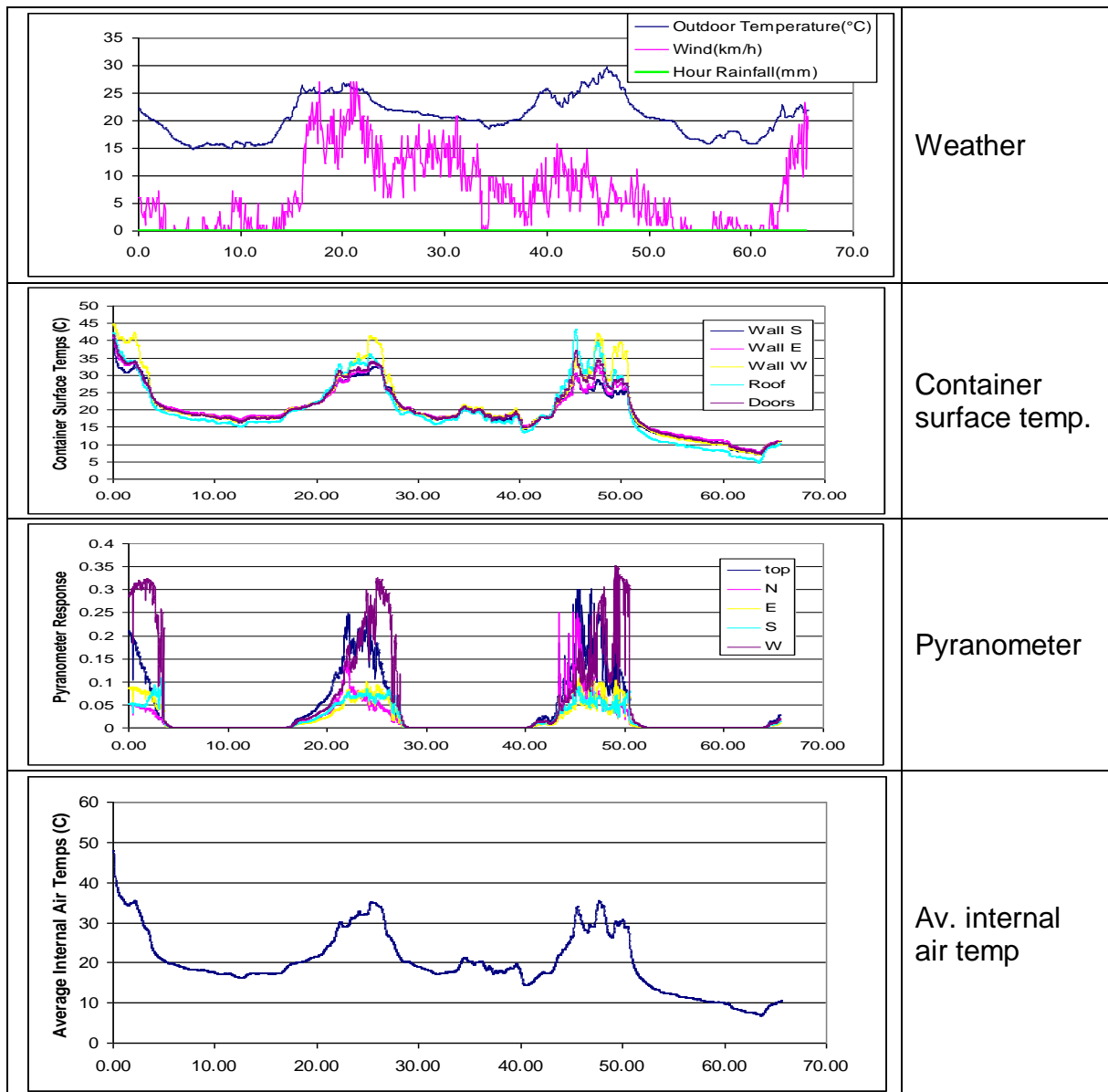


Fig 4.8: Empty container Test 8: Plots of external variables and internal air temperature. The test started at 15:27 h on 26 March 2010, and finished at 09:02 h on 29 March 2010, and had no heat input. It covered the cool down period after 6 kW heat input in Test 7.

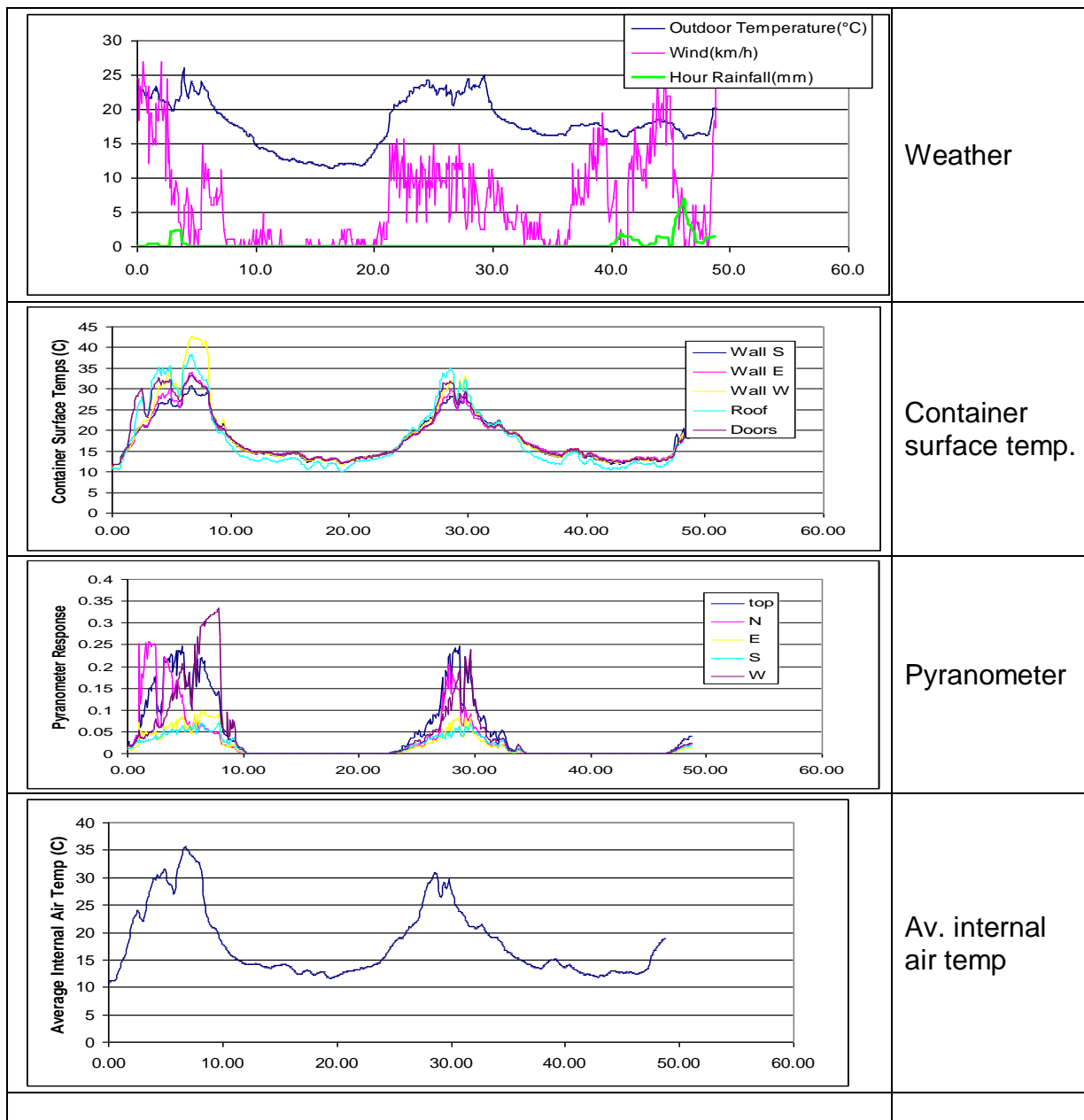


Fig 4.9: Empty container Test 9: Plots of external variables and internal air temperature. The test started at 09:08 h on 29 March 2010, and finished at 09:53 h on 31 March 2010, and had no heat input.

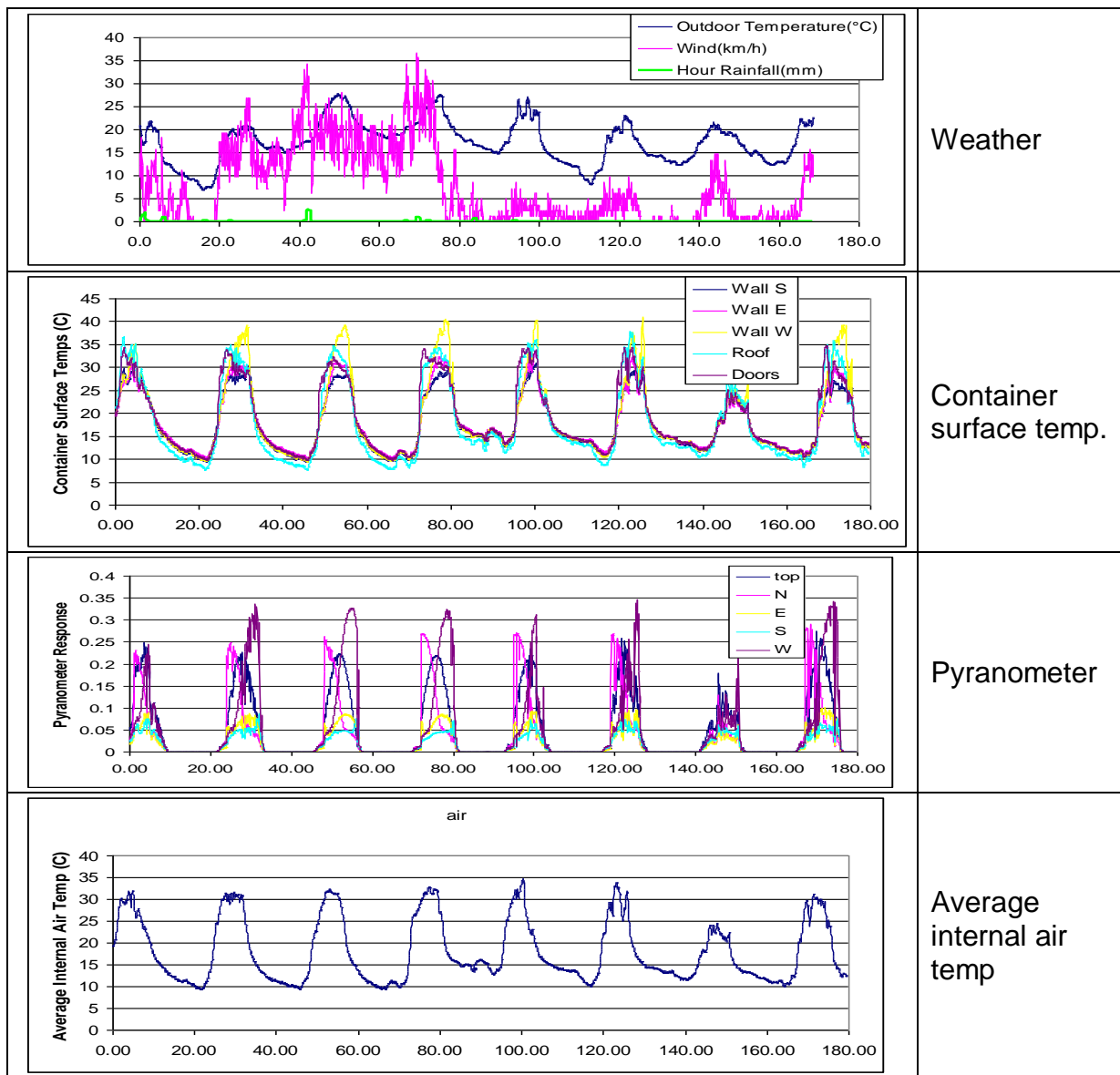


Fig 4.10: Empty container Test 10: Plots of external variables and internal air temperature. The test started at 10:04 h on 31 March 2010, and finished at 21:38 h on 7 April 2010, and had no heat input.

5 Tests on simulated cargo items

In order to account for the impact of low and high heat capacity loads on the feasibility of treatment, data sets were obtained from a series of indoor tests conducted between 10 - 19 March 2010. These involved subjecting the air surrounding a filled cardboard carton or a pail of water to heating and cooling cycles (Section 3.7).

As well as using this information for constructing the computer model, it also provided basic insights into the feasibility of using heat treatment through providing opportunities to obtain readings of surface temperatures and determining the length of time required to achieve treatment specifications for these two types of load.

5.1 TESTS WITH A 20 LITRE PAIL OF WATER TO REPRESENT A HIGH HEAT CAPACITY LOAD.

Water was used to simulate high heat capacity cargo because it has a low viscosity and high thermal conductivity, and was therefore likely to demonstrate the challenge of achieving the required cargo surface temperatures for similar loads.

Initial measurements showed that the air in the MDF test enclosure and surrounding the pail was uniform, and the target temperature was reached an hour after starting heating. Air temperatures throughout the enclosure varied by only 2 °C which was accepted for the purpose of this experimentation (Figure 5.1).

Thermocouples placed at various locations on the surface of the pail and in the water inside provided a record of temperature increase as the pail warmed up (Figure 5.2). Water temperatures were found to be relatively uniform, indicating that convection within the pail was mixing the water well. The side surface temperature tracked slightly above the water temperature. The top surface temperature was higher because there was an air pocket between the lid and the water surface that provided an insulating buffer. The thermocouple between the pail base and the pallet effectively tracked the water temperature because the pallet isolated the base from the warm air in the enclosure.

Within 30 minutes, the air surrounding the pail of water reached 60 °C. The pail surface reached treatment temperature within 5 hours and the contents of the pail reached equilibrium with the surface after 12 hours. This indicated that while it might be challenging, it may be possible to reach specified temperatures for equivalent high heat capacity loads within the specified time frames, even though this would involve heating the cargo.

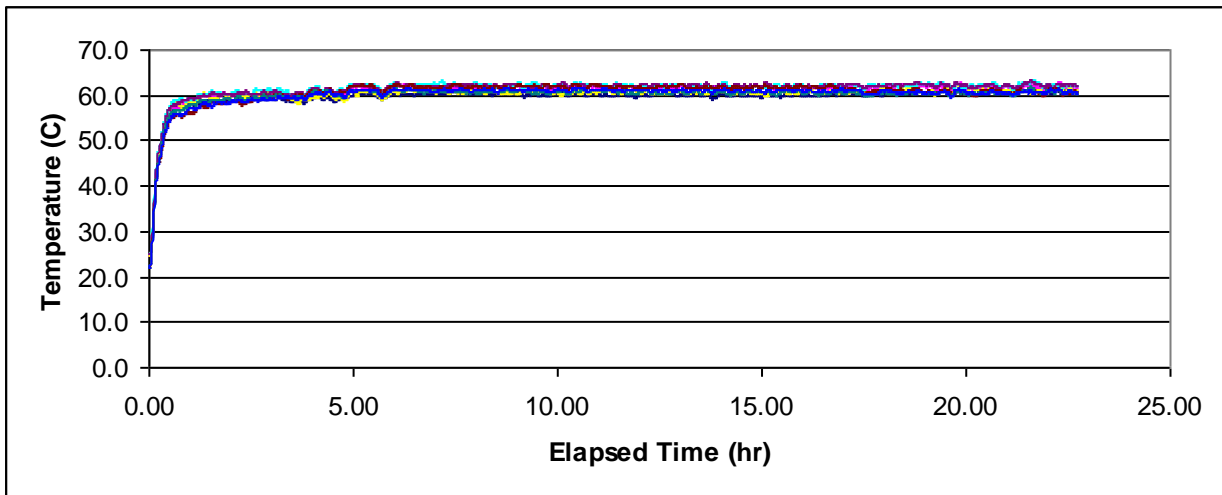


Figure 5.1: Air temperatures in the heating enclosure during the test on a single pail filled with water.

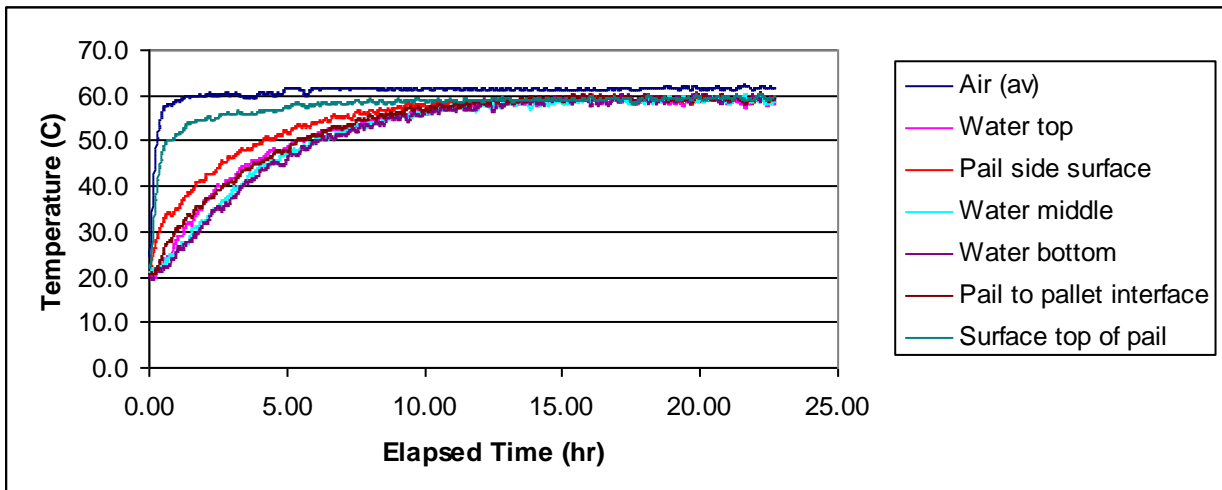


Figure 5.2: Temperatures recorded from the surrounding air and by thermocouples placed within a single pail of water during heating of the container.

5.2 TESTS WITH A CARTON FILLED WITH PAPER TO REPRESENT A LOW HEAT CAPACITY LOAD.

Cardboard and paper are low density materials with low thermal conductivity. They are common commercial packing materials and are often used alongside materials such as bubble wrap and expanded polystyrene. A carton filled with bubble wrap was therefore an ideal load to simulate low heat capacity cargo.

Initial measurements showed that the air in the MDF test enclosure and surrounding the carton again varied by 2 °C. Air temperatures in the enclosure followed the same pattern as the previous test on the pail of water and the target temperature was reached within an hour after starting heating (Fig. 5.3). However, in this case the surface temperatures on the carton

followed the air temperatures relatively closely and reached the target temperature within an hour (Figure 5.4). This behaviour confirmed that low heat capacity loads require less energy to reach the specified treatment regime than high heat capacity loads.

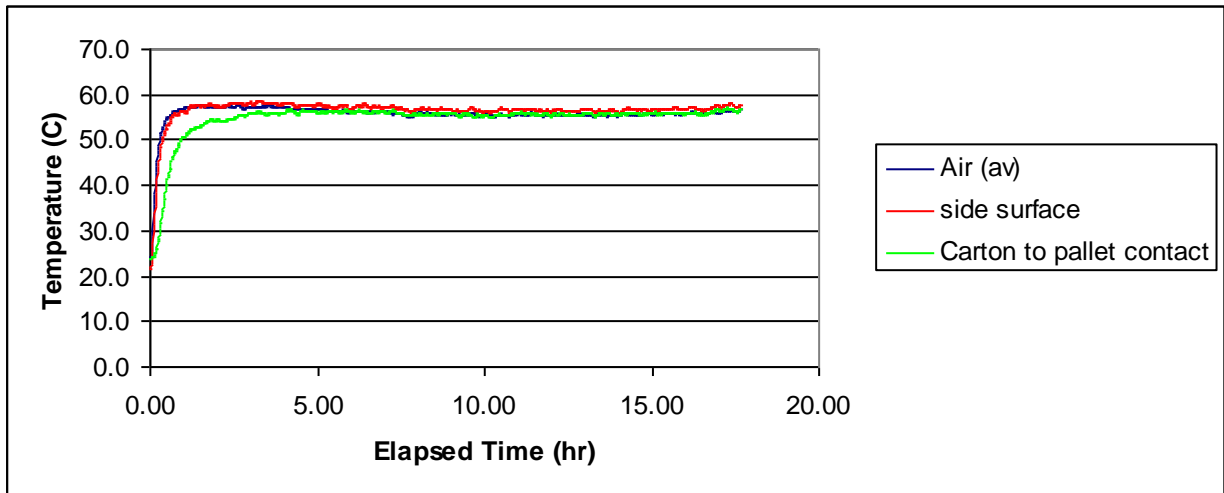


Fig. 5.3: Temperatures recorded from the surrounding air, carton side surface and area of carton to pallet contact during heating of the container.

The contents of the carton rose slowly during the test and reached equilibrium with the surface after 6 hours (Figure 5.4). These findings further indicate that for this type of load, the air temperature in a container could be raised and held at the target temperature for 30 minutes without exposing the contents of cartons to the full treatment temperature.

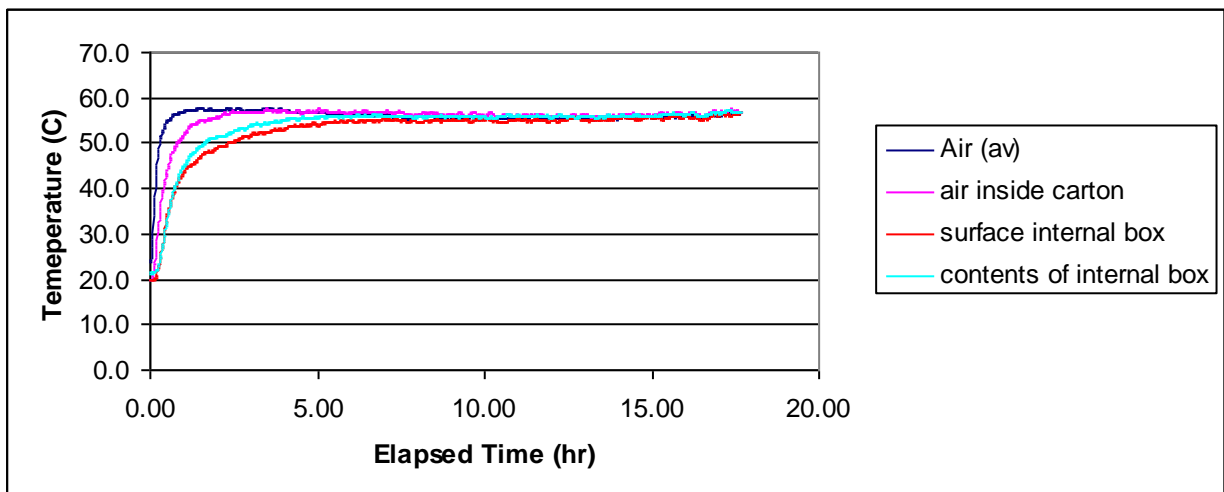


Figure 5.4: Temperatures recorded from the surrounding air, air inside the carton, carton internal surface and internal box contents during heating of the container.

5.3 DISCUSSION AND CONCLUSIONS

The tests that were conducted provided real life measurements, which enabled projections on the impact of loads to be built into the simulation model.

The tests demonstrated that it is feasible to take the surfaces of cargo up to treatment temperatures. Low heat capacity cargo presented a relatively straightforward challenge, as in these tests surfaces reached treatment temperature within 5 hours from turning on the heater and initiating the treatment. The tests conducted here confirmed that high heat capacity loads will undoubtedly require increased amounts of heat input. The loads themselves will inevitably be subjected to temperature rises, which will be close to the specified treatment temperature. In these tests, the load surface reached the required treatment temperature within 12 hours, and therefore treatment of containers with high capacity loads may still be feasible within a 24 hour time period. Constraints are more likely to relate to energy costs to heat, and possible issues arising from heating the load.

6 Tests on a 20-foot Container Packed with Low Heat Absorbing Cargo

6.1 BACKGROUND

Following the experimental process described in Section 3.8, a series of tests was conducted between 23 June and 10 August 2010 on the 20 Foot container packed with a low heat absorbing load, in order to ascertain heat input required to reach the specified temperature threshold, evaluate temperature variation and explore how this can be controlled.

The tests explored driving heat into:

- the bare container;
- the bare container covered with a tarpaulin;
- applying insulation; and
- with insulation, varying the heat input and the direction and velocity of hot air coming from the heat source.

Weather measurements recorded during each run included ambient temperature, wind speed, radiation and rainfall. There was no rainfall during the tests reported in this section.

6.2 TEST 1: BARE CONTAINER WITHOUT INSULATION, 9KW HEATING

The first test was conducted over a 2.5 hour time period on 23 June 2010 at 16:43 using 9kW heat input. The weather conditions during the test were dry and cool with a light wind. Air was forced into the container out of the top heater outlet and returned to the heater via the lower one. The external ambient temperature during the test ranged between 7-8 °C. It was found that the temperatures in the container levelled off after 2 hours, when an average of 21.5 °C was reached, with a minimum of 14.0 °C and maximum of 38.1 °C (Fig 6.1).

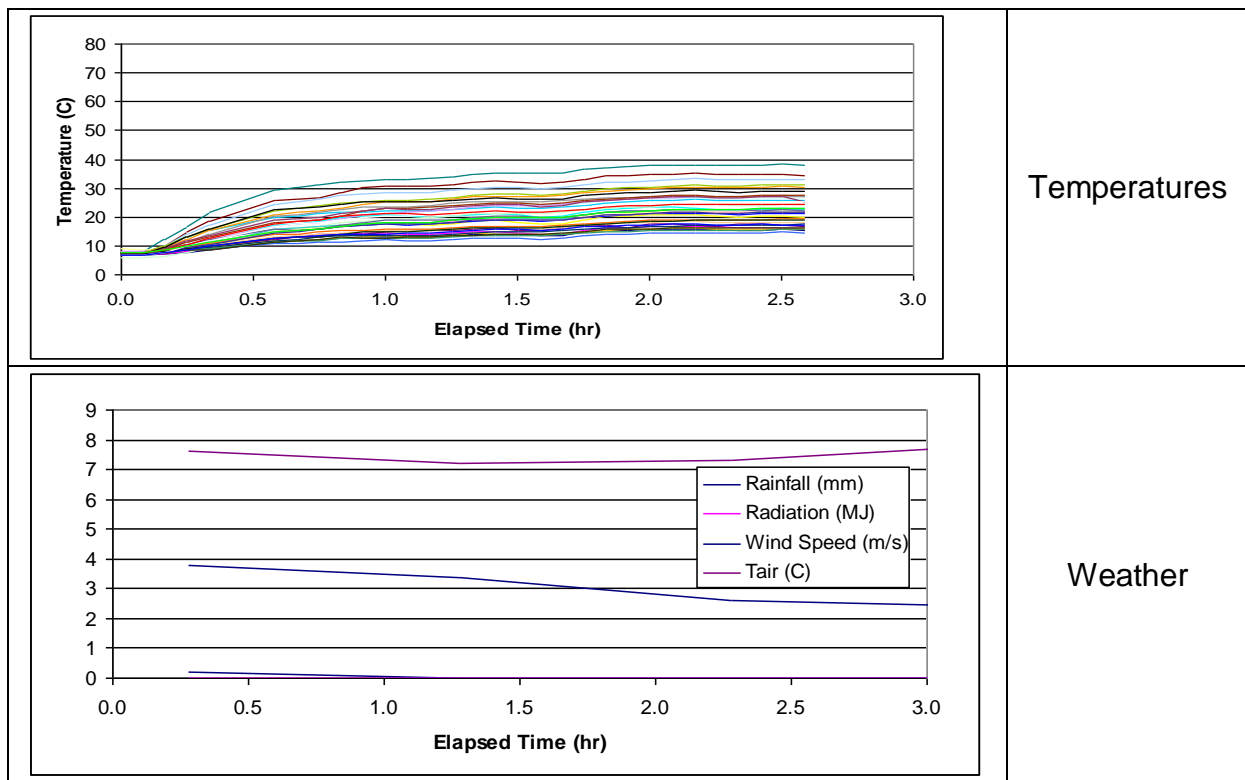


Figure 6.1: Loaded container Test 1: Internal air temperature plots for each thermocouple and weather, bare container with 9 kW heat input, start 16:43 23 June 2010.

6.3 TEST 2: BARE CONTAINER WITHOUT INSULATION, 12KW HEATING

The second test was conducted immediately after the first test on the same evening and was conducted overnight for a 13 hour period, starting from 19:22. To increase the temperatures in the container the heat input was increased to 12 kW. During this time, the ambient temperature fell from 8 °C to 5 °C and then started to climb after 9 hours, when it reached 9 °C. Container temperatures followed this rise. At the end of the run the minimum temperature reached 20 °C and maximum 51 °C (Fig 6.2). As expected, thermocouples in the upper part of the container recorded the highest temperatures, and those along the floor recorded the coolest. The temperature profile was consistent with hot air exiting from the upper outlet of the heater and losing heat through the walls of the container as it circulated, with cooler air returning to the lower inlet near the floor of the container. The plots showed warm air temperatures extended to the rear of the container which indicated that there was a reasonable circulation of air throughout the container.

It was concluded that the required temperature regime would not be met with an un-insulated container under these cool conditions. Heat loss through the walls was causing too large a variation in temperature and it would not be possible to maintain temperatures throughout the container within the specified limits.

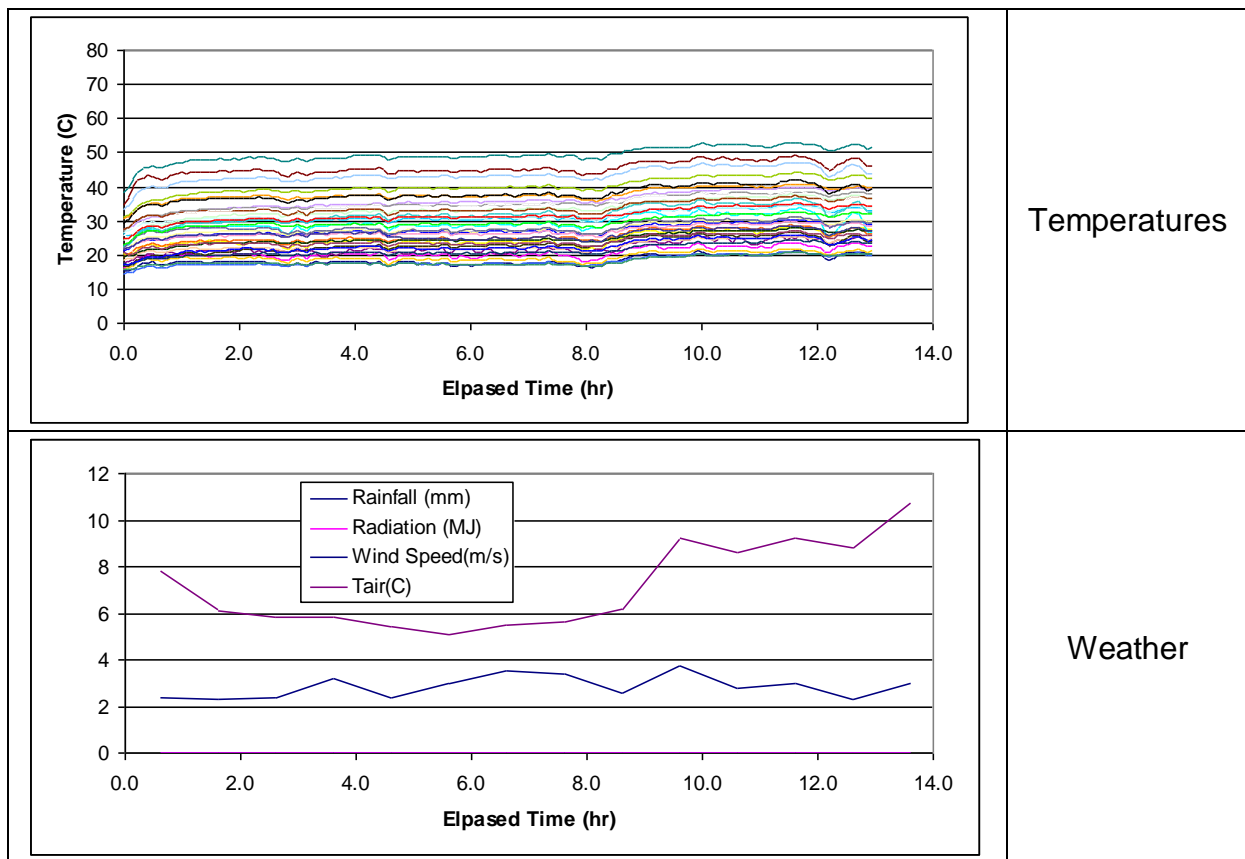


Figure 6.2: Loaded container Test 2: Internal air temperature plots for each thermocouple and weather, bare container with 12 kW heat input, start 19:22 23 June 2010.

6.4 TEST 3: STANDARD TARPAULIN PLACED OVER THE CONTAINER.

To reduce heat loss, the container was covered with a tarpaulin and the same heating arrangement using 12 kW input was used. This test was started at 17:08 on 24 June and continued for 16.5 hours, with an ambient temperature of between 11-13 °C and a light wind. It was found that while the average temperature inside the container increased to 44.9 °C, there was still a wide spread of temperatures, with a minimum of 28.4 °C and maximum of 66.4 °C (Fig 6.3). As before, the coolest temperatures were recorded at the bottom of the container and highest temperatures at the top (Fig 6.4). During this test the exit temperature of the heater was raised above 60 °C in an attempt to raise the body of the cargo into the required temperature range. This resulted in the temperatures in some part of the container exceeding the required limits.

The large variation in temperatures at the end of this run indicated that there was still a significant level of heat loss from the container and that the level of insulation needed to be increased.

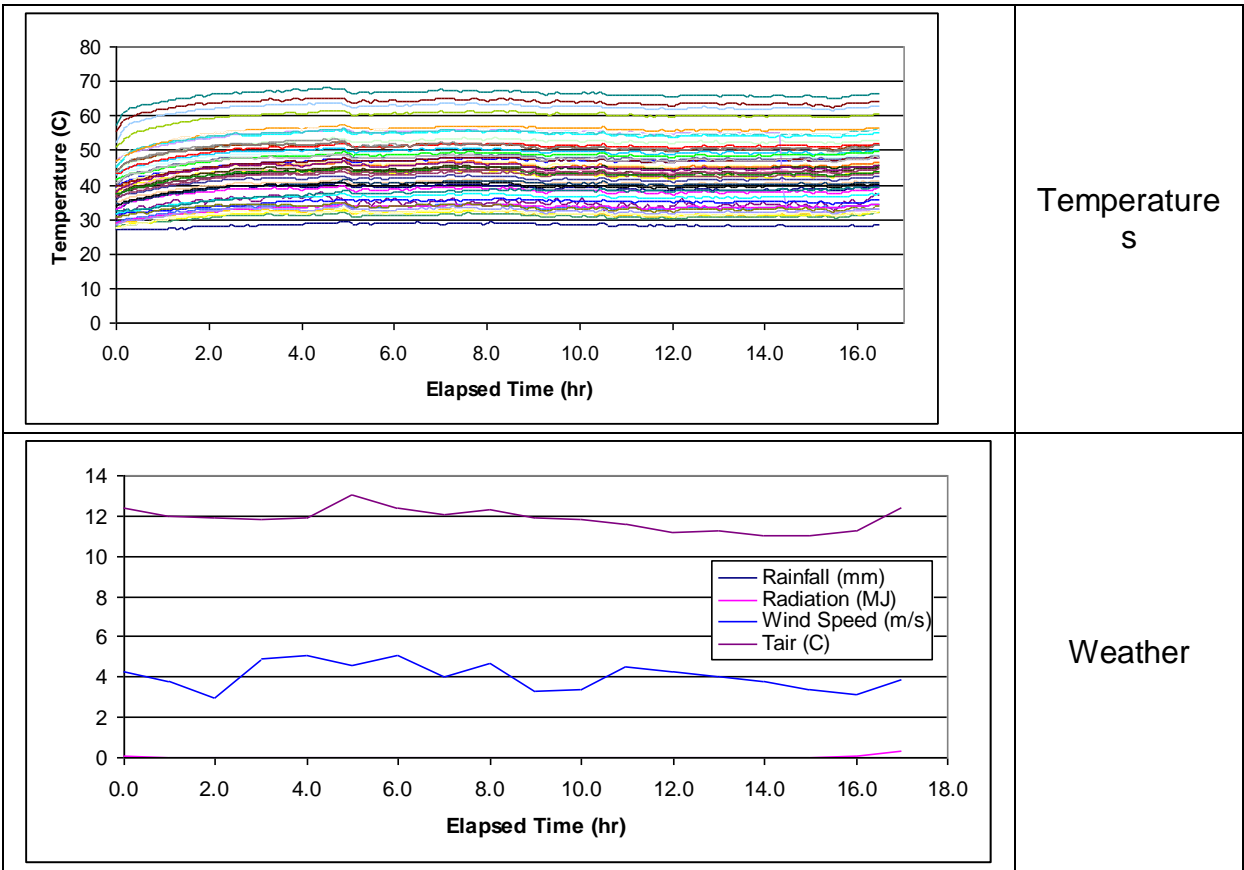


Figure 6.3: Loaded container Test 3: Internal air temperature plots for each thermocouple and weather, container covered with a tarpaulin and 12 kW heat input.

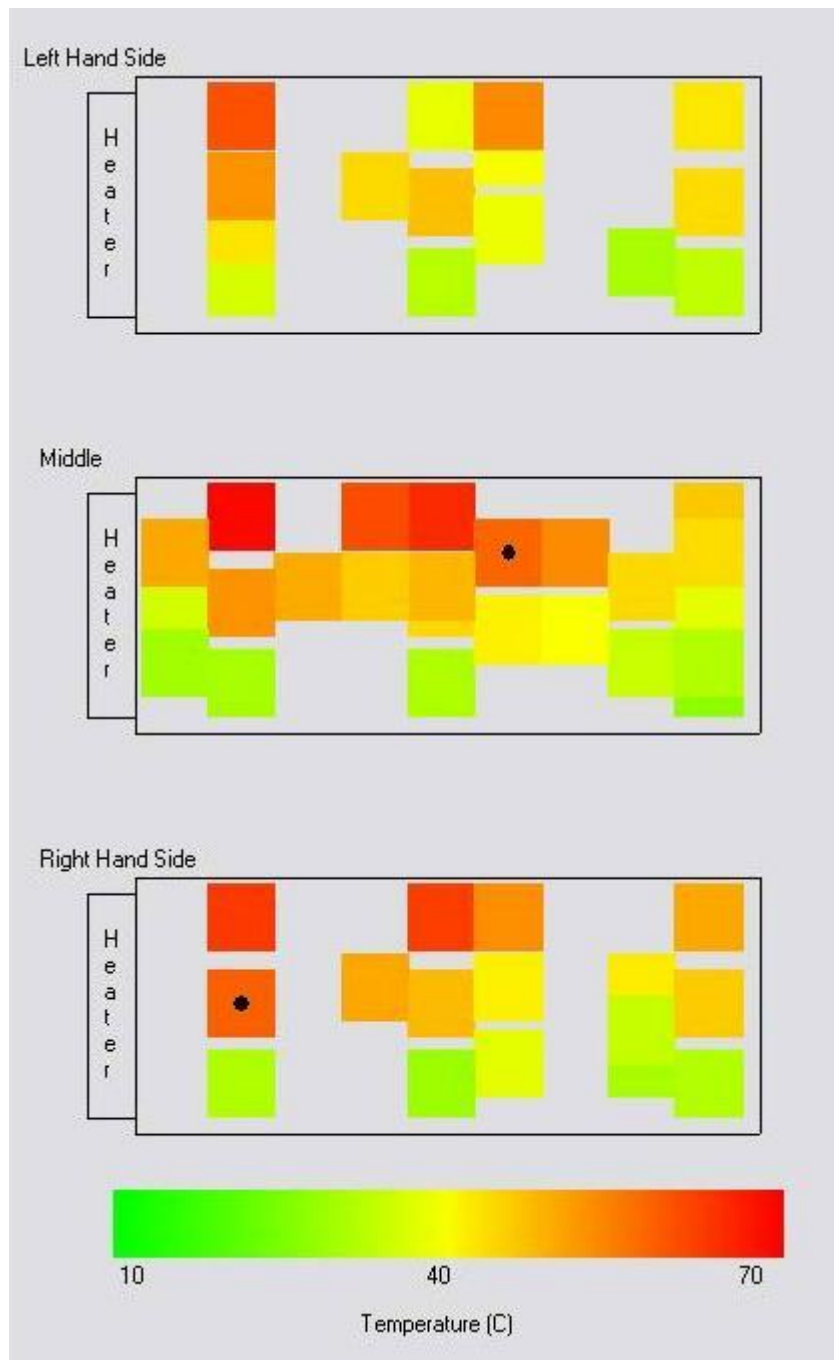


Figure 6.4: Loaded container Test 3: Steady state temperature distributions for the container covered with a tarpaulin and heat input of 12 kW.

6.5 TEST 4: POLYSTYRENE INSULATION PLACED AROUND THE CONTAINER

Test 4 was conducted on 5 July 2010 for 22 hours from 12.00 pm. The external air temperature started at 10°C and after an hour rose to 12°C for about three hours, then gradually declined to a minimum of 2°C. To reduce heat losses and thus temperature variation, polystyrene insulation was placed around the roof and walls of the container as described in Section 3.8.4. An initial heat input of 12 kW was used, and as a result of monitoring the temperature plots this was reduced to 9kW to avoid exceeding the upper specified limit of 60 °C.

A reduction in temperature variation was observed, with the lowest temperature of 26.8 °C, and the highest at 50.9 °C (Fig 6.5). The insulation also reduced the impact of varying outdoor air temperatures. While the outdoor air temperature varied between 12 °C and 2 °C during the test the internal temperatures remained relatively constant. Cooler temperatures were again recorded from the lower levels (Fig 6.6).

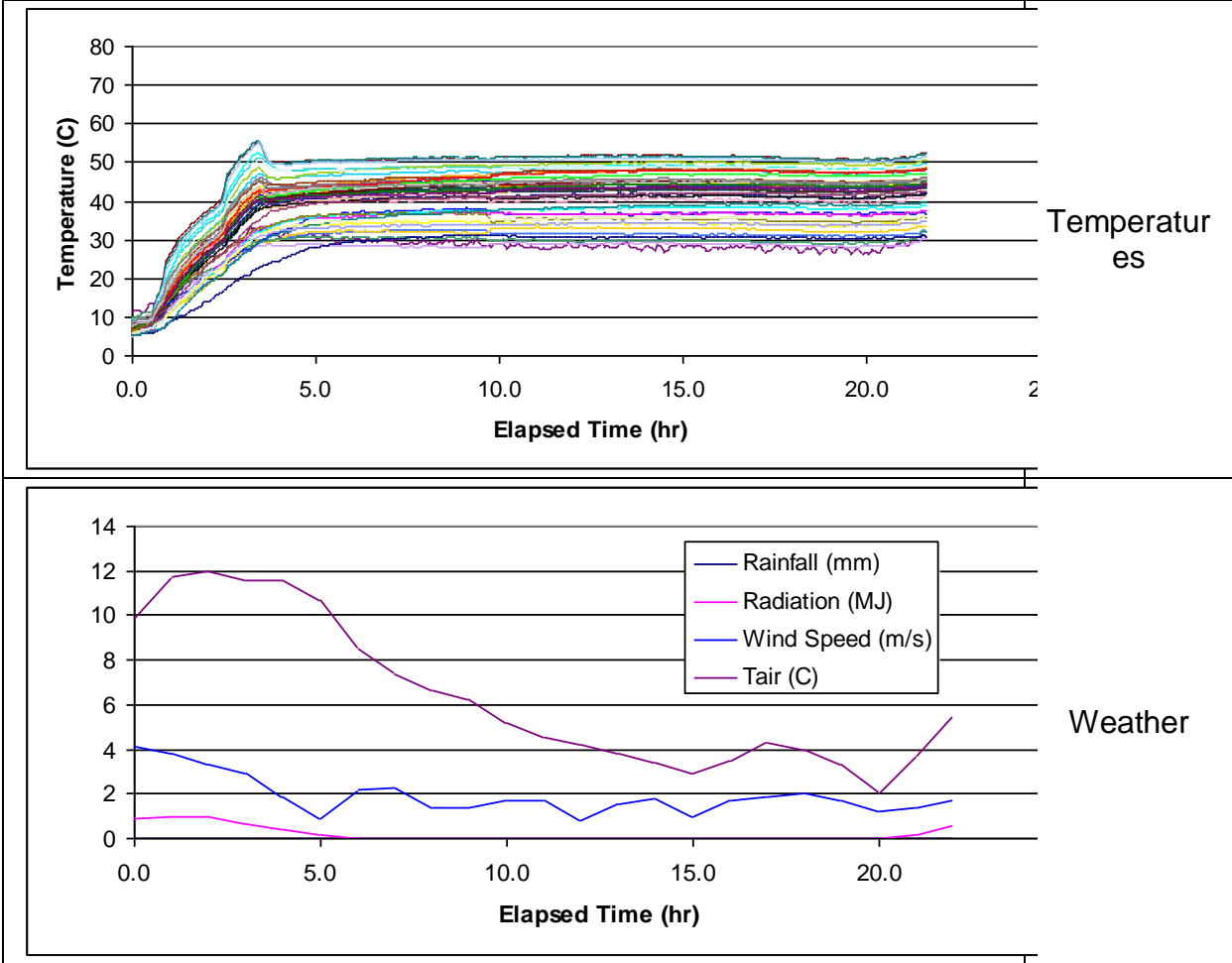


Figure 6.5: Loaded container Test 4: Internal air temperature plots for each thermocouple and weather, container insulated with polystyrene sheet, 12 kW heat input initially to 3.5 h, followed by 9 kW input.

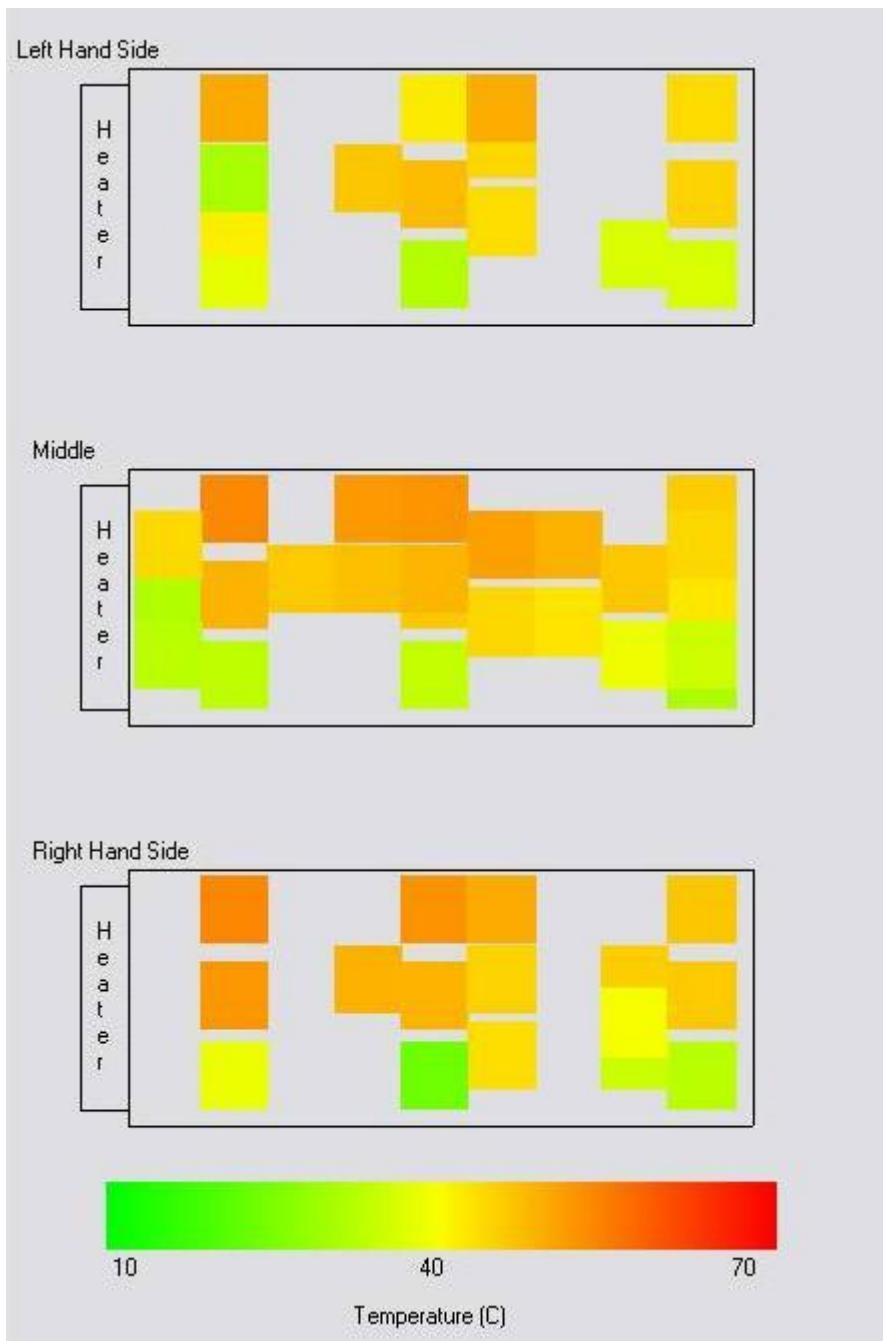


Figure 6.6: Loaded container Test 4: Steady state temperature distributions for the container covered with polystyrene sheet and 9 kW heat input.

6.6 TEST 5: POLYSTYRENE INSULATION PLACED ON DOOR

Given the improvements obtained by adding insulation Test 5 was run immediately after Test 4, and the door of the container was insulated as well as the walls and roof. This test was continued for 2.5 hours and stopped when little improvement was observed.

6.7 TEST 6: INVERTED HEATING ARRANGEMENT

In Tests 1 to 5 the heater was installed so that it drew cooler air in at the bottom of the container and pushed hot air out at the top. It was expected that this arrangement would be most effective in distributing air throughout the container because it should enhance the natural circulation of air. It was thought that an inverted heating arrangement would be less effective because the hot air exiting low in the container would tend to rise to the roof and return to the inlet of the heating unit, rather than circulating to the rear of the container. This was tested on 6 July, when Test 6 was conducted where the heating unit was inverted to deliver 6 kW heat into the bottom of the container. As expected, the thermal plots showed cooler temperatures at the lower rear of the container, but the spread of temperatures for an increased proportion of thermal couples was reduced.

6.8 TEST 7: INVERTED HEATING ARRANGEMENT WITH ADDITION OF AN AUXILIARY FAN

To further improve temperature uniformity within the container, it was decided to increase the air velocities within the container by adding an auxiliary fan while retaining the inverted arrangement. The booster fan (section 3.8.5) was introduced into the container to direct air down the centre of the load, and a heat input of 9kW was used. This test was run over a 23 hour period starting on 8 July at 14:26.

The weather followed a similar pattern to Test 4, starting at 10 °C, rising to 12 °C and then approaching 0 °C after 15 hours. Temperature plots in the container showed a marked improvement over previous tests (Figs 6.7 and 6.8), and the test provided good evidence that the method will be viable in practice.

The distribution of temperatures at an elapsed time of 8.0 hours is given in Table 6.1. Sixty percent of the measured temperatures were within specification and 84% were within 1 °C of specification. The three sensors in the 49 - 54 °C range were close to the floor. Placing the container on an insulated pad would be expected to eliminate these. Five sensors in the 62 – 74 °C range were in the hot air stream exiting the fan. If needed, these could be managed by further increasing air velocities to allow the inlet air temperatures to be reduced, while still delivering the same amount of energy to the container.

As with Test4, temperatures inside the container remained relatively constant (± 1 °C), while the outdoor temperature varied between 0.5 and 7 °C

Table 6.1: Distribution of temperatures during Test 7.

| Temperature Range (°C) | Number of Thermocouples in Range |
|------------------------|----------------------------------|
| 49-54 | 3 |
| 55 | 6 |
| 56-60 | 30 |
| 61 | 6 |
| 62-74 | 5 |

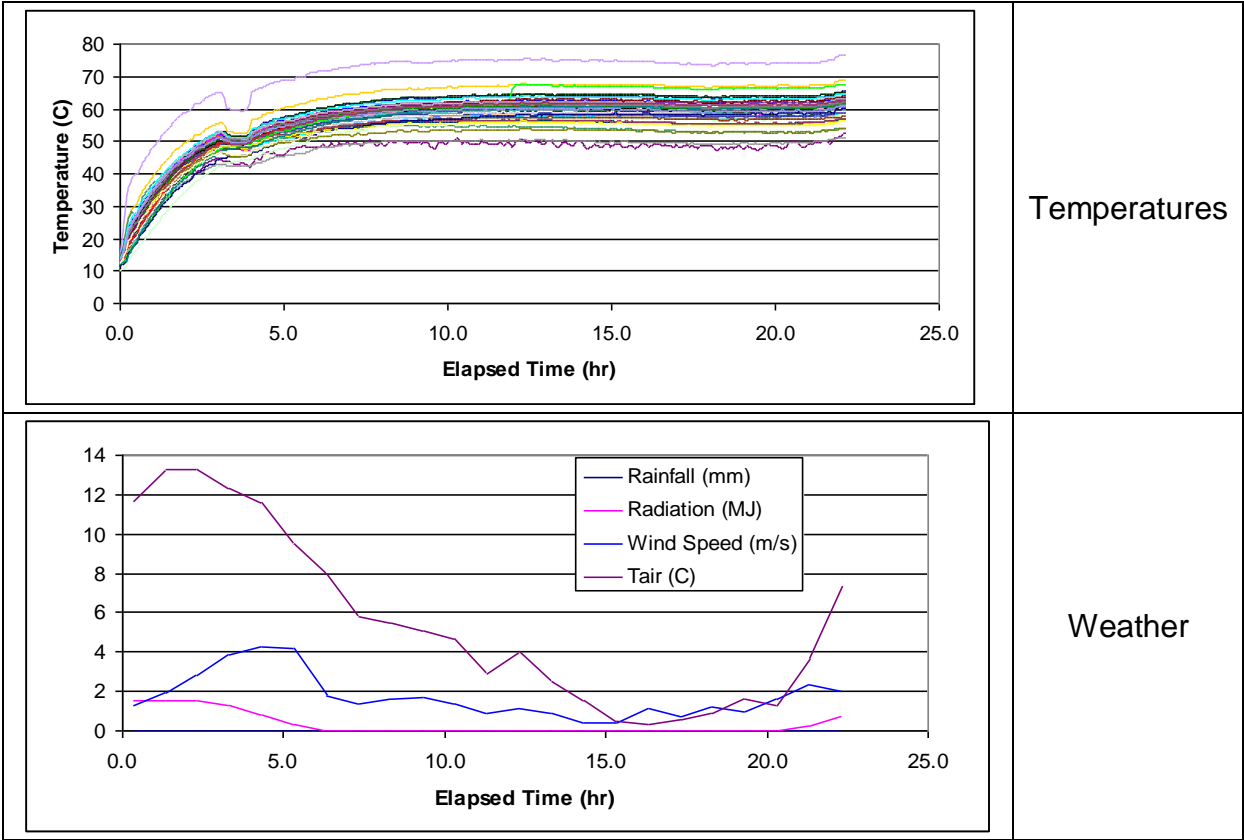


Figure 6.7: Loaded container Test 7: Internal air temperature plots for each thermocouple and weather, container insulated with polystyrene sheet, inverted heat input, auxiliary fan and 9 kW heat input, start 14.26 8 July.

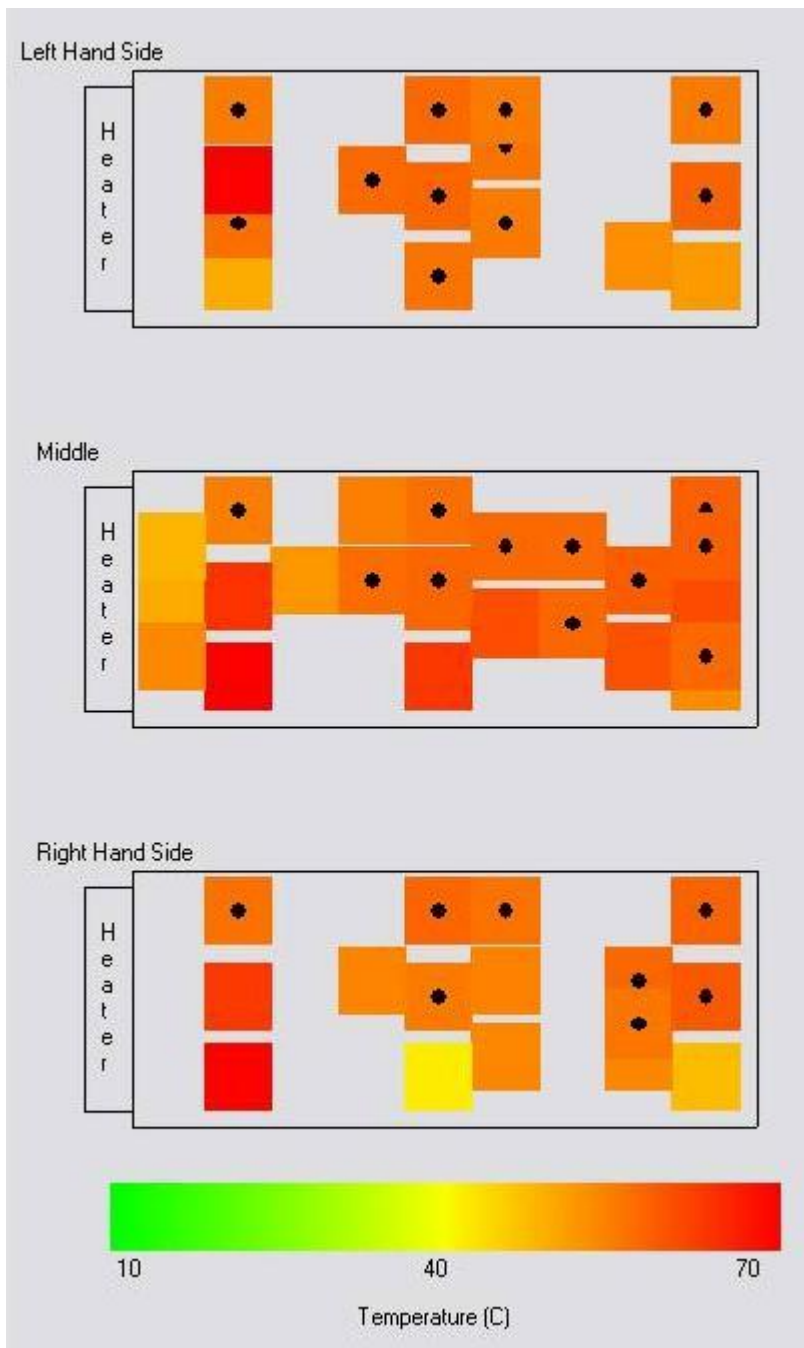


Figure 6.8: Loaded container Test 7: Steady state temperature distributions for the insulated container, inverted heat input with auxiliary fan and 9 kW heat input.

6.9 FURTHER TESTS

Additional tests were conducted which explored ducting air to the top or floor of the container either in multiple ducts, None of these tests improved on the performance that was obtained in Test 7.

6.10 EFFECT OF INSULATION ON CONTAINER WALL TEMPERATURES.

During these tests five thermocouples were taped to the walls, one placed in the centre of each wall.

Table 6.2 presents raw data readouts from 15 thermocouples recording internal air temperatures and the five thermocouples recording wall temperatures in loaded container Tests 2 and 7. The portions of the graphs provided in Figs 6.2 and 6.7 that these readings were taken from are presented in Fig. 6.9. These readings occurred when the system was in equilibrium and, other than responding to external change, running in stable state, at 08:21 on 24 June for Test 2 and 08:04 on 9 July for Test 7.

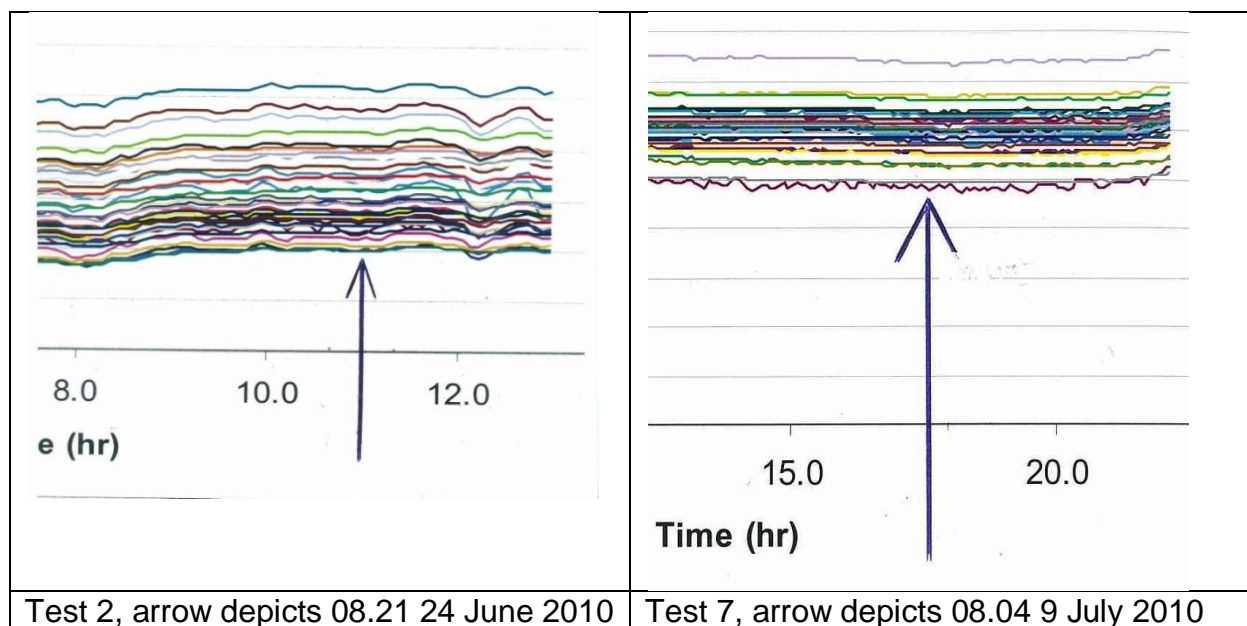


Fig 6.9: Timing of temperature snapshots taken from loaded container Tests 2 and 7, complete graphs presented in Figs 6.2 and 6.7.

The data in Table 2 have been placed in ascending order from cool to hot, to enable direct comparison of wall thermocouples with air thermocouples, because their spatial arrangement precluded comparison of means. In Test 7, it was found that four of the five wall thermocouples either reached or exceeded the treatment threshold, and the fifth was approaching it. This thermocouple was placed in one of the cooler spots in the container, where cooled air was being drawn back into the heater unit.

Table 6.2: Effect of insulation on wall temperatures.

| Test 2 Without Insulation | | Test 7 With Insulation | |
|--------------------------------------|--|--------------------------------------|--|
| Air Temperatures 15 thermocouples | Wall Surface Temperatures 5 thermocouples | Air Temperatures 15 thermocouples | Wall Surface Temperatures 5 thermocouples |
| 19.9 | | | 49.7 |
| | 20.3 | 52.9 | |
| 21.1 | | | 55.4 |
| 21.7 | | 57.2 | |
| | 22.6 | 57.6 | |
| 23.8 | | | 58.0 |
| 24.2 | | 58.5 | |
| | 24.6 | | 58.6 |
| 26.3 | | 59.6 | |
| | 26.7 | 60.3 | |
| | 27.5 | 60.3 | |
| 29.1 | | 60.6 | |
| 29.5 | | 60.7 | |
| 30.0 | | 61.1 | |
| 33.2 | | 61.5 | |
| 33.6 | | 61.6 | |
| 33.8 | | 61.9 | |
| 39.1 | | 61.9 | |
| 46.3 | | | 63.6 |
| 51.4 | | 67.3 | |

6.11 DISCUSSION AND CONCLUSIONS

This series of tests provided opportunity to explore application of a prototype heating unit to explore real life options for effective application of heat treatment to container internal surfaces.

Given the challenge of managing the surfaces associated with a load on pallets as well as the container walls, the tests showed that application of the method will involve balancing heat input with surface insulation, with possible opportunities to make adjustments according to ambient conditions, and in particular to adjust insulation according to availability of solar input or to deal with cold conditions. It was confirmed that a critical component of any system will be the design of the air circulation system, and this must be capable of forcing hot air between gaps in the load and between the load and container walls, so that all surfaces are reached. In this case, it was found that forcing air into the system at ground level through a single outlet produced the best results. Future systems may improve on this arrangement through adjusting outlet air velocities, the number of outlets etc.

The Test on 8 July 2010 that demonstrated that the approach is feasible still had a few thermocouples that fell outside the required treatment limits. Given the cold external air temperatures that occurred during the test, this result was probably expected and the fact that quite a high degree of conformance was achieved further indicates feasibility. Depending on the degree of conformance required from an operational system and benefits derived from the increased investment, measures can be taken to manage and further reduce temperature

variation. For cold spots that tend to occur close to the floor, this could include placing containers on an insulated and, if appropriate, heat reflective base. For cold spots that occur from cooled air returning to the heater inlet, this could include increasing heat output and volume of forced air and ensuring the treatment time is sufficient to allow the returned air to reach the required temperature and to heat surrounding surfaces. Depending on the degree of tolerance for higher temperatures, these can be managed by ensuring that air leaving the heater unit is close to or does not exceed the upper limit, and compensating for any lost heating capability by increasing the volume of heated air being forced into the container. As demonstrated by these tests, all of the discussed parameters can be controlled. Baseline data provided in this report will assist with designing a heating system that can deliver the appropriate volumes of hot air for efficient and effective circulation at known cost.

7 External Thermocouple Placement Test

On 6 October 2010, a brief 3.5 hour test was performed to determine the feasibility of using an externally placed insulated thermocouple to monitor internal air temperature. The external thermocouple was compared with an internally placed counterpart (Section 3.9). It was found that the externally recorded temperature closely matched the temperature recorded by the internal counterpart to within 1 °C (Fig. 7.1).

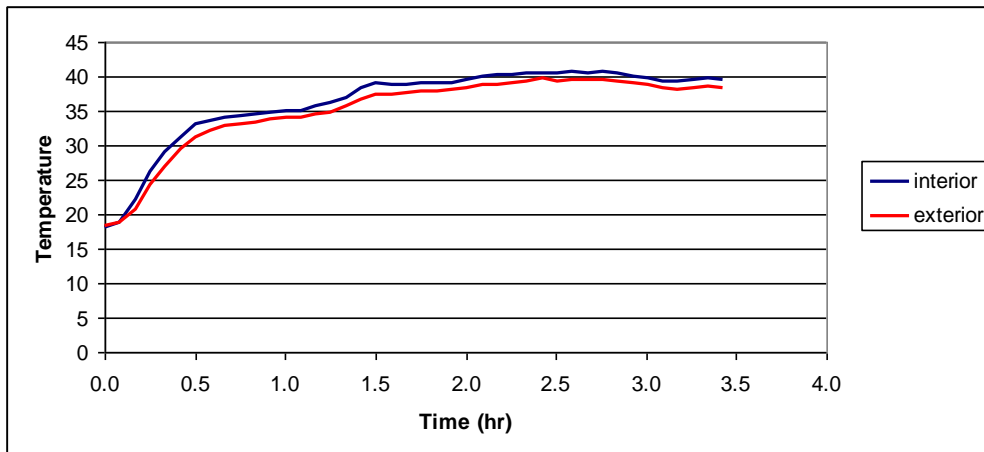


Figure 7.1: Internal and external temperatures when the external thermocouple is insulated with a 40 mm thick layer of polystyrene sheet.

7.1 DISCUSSION AND CONCLUSIONS

This simple and unreplicated test provided good evidence that externally placed thermocouples covered with closely applied insulation can be a useful contributor to temperature monitoring, particularly as this approach will be monitoring the actual surfaces of the container rather than air to confirm effective treatment.

Decisions on deployment of externally placed monitoring devices will need to be based on understanding internal variation to ensure this is managed appropriately. To confirm effective treatment, placement of these devices in the known coldest places would enable focus to be placed on obtaining the most critical information in a cost effective way. The only complication to this approach might be that cold spots shift according to load and container placement, but it is likely that cold spots will equate to the return inlet on the heater and the surfaces close to the floor, particularly on sides in permanent shade (e.g. south facing).

8 The Computer Model

A model was conceptually developed in Excel and then programmed in Visual Basic to simulate the heat balance and temperature of the container and its contents. Conceptual development in Excel involved using standard thermodynamic equations (e.g. Suehrcke, Petersen and Selby 2007; Long Sayma 2009; Lienhard and Lienhard 2012) as a foundation and adjusting constants in order to achieve good fit of model output against data collected from the container and simulated loads. The model was then programmed in visual basic when its output was providing good fit with recorded data, and was validated against data sets that included the container with and without loads, and measurements on low and high heat capacity loads.

Output from the model included calculating the amount of energy used during simulated heating of a container and its contents, which enabled the cost effectiveness of the method to be explored under different heat delivery options (e.g. comparing directly generated heat from heating elements with application of heat pump technology).

The model was developed using finite difference methods, which are commonly used to analyse and model heat transfer processes (Thirumaleshwar 2006), in conjunction with the equations. The model was developed around four nodes which covered the two basic processes for which data had been collected for calibration. These were external conditions driving internal air temperature and measurements on the empty container, and internal air temperature driving temperatures of internal surfaces and the load and measurements on low and high heat capacity loads (Figure 8.1).

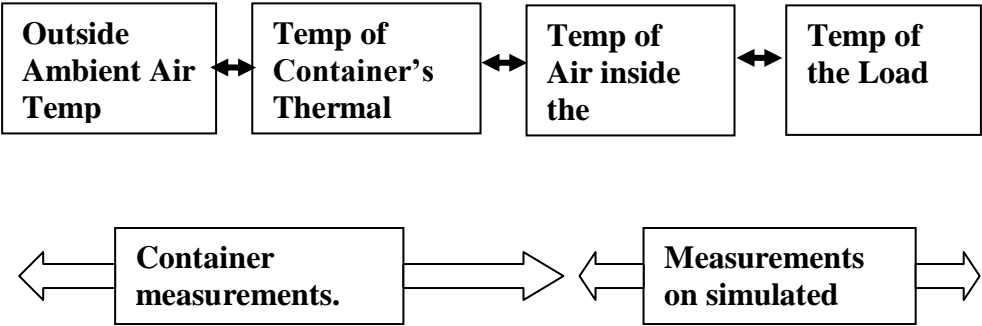


Figure 8.1: The nodes used in model.

Using the finite difference method, projected temperatures and heat flows were calculated over small time increments and the process was repeated iteratively (Figure 8.2). This enabled simulation of tests that had been conducted, and predicted versus actual comparisons to be made to adjust, calibrate and validate the model.

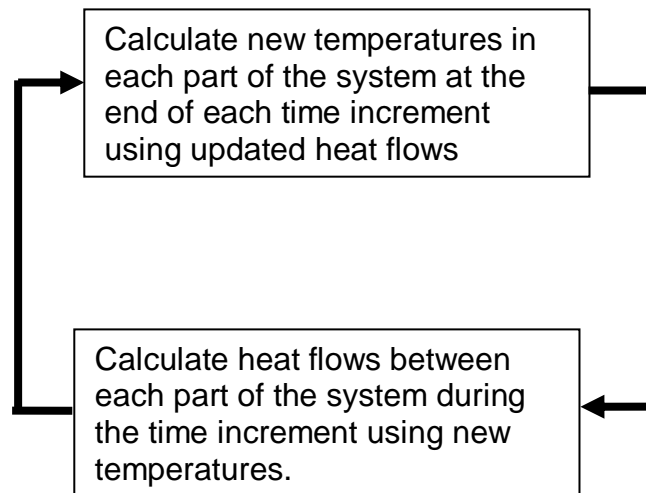


Figure 8.2: Process for iterative calculations of heat flows and temperatures.

The model was validated against test data obtained from the empty container over a nineteen day period, and a specific data set obtained from a test conducted on the loaded container which demonstrated that the method may be feasible.

Once validated, the model was used to confirm the key factors driving thermal performance, predict the heat output that would be needed from the prototype treatment unit and to evaluate feasibility by predicting thermal performance and costs under different conditions.

The following applies to version 1.03, 1.04 and 1.05 (Appendix 1).

8.1 HEAT FLOWS, PHYSICAL PARAMETERS AND EQUATIONS

Changes in the temperature of the container and its contents result from heat flow, where, for example, outward flow through the walls has a negative influence on temperature. Equations covering these flows are well established, and using these as a foundation, a pragmatic and minimalist approach was followed to identify the key factors that needed to be included in order to obtain acceptable fit for the purposes of this research. The most important heat flows exerting greatest influence were modelled to provide fit for purpose agreement between predicted and observed data while avoiding complexity.

The following heat flows (Fig 8.3) were modelled as two sub-sets:

Sub-set 1 External conditions driving internal air temperature

- solar heat input into the container walls (Q_{sun});
- container walls and external surrounding air (Q_{am});
- container walls and internal air (Q_{ma});
- heat input from the heater (Q_{heat});

Sub-set 2 Internal air temperature driving temperatures of internal surfaces and the load

- air inside the container and the load (Q_{load}).

where Q is heat flow per unit area.

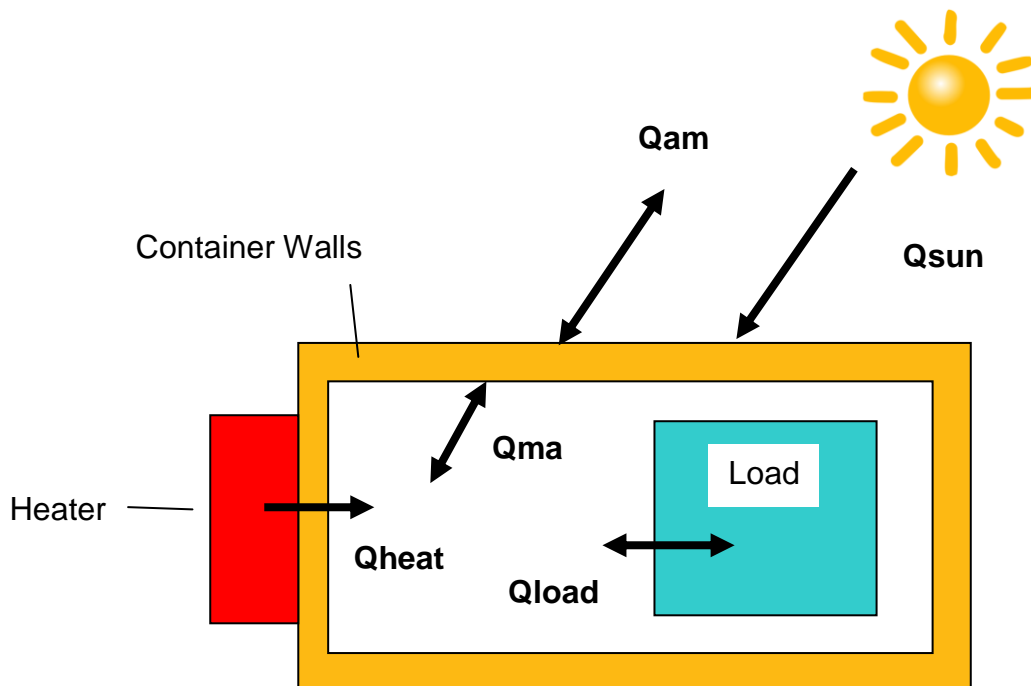


Figure 8.3: Heat flows between the outdoors, container and load.

The equations that were used, listed below, are well known and widely documented (e.g. Suehrcke, Petersen and Selby 2007; Lienhard and Lienhard 2008; Long Sayma 2009). Definitions of the terms that were used are provided in Table 8.1, along with the other physical parameters included in the model:

The equations used to calculate the heat flows for each time step are:

Sub-set 1 External heat flows driving internal air temperature

Heat gain from solar energy (Q_{sun}):

$$Q_{sun} = \alpha G$$

Heat flow from the surrounding air to the container wall (Q_{am}):

$$Q_{am} = K_1(T_{amb} - T_{mass})$$

Heat flow from the walls to the inside air (Q_{ma}):

$$Q_{ma} = K_2(T_{mass} - T_{air})$$

Sub-set 2 Heat flow between internal air and the load

Heat transfer from air in the container to the load surface (Q_{load}):

$$Q_{load} = K_{load}(T_{air} - T_{load})$$

The change in temperature from one time to the next are then calculated from the heat flows as follows:

$$\Delta T_{\text{mass}} = (Q_{\text{am}} - Q_{\text{ma}}) / (C_p \text{ mass}) (T_{\text{are}})$$

$$\Delta T_{\text{air}} = (Q_{\text{ma}} - Q_{\text{load}} + Q_{\text{heat}}) / (C_p \text{ air}) (V) (\text{AirDensity})$$

$$\Delta T_{\text{load}} = (Q_{\text{load}}) / (C_p \text{ load}) (\text{Load})$$

8.2 DEVELOPMENT, CALIBRATION AND VALIDATION

Developing the model so that it generated output in acceptable conformance with real data sets involved a step wise process. For both sub-sets, specific real-life measurements were made to collect data on which to base preliminary adjustments to the model. For sub-set one, this involved measurements using the empty container, and for sub-set two, measurements on the behaviour of representative loads as a result of heating the surrounding air. Once the two sub sets were producing outputs that related closely to the actual data, the model was calibrated and validated against another series of data sets including loaded container Test 7 (Section 6.8).

8.2.1 Sub-set 1 Initial adjustments using the empty container

The data set from empty container Test 1 (Section 4) was used to adjust constants in the model. These data sets covered a variety of weather events which included an 18 °C variation in ambient temperature, winds up to 27 kph, periods of rain and changes in humidity between 29 and 89%. Adjustment consisted of running a series of simulations with the model and tuning the values of coefficients between each run to obtain best fit of model output to real data. The values for the coefficients obtained through this process were checked against values reported in the literature for convective heat transfer, and they were found to be comparable (Table 7.1).

As a result of this process, a satisfactory fit of model-predicted internal air temperature with measured internal air temperature for the three day trial was obtained. The average difference between actual and predicted temperatures was 0.68 °C, which was taken as adequate for predicting heat flows within the container and demonstrating proof of concept. Given the variation in conditions that were experienced, it was also concluded that restricting model inputs to external (ambient) temperature and solar radiation would be sufficient for this project, and that little additional value would be obtained by including the impact of rain, wind and humidity into the model for the cost and complexity that would be entailed.

Table 8.1 Parameters and assumptions included in the model.

| Parameter | Value | Comment |
|---------------------------------|---|---|
| Absorptivity, α | 0.44 for an uninsulated container, 0 for an insulated container | The proportion of solar energy incident on the container which is absorbed. The value depends on the colour and type of surface and typically varies between 0.3 and 1 for painted metal surfaces (Parker et al 2007). The value used in the model of uninsulated containers was obtained by fitting data obtained during sunshine. |
| G | Measured (pyranometer) | Solar radiation per unit area in Watts per m^2 . A watt is a joule per second and input may be of the order of 700 joules of energy per second per square meter. |
| Q _{heat} | 0 to 30 kW | The actual energy input into the container from the heat source (heater or heat pump) for each simulation, assumed to be applied directly to the internal air. This is the numerical value for Q _{heat} in Fig 4.1.3 |
| K1 | 0.0135 kW/m ² K un-insulated container. | Heat transfer coefficient for the external surface of the container, the thermal resistance of any insulation and the thermal resistance of the external paint film. The value used in the model was obtained by fitting the data. The value for the un-insulated container falls in the typical range of 0.005 – 0.025 kW/m ² K for convection to free air. (Engineering Tool Box 2012) |
| K2 | 0.0024 kW/m ² K Insulated container 0.0135 kW/ m ² K | Heat transfer coefficient for heat transfer between the container surfaces and the air inside the container. For convenience in the model this was set to the same value as K1 for the un-insulated container... The value used in the model falls in the typical range of 0.010 – 0.2 kW/m ² K for forced convection. (Engineering Tool Box 2012). |
| K _{load} | 0.0120 kW/ m ² K | Average heat transfer coefficient for heat transfer between the air inside the container and the load The value used in the model was obtained from fitting the data. |
| A1 | 78.8 m ² | The surface area of the container involved in heat transfer between the air inside and outside the container. The value used in the model was the entire surface area of the container. |
| A2 | 64 m ² | The surface area of the container absorbing sunlight (direct and diffuse). The value used in the model was A1 less the floor area. |
| AL | 500 m ² | The surface area of the load exposed to the air in the container. This needs to be calculated for a particular load. |
| V | 40 m ³ | The volume of air in the container. This is the volume of the container less the volume of the load. |
| AirDensity | 1.1 kg/m ³ | Air Density – varies with air temperature (Engineering Tool Box 2012) |
| C _p air | 1 kJ/kgK | Specific heat capacity of air (Engineering Tool Box 2012) |
| C _p load | 4.2 kJ/kgK | Average heat capacity of load, assumed to be represented by a single thermal mass. Compilations of heat capacity data are readily available. See for example: ASHRAE 2009, Perry R.H. Green D 1984, Engineering Tool Box 2012. The value of 4.2 kJ/kgK is the specific heat capacity of water which was used for modelling high heat absorbing loads. |
| T _{amb} | | Outside air temperature. This is either set or drawn from the weather data file (depending on how the model is run). |
| T _{air} | | Internal air temperature (calculated by the model), assumed to be uniform given need for effective mixing in order to treat within specified limits. |
| T _{mass} | | Container wall temperature (calculated by the model). The model assumes rapid heat transfer through the walls and floor, and therefore is an average. |
| T _{load} | | Load temperature (calculated by the model) |
| C _p mass | 0.46 kJ/kgK | Average heat capacity of the container, assumed to be represented by a single thermal mass. The value of 0.46 kJ/kgK used in the model is the value for steel (Engineering Tool Box 2012) |
| Tare | 2350 kg | Tare weight of the container – relates to the capacity of the container to store heat |
| Load | 20,000 kg | The mass of the load in the container |
| User adjusted parameters | | |
| Dt | 2 secs | The time difference between each iteration. Dt, needs to be sufficiently small so that the model is accurate while not creating an unduly long computation |
| T _{max} | 60.0 °C | Temperature above which the heater is switched off during simulation with temperature control enabled |
| T _{min} | 59.8 °C | Temperature below which the heater is switched on during simulation with temperature control enabled. |
| N _{max} | 40,000 | The number of iterations after which the simulation terminates. For example 40,000 x 2 second iterations generates a 22 hour simulation. This is adjusted along with Dt so that the simulation covers the time of the treatment with adequate resolution. |

8.3 MODEL VALIDATION

Data sets from empty container Tests 3 to 10 (Section 4) and loaded container Test 7 (Section 6.8) were used to check and validate the model through comparisons of model output with observed internal temperatures.

The model performed consistently throughout all the tests, providing realistic output (Fig 8.4), and satisfactory R^2 values ($R^2 > 0.89$, Table 8.2)

Table 8.2: Agreement between actual and predicted temperatures: Coefficient of determination (R^2) values for empty container Tests 3 – 10 and loaded container Test 7.

| Empty container test number (Section 4) | Test date | Comment | Test duration | R^2 |
|---|------------------|--|---------------|-------|
| 3 | 19-23 March 2010 | 3 kW heat, empty | 66 hr 27 min | 0.90 |
| 4 | 23-25 March 2010 | 3 kW heat, empty | 46 hr 30 min | 0.89 |
| 5 | 25 March 2010 | 12 kW heat, empty | 5 hr | 0.96 |
| 6 | 25 March 2010 | Cool down and no heat, empty | 15 hr | 0.92 |
| 7 | 26 March 2010 | 6 kW heat, empty | 2 hr 45 min | 0.99 |
| 8 | 26 March 2010 | Cool down and no heat, empty | 65 hr 25 min | 0.96 |
| 9 | 29 March 2010 | No heat, empty | 48 hr 45 min | 0.97 |
| 10 | 31 March 2010 | No heat, empty | 179 hr 34 min | 0.95 |
| Loaded container Test 7 | 8 July 2010 | 9 kW fan assisted, insulated container with low heat capacity load | 22 hr 10 min | 0.96 |

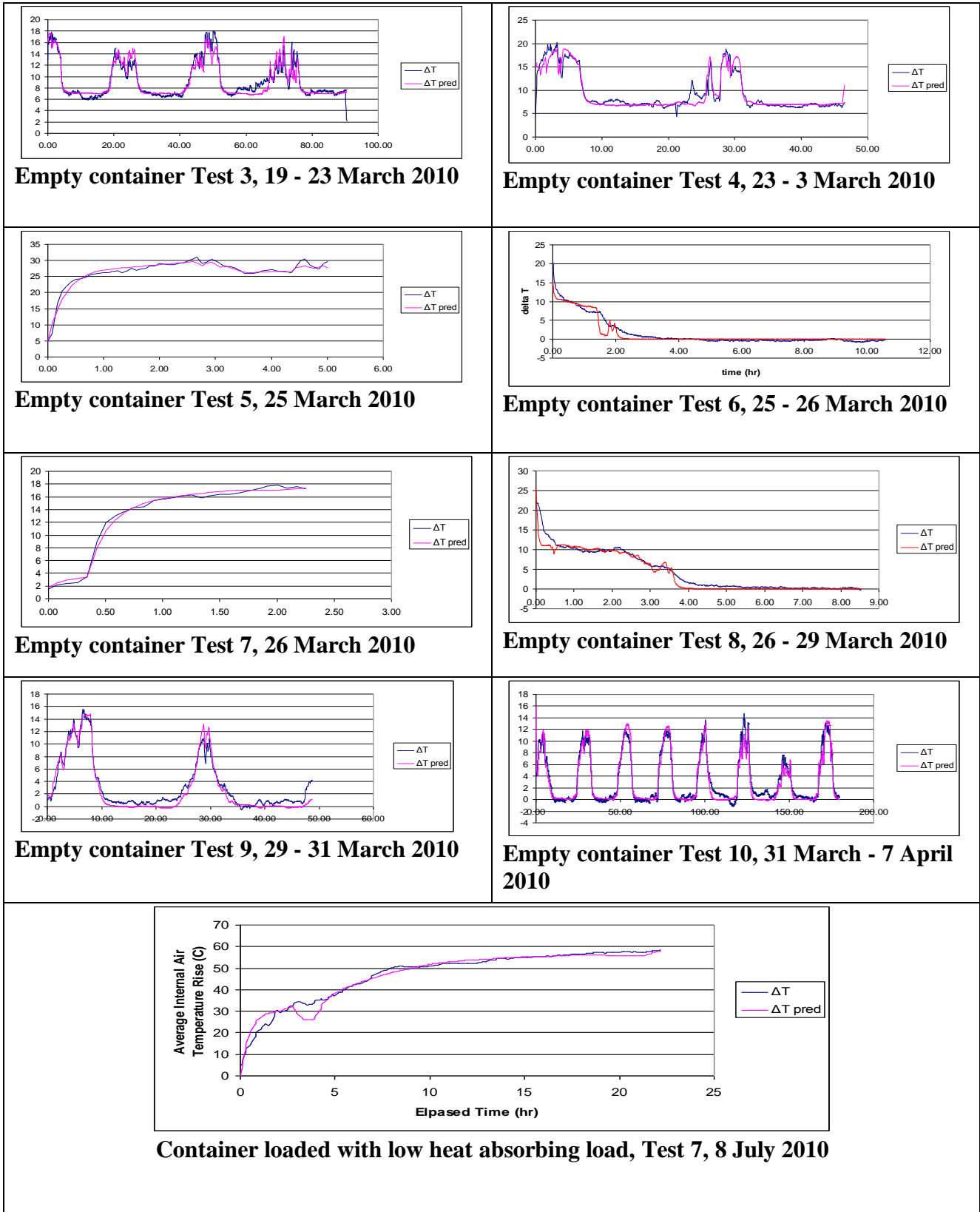


Fig. 8.4: Model output for validation for empty container Tests 3 – 9 and loaded container Test 7, predicted average internal temperatures against actual.

9 Modelling heat inputs to achieve required temperature for treatment

9.1 INTRODUCTION

Validation of the model and demonstration of its adequacy for predicting energy usage under different conditions enabled its use to further explore the feasibility of heat treating in light of findings from experimental measurements. To summarise previous experimental measurements:

- Baseline heat flow data collected from the empty container located outside outdoors, with and without heat input, with no insulation and where internal temperature was not driven up to the 56 °C treatment threshold;
- Baseline data collected using simulated cargoes to cover high and low heat capacity situations, and exploration of response when surrounded by heated air held at treatment temperature;
- Exploration of response to heating the container loaded with low heat capacity cargo, where feasibility of heat treatment was demonstrated with 9 kW heat input, use of a booster fan to direct hot air along the bottom of the load at and with external insulation applied to all surfaces other than the floor. Ambient conditions during this test included 6 hours when the external air temperature fell below 5 °C.

The above did not provide data to cover all situations, in particular the likely energy inputs required for high heat capacity loads and for 40 foot containers. The model was therefore used to estimate the energy input needed to achieve treatment temperatures at 5 °C, 25 °C external ambient temperatures with and without sun. To do this the model was used to simulate the following situations:

- Empty 20 foot high cube container without insulation, to round off field measurements where treatment temperatures were not reached
- Empty 20 foot high cube container with equivalent insulation to the EXPOL ThermaSlab S applied in field experiments, using an R value of 1.05 m²K/W
- 20 foot high cube container loaded with a low heat capacity load and covered with insulation as above
- 20 foot high cube container loaded with a high heat capacity load and covered with insulation as above
- Predicted behaviour of a 40 foot container under the above circumstances

Data from these simulations provided a comprehensive prediction of likely energy inputs needed to deploy this approach, and enable an evaluation of likely best case and worst case conditions with application of insulation to external surfaces. All the previous tests conducted with the low heat capacity load, either without insulation or with standard tarpaulins, resulted in high levels of internal temperature variation. While this might be managed through increased air flow, application of insulation demonstrated that effective management of this variation is feasible. While the model will predict the energy inputs needed to bring internal air temperatures up to the required level under conditions where the air temperature inside the container is kept uniform with adequate air circulation. (that might be considered to represent the required treatment, It does not it will not predict temperature variation resulting

from including a load. It was therefore necessary to run the model under conditions where it was known that variation would be minimal within the container or load).

9.2 RESULTS

The results from a series of simulations to cover a 20 foot high cube container are presented in Table 9.1. Treatment was considered to be complete when the air temperature inside the container had been maintained at greater than 55 °C for more than 30 minutes. Simulations on an empty uninsulated container indicated that 53% more energy would be required to heat treat the container at 5 °C than at 25 °C, and solar input on a hot day would reduce required energy input by 23% for a blue container of the type used to conduct field tests. (only a portion of the 7.6 kWh available from the sun is absorbed by the blue container). Solar capture would be higher with darker colours. Using this information as a baseline, it was found that:

- Insulating the outside of the container markedly reduces the energy requirements and shortens treatment times when outdoor temperatures are low (but prevents heating by the sun)
- Including a low heat capacity load with insulation in an insulated container can be treated in less than 1 hour....
- Including a high heat capacity load in an insulated with insulation container will take much longer to treat and will require a substantial energy input.

Table 9.1: Results from modelling energy inputs required to treat an unloaded and loaded 20 foot high cube container. The steady state power is the amount of power required to maintain the air inside the container at the target temperature once the container has heated up.

| | Ambient °C | Sun W/m ² | Available heat input kW | Steady State Power Requirement kW | Time to reach Temperature Complete Treatment Hr | Energy from Sun kWhr | Energy from Heater kWhr |
|---|---------------|-------------------------|----------------------------------|--|--|-------------------------------|----------------------------------|
| Empty 20 foot high cube, no insulation | 5 | 0 | 30 | 29.01 | 0.750.96 | 0 | 145.928.7 |
| | 25 | 0 | 30 | 18.56 | 0.160.55 | 0 | 95.312.7 |
| | 25 | 516500 | 30 | 11.58 | 0.080.54 | 69.77.6 | 61.89.8 |
| Empty 20 foot high cube, with insulation* | 5 | 0 | 30 | 9.8 | 0.77 | 0 | 18 |
| | 25 | 0 | 30 | 6.3 | 0.55 | 0 | 10.2 |
| | 25 | 516500 | 30 | 6.3 | 0.55 | 0 | 10.2 |
| 20 foot high cube, with insulation* and low heat capacity load | 5 | 0 | 30 | 10.0 | 0.98 | 0 | 25.3 |
| | 25 | 0 | 30 | 6.4 | 0.64 | 0 | 14.2 |
| | 25 | 516500 | 30 | 6.4 | 0.64 | 0 | 14.2 |
| 20 foot high cube, with insulation* and high heat capacity load, | 5 | 0 | 30 | 10.3 | 44.3 | 0 | 1330 |
| | 25 | 0 | 30 | 6.4 | 23.2 | 0 | 696 |
| | 25 | 516500 | 30 | 6.4 | 23.2 | 0 | 696 |

* To exploit solar energy, insulation removed from surfaces exposed to sun, and retained for all surfaces not exposed

In the above simulations, available heat input is the capacity of the heater if run continuously while the steady state power requirement is the heat input estimated by the model to maintain a steady temperature once the air has reached the required treatment temperature. A large heater may be useful in raising the contents rapidly to treatment temperature, provided this

can be done without exceeding the specified maximum temperature in any part of the container.

To illustrate the principle further, Figs 9.1 and 9.2 provide two comparative simulations run for an uninsulated 20 foot high cube with a high heat capacity load and available heat inputs of 30kW and 150 kW, respectively, to take the internal air from 20 °C to the required treatment temperature. With the 30 kW input, a very slow rate of heating was predicted with the internal temperature reaching 32 °C after 12 hrs, while it was predicted that increasing input to 150 kW would result in the internal air reaching treatment temperature after 3.25 hrs and the load after 12 hrs.

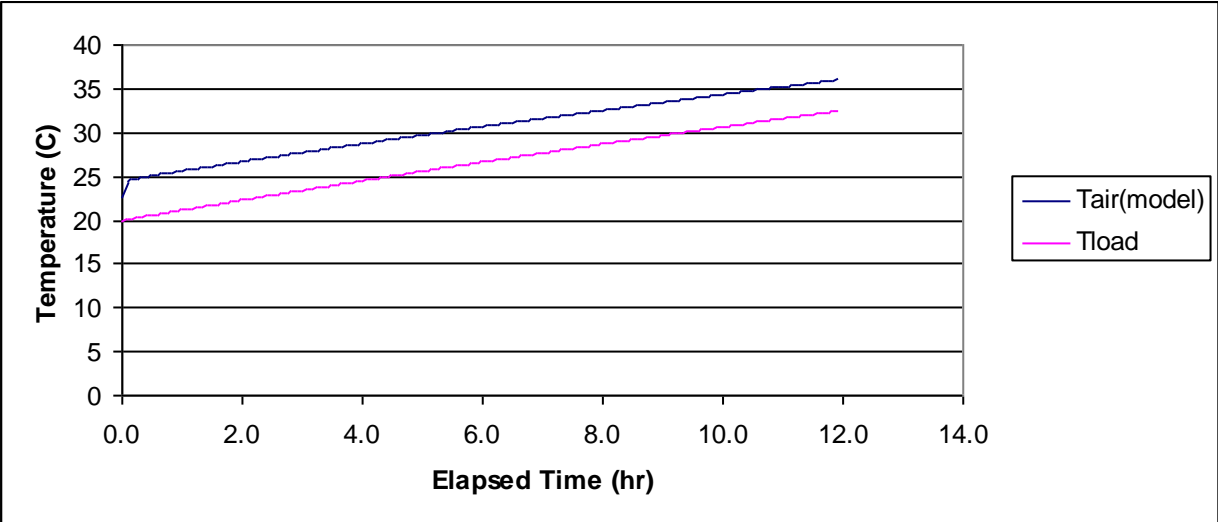


Figure 9.1: Model predicted rates of temperature increase for air temperature in a 20 foot high cube and a high heat capacity load of 1000 x 20 litre pails using a 30kW heater, starting at 20 oC.

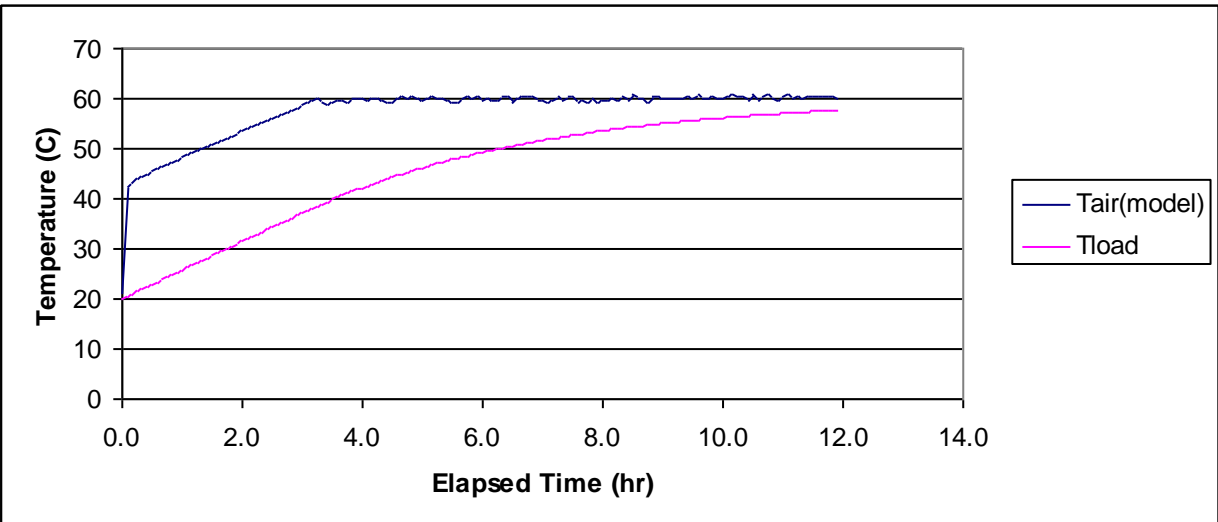


Figure 9.2: Model predicted rates of temperature increase for air temperature and a high heat capacity load of 1000 x 20 litre pails using a 150kW heater, starting at 20 °C.

In order to explore how these results might relate to a 40 foot container, two simulations were conducted to compare the relative inputs of heating a container of this size when empty and

uninsulated and insulated and filled with a low heat capacity load, at an external ambient temperature 5 °C. These simulations indicated that even with a cold external air temperature, a treatment could be completed in a comparable time by increasing the available heat input from 30 to 50kW, and an approximate doubling of energy input may be expected (Table 9.2). While the simulation output for the uninsulated empty containers look to be favourable, previously findings about cooling and impacts on wall surface temperatures need to be taken into account.

Table 9.2: Comparison of energy input required to treat a 40 foot container compared with the 20 foot high cube container at an external air temperature of 5 °C.

| Container Type | Tare kg | Available Heat Input kW | Steady State Power Requirement kW | Time to Complete Treatment Hr | Energy from Heater kWhr |
|---|------------|----------------------------|--------------------------------------|----------------------------------|----------------------------|
| Unloaded and without insulation | | | | | |
| 20 foot high cube | 2350 | 30 | 29.1 | 0.96 | 28.7 |
| 40 foot Standard | 3730 | 50 | 49.9 | 0.99 | 49.8 |
| With low heat capacity load and insulation | | | | | |
| 20 foot high cube | 2350 | 30 | 10.0 | 0.98 | 25.3 |
| 40 foot Standard | 3730 | 50 | 29.2 | 1.04 | 45.2 |

9.3 DISCUSSION AND CONCLUSIONS

The simulations were run to cover a broad range of circumstances and indicate likely energy input required to treat shipping containers and cargo surfaces under best and worst case circumstances. The model can be used to predict energy inputs, and heating rates for a range of container sizes, levels of insulation and types of load. In evaluating heat inputs, the model will not predict wall temperatures, and previous findings on adding insulation need to be taken into account, particularly under cool conditions, when walls will be subjected to significant cooling in the absence of insulation.

Given appropriate management of insulation to ensure wall surfaces reach required temperatures, use of circulated heated air is well suited for treating empty containers, and energy requirements may be modest depending on external conditions. To compensate for lack of insulation, it would be feasible to increase treatment temperatures beyond those covered by this research because possible damage to cargo is not a consideration, and such a system is currently in operational use (K. Glassey pers. comm.).

When applied to loaded containers, the simulations further indicated that low heat absorbing loads could be readily treated in insulated containers, provided air is adequately circulated. Treatment of containers filled with higher heat absorbing loads would be more challenging, but could potentially be achieved with more powerful heat sources, extended treatment times., and making allowance for the load to heat up.

The New Zealand Ministry of Business, Innovation and Employment’s Archive of electricity price surveys (<http://www.med.govt.nz/sectors-industries/energy/electricity/prices/electricity-tariff-surveys/archive>) are available to obtain an up to date view on current prices, and therefore enable current costings to be evaluated.

10 Final Discussion and Conclusions

This project raised significant challenges in regard to controlling complexity. Complex measurements were obtained which included under controlled indoor conditions and with multi channel data logging of measurements made on a real container exposed to the elements. The parallel development of the simulation model proved to be useful in refining design, and then enabling field measurements to be used for model development. As a result, a model has been developed which will form a useful foundation for further developing and applying this treatment method, and this could include its use as the basis of a control mechanism for controlling and monitoring treatments operationally.

While the research highlighted challenges related to heating container surfaces which are cooled by external conditions, the need to obtain adequate air circulation throughout the load, and potential lags created as high heat absorbing loads warm up, it was evident that this is a useful approach which has potential application. While the method has currently been adopted under relatively straightforward circumstances, this research has demonstrated potential to use the method in a sustainable way for the long term, by addressing increasing energy costs through use of heat pumps and adding insulation, as pads on the ground on which containers sit and as insulated covers. There may be additional opportunities to enhance efficiency through exploiting solar heating when available.

Container loads are a major consideration in useful deployment, and for this study, palletised cargo which resulted in air gaps between the floor, walls and adjacent rows enabled air to circulate through the container. This approach is unlikely to be useful where loads are crammed into containers to severely restrict circulation.

11 Acknowledgements

Barney Stephenson and Sarah Meadows of the Ministry for Primary Industries provided valuable advice which assisted with preparing the final report, particularly in teasing out the complex relationships between various facets of the work, establishing the structure of the report, resolving how best to present data, and providing suggestions on demonstrating the scope and robustness of the model.

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Specific Heat Capacity of Air: http://www.engineeringtoolbox.com/air-specific-heat-capacity-d_705.html

Specific Heat Capacity of Solids: http://www.engineeringtoolbox.com/specific-heat-solids-d_154.htmlhttp://www.engineeringtoolbox.com/specific-heat-solids-d_154.html

Heat Transfer Coefficients: http://www.engineeringtoolbox.com/convective-heat-transfer-d_430.html

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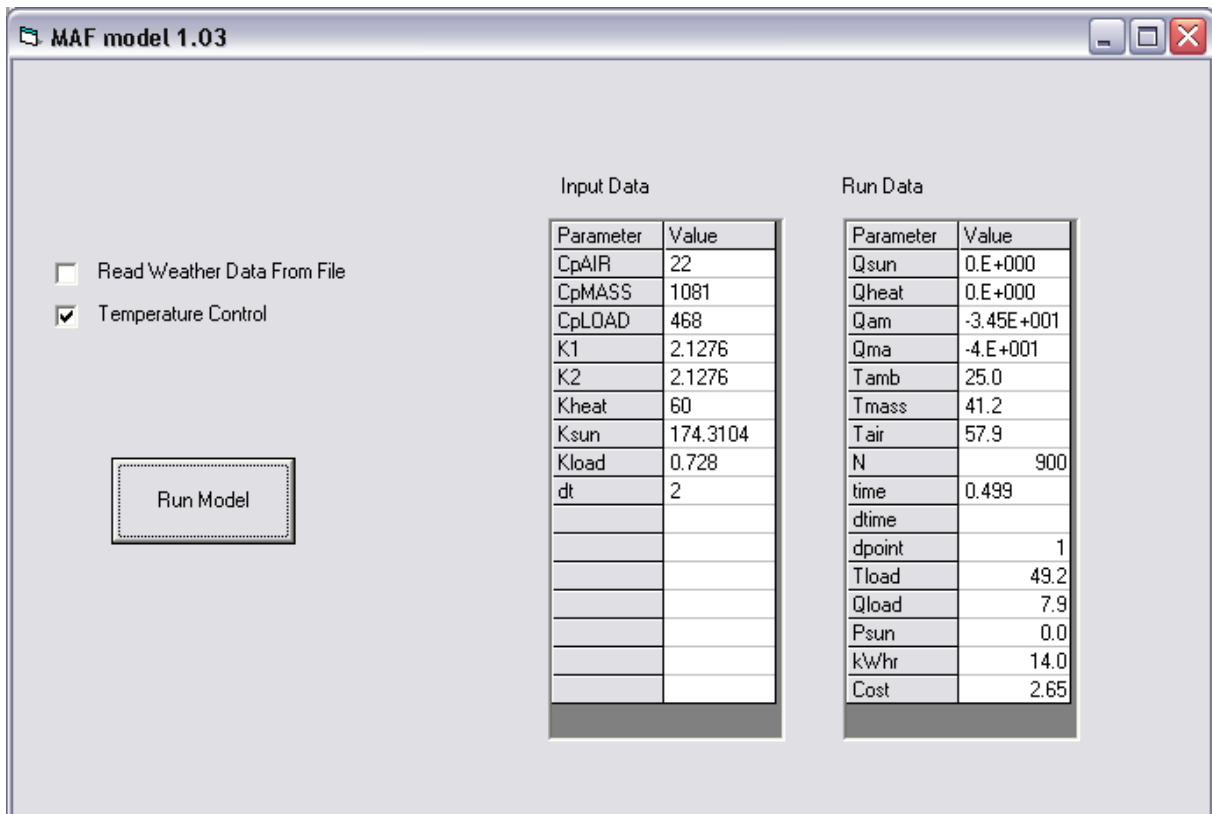
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13 Appendices

Appendix 1 Operating the Model

The model has been implemented in Visual Basic. The information here relates to Version 1.03 which covers the simulations provided in Chapter 9.

The user interface for version 1.03 is shown below.



The two grids enable the input data to be checked, and progress with the simulation to be monitored to enable early identification of problems.

Two later versions cover the following:

1. Version 1.04 which is the same as 1.03 minus MS FlexGrid Activex controls, and the two flexgrids on the input screen have been removed; this version has been provided to enable the programme to be run without MS FlexGrid;
2. Version 1.05 which provides two options: to terminate the programme once internal air temperature has reached the specified level, and to allow the program to run without updating the FlexGrid each iteration. These substantially reduce the time needed for each simulation to run. This version also has improved data output, where the data are ordered in a more consistent sequence making interpretation more straightforward.

Otherwise, output from both of these versions is the same as Version 1.03

To run the model, the information used to control the program (see sections 2.1 to 2.3 of this report) is loaded from a data file File (MAFdata.dat). This can be edited prior to each run

using Notepad or any text editor. The contents of the data file are listed in the table below, and entered data must conform with this format. Data fields are separated by carriage returns, and these are already present in the existing file.

Fig 12.1 IModel Input Data in sequence for MAFdata.dat

| | Parameter | Units | Description |
|----|----------------|----------------------|--|
| 1 | dt | seconds | Length of time increment |
| 2 | Nmax | | max allowed number of iterations |
| 3 | MaxTime | seconds | max allowed elapsed time |
| 4 | RecordInterval | minutes | used when weather data is not read in. The weather data interval is used when it is. |
| 5 | Pyrocal | kW/m ² V | Pyranometer Calibration Factor |
| 6 | Absorptivity | | Absorptivity of container surface |
| 7 | Kheat | kW | kW heat in from heater |
| 8 | K1 | kW/m ² K | ambient<->mass CHTC |
| 9 | K2 | 'kW/m ² K | mass<->air in container CHTC |
| 10 | A1 | m ² | surface area of container for heat transfer |
| 11 | A2 | m ² | surface area of container absorbing sun |
| 12 | V | m ³ | volume of air in container |
| 13 | Tare | kg | tare weight of container |
| 14 | AL | m ² | surface area of load exposed to air |
| 15 | CpLOAD | kJ/kgK | average heat capacity of load |
| 16 | Load | kg | mass of load |
| 17 | Kload | kW/m ² K | air<->load overall transfer coefficient |
| 18 | CpAIR | kJ/kgK | heat capacity of air |
| 19 | AirDensity | kg/m ³ | air density |
| 20 | CpMASS | kJ/kgK | average heat capacity of container |
| 21 | Tmax | C | maximum control temp |
| 22 | Tmin | C | minimum control temp |
| 23 | Charge | \$ | cost of power |
| 24 | G\$ | | weather data file path and name |

During the simulation the data is outputted to a file which can be subsequently loaded to a spreadsheet for analysis and graphing. A sample of the data file is given in the table below:

| Time | Tamb | Sun | Tmass | Tair(model) | Tload | kWhr |
|------|-------|------|-------|-------------|-------|------|
| 0.00 | 25.00 | 0.00 | 25.00 | 27.73 | 25.00 | 0.02 |
| 0.08 | 25.00 | 0.00 | 30.08 | 50.75 | 29.68 | 2.52 |
| 0.17 | 25.00 | 0.00 | 34.10 | 55.03 | 34.54 | 5.02 |
| 0.25 | 25.00 | 0.00 | 37.18 | 58.54 | 39.20 | 7.52 |
| 0.33 | 25.00 | 0.00 | 39.36 | 59.13 | 43.35 | 9.90 |

At the completion of the simulation a data file is produced summarising the entire simulation. An example is given in the table below.

Output from MAFmodel 1.03 on 05-07-2010 at 10:53:19

Weather data file c:\HOLD\con1a.txt

| | |
|----------------------|--------|
| Read from file | 0 |
| Temp control enabled | 1 |
| Pyrocal | 3.095 |
| Absorptivity | 0.44 |
| Kheat | 30 |
| K1 | 0.0135 |
| K2 | 0.0135 |
| Kload | 0.0016 |
| A1 | 78.8 |
| A2 | 64 |
| AL | 227.5 |
| V | 20 |
| Tare | 2350 |
| Load Wt | 260 |
| CpAIR | 1 |
| CpLOAD | 1.8 |
| CpMASS | 0.46 |
| Air Density | 1.1 |
| Tmax | 60 |
| Tmin | 59.8 |
| Charge | 0.19 |

End of Run Data

| | |
|-------|-------|
| N | 9001 |
| t | 5 |
| Tamb | 25 |
| Tmass | 42.3 |
| Tair | 60.6 |
| Tload | 59.7 |
| Psun | 0 |
| kWhr | 98.4 |
| Cost | 18.69 |

view on current prices, and therefore enable costings to be evaluated.

Appendix 2 Program Listing

```
'MAFmodel
'P1644 Simulaton of heating of container for biosecuriuty purposes

Private a(10000, 4) 'real time data array (read in from file)
Private Kheat 'Heat input from heater in kW
Private Ksun 'Converts pyranometer input in volts to kW
Private K1 'Convective heat transfer coefficient ambient<->mass
Private K2 'convective heat transfer coefficient mass<->air in container
Private Kload 'heat transfer coefficient into load
Private t 'time elapsed
Private N 'Number of iterations
Private A1 'm2 surface area of container for heat transfer
Private A2 'm2 surface area of container absorbing sun
Private AL 'm2 surface area of load exposed to air
Private V 'volumer
Private AirDensity 'Density of air kg/m3
Private Qheat 'heat input from heater
Private Pyro 'pyranometer reading in volts
Private Qsun 'heat input in dt from sun in kJ
Private Qam 'heat transfer between container mass and ambient in dt
Private Qma 'heat transfer between container mass and air in container in dt
Private Qload 'heat transfer from air into load
Private CpAIR 'heat cpacity of air
Private CpMASS 'heat capaciaty of container mass
Private CpLOAD 'heat capacity of load
Private Tamb 'Ambient T
Private Tmass 'Temp of Container Mass
Private Tair 'Temp of air in container
Private Tload 'Average internal temp of load
Private Pyrocal 'Pyranometer calibration constant kW/m2
Private Absorptivity 'absorbitivity of container surface
Private Tare 'Tare weight of conatiner kg
Private Load 'Mass of load in kg
Private LBL2(20) As String 'labels for FlexGrid1
Private Nmax 'max allowed number of iterations
Private dpoint
Private TControl% 'Flag indicating whether temp control is present
Private Tmax 'Maximum temperature allowed by temperature controller
Private Tmin 'Minimum temperature allowed by temperature controller
Private MaxTime 'Maximum time simulation is allowed to run for
Private kWhr 'Heating Power consumed during simulation
Private Psun 'kWhr provided by sun
Private Charge 'Cost of power per kWh
Private Cost 'total cost of run
Private RecordInterval 'Recording interval
Private wcount% 'counter for writing to disk
Private rff% 'flag indicating if weather data is to be read from file or not
Private G$ 'Filename of weather data file
Private dt 'time in seconds per iteration of model
Private VER$ 'Model version number
Private Heater% 'Status of heater
```

```

Private Sub Form_Load()
VER$ = "1.04"
Form1.Caption = "MAF model " + VER$
Grid1Setup
Grid2Setup
dpoint = 1 'first position in data file
read_datafile

End Sub

Private Sub Check1_Click()
'rff% = Abs(rff - 1) 'read from file
End Sub
Private Sub Command1_Click()

kW hr = 0
P sun = 0
N = 0
'read ambient data from file - if check box checked
If Check1 = vbChecked Then rff% = 1 Else rff% = 0
If Check2 = vbChecked Then TControl% = 1 Else TControl% = 0

result1 'Writes model parameters to disk file
If rff% = 1 Then reader 'reads in weather data
diskopen 'opens file for output of model run data

'Calculate and Display Model Parameters
CpAIR = CpAIR * AirDensity * V
CpMASS = CpMASS * Tare
CpLOAD = CpLOAD * Load
K1 = K1 * A1 * dt
K2 = K2 * A1 * dt
Kheat = Kheat * dt
Ksun = Pyrocal * Absorptivity * A2 * dt
Kload = Kload * AL * dt
MSFlexGrid2.Col = 1
MSFlexGrid2.Row = 1: MSFlexGrid2.CellAlignment = flexAlignLeftCenter: MSFlexGrid2.Text
= CpAIR
MSFlexGrid2.Row = 2: MSFlexGrid2.CellAlignment = flexAlignLeftCenter: MSFlexGrid2.Text
= CpMASS
MSFlexGrid2.Row = 3: MSFlexGrid2.CellAlignment = flexAlignLeftCenter: MSFlexGrid2.Text
= CpLOAD
MSFlexGrid2.Row = 4: MSFlexGrid2.CellAlignment = flexAlignLeftCenter: MSFlexGrid2.Text
= K1
MSFlexGrid2.Row = 5: MSFlexGrid2.CellAlignment = flexAlignLeftCenter: MSFlexGrid2.Text
= K2
MSFlexGrid2.Row = 6: MSFlexGrid2.CellAlignment = flexAlignLeftCenter: MSFlexGrid2.Text
= Kheat
MSFlexGrid2.Row = 7: MSFlexGrid2.CellAlignment = flexAlignLeftCenter: MSFlexGrid2.Text
= Ksun
MSFlexGrid2.Row = 8: MSFlexGrid2.CellAlignment = flexAlignLeftCenter: MSFlexGrid2.Text
= Kload
MSFlexGrid2.Row = 9: MSFlexGrid2.CellAlignment = flexAlignLeftCenter: MSFlexGrid2.Text
= dt

'Run model
If rff% = 1 Then

```

```

Tamb = a(1, 2)
Pyro = a(1, 3)
Tair = a(1, 4)
Tmass = a(1, 4)
Tload = a(1, 4)
End If
If rff% = 0 Then
  Tamb = 5
  Pyro = 0
  Tair = 5
  Tmass = 5
  Tload = 5
End If

N = 1
kWhr = 0
t = 0

1000 'Start

If rff% = 1 And t > a(dpoint, 1) * 3600 Then
  writer
  Tamb = a(dpoint, 2)
  Pyro = a(dpoint, 3)
  dpoint = dpoint + 1
End If
If rff% = 0 And t > wcount% * RecordInterval * 60 Then
  writer
  wcount% = wcount% + 1
End If

If TControl% = 1 Then
  'Temperature control enabled
  If Tair > Tmax Then Qheat = 0: Heater% = 0
  If Tair < Tmin Then Qheat = Kheat: Heater% = 10
  Print #2, Tair, Tmin, Tmax, Heater%
End If

kWhr = kWhr + Qheat / 3600
Cost = Charge * kWhr

If TControl% = 0 Then
  'Temperature control disabled
  Qheat = Kheat: Heater% = 5
End If

Qsun = Ksun * Pyro

Psun = Psun + Qsun / 3600

Qam = (Tamb - Tmass) * K1
Qma = (Tmass - Tair) * K2
Qload = (Tair - Tload) * Kload
Tair = Tair + (Qheat + Qma - Qload) / CpAIR

```

```

Tmass = Tmass + (Qam - Qma + Qsun) / CpMASS
If Load <> 0 Then Tload = Tload + (Qload) / CpLOAD
If Load = 0 Then Tload = Tload
MSFlexGrid1.Col = 1
MSFlexGrid1.Row = 1: MSFlexGrid1.CellAlignment = flexAlignLeftCenter: MSFlexGrid1.Text
= Format(Qsun, "0.##E+000")
MSFlexGrid1.Row = 2: MSFlexGrid1.CellAlignment = flexAlignLeftCenter: MSFlexGrid1.Text
= Format(Qheat, "0.##E+000")
MSFlexGrid1.Row = 3: MSFlexGrid1.CellAlignment = flexAlignLeftCenter: MSFlexGrid1.Text
= Format(Qam, "0.##E+000")
MSFlexGrid1.Row = 4: MSFlexGrid1.CellAlignment = flexAlignLeftCenter: MSFlexGrid1.Text
= Format(Qma, "0.##E+000")
MSFlexGrid1.Row = 5: MSFlexGrid1.CellAlignment = flexAlignLeftCenter: MSFlexGrid1.Text
= Format(Tamb, "####0.0")
MSFlexGrid1.Row = 6: MSFlexGrid1.CellAlignment = flexAlignLeftCenter: MSFlexGrid1.Text
= Format(Tmass, "####0.0")
MSFlexGrid1.Row = 7: MSFlexGrid1.CellAlignment = flexAlignLeftCenter: MSFlexGrid1.Text
= Format(Tair, "####0.0")
MSFlexGrid1.Row = 8: MSFlexGrid1.Text = N
MSFlexGrid1.Row = 9: MSFlexGrid1.CellAlignment = flexAlignLeftCenter: MSFlexGrid1.Text
= Format(t / 3600, "###0.000")
MSFlexGrid1.Row = 10: MSFlexGrid1.Text = Format(a(dpoint, 1), "###0.00")
MSFlexGrid1.Row = 11: MSFlexGrid1.Text = dpoint
MSFlexGrid1.Row = 12: MSFlexGrid1.Text = Format(Tload, "####0.0")
MSFlexGrid1.Row = 13: MSFlexGrid1.Text = Format(Qload, "####0.0")
MSFlexGrid1.Row = 14: MSFlexGrid1.Text = Format(Psun, "####0.0")
MSFlexGrid1.Row = 15: MSFlexGrid1.Text = Format(kWhr, "####0.0")
MSFlexGrid1.Row = 16: MSFlexGrid1.Text = Format(Cost, "###0.00")

```

```
'writer
```

```
N = N + 1
```

```
t = t + dt
```

```
If N > Nmax Then
```

```
'result
```

```
Close #1
```

```
Close #2
```

```
result2
```

```
Exit Sub
```

```
End If
```

```
'If Time > maxtime then Exit Sub
```

```
GoTo 1000
```

```
End Sub
```

```
Private Sub Grid1Setup()
```

```
'Headers
```

```
MSFlexGrid1.Row = 0
```

```
MSFlexGrid1.Col = 0
```

```
MSFlexGrid1.Text = "Parameter"
```

```
MSFlexGrid1.Col = 1
```

```
MSFlexGrid1.Text = "Value"
```

```
MSFlexGrid1.CellAlignment = flexAlignLeftCenter
```

```
'Labels
```

```
'Assign Labels
```

```

LBL2(1) = "Qsun"
LBL2(2) = "Qheat"
LBL2(3) = "Qam"
LBL2(4) = "Qma"
LBL2(5) = "Tamb"
LBL2(6) = "Tmass"
LBL2(7) = "Tair"
LBL2(8) = "N"
LBL2(9) = "time"
LBL2(10) = "dtime"
LBL2(11) = "dpoint"
LBL2(12) = "Tload"
LBL2(13) = "Qload"
LBL2(14) = "Psun"
LBL2(15) = "kWhr"
LBL2(16) = "Cost"

```

```

'Place Labels
MSFlexGrid1.Col = 0
For i = 1 To 16
MSFlexGrid1.Row = i
MSFlexGrid1.Text = LBL2(i)
Next i

```

```

End Sub
Private Sub Grid2Setup()
'Headers
MSFlexGrid2.Row = 0
MSFlexGrid2.Col = 0
MSFlexGrid2.Text = "Parameter"
MSFlexGrid2.Col = 1
MSFlexGrid2.Text = "Value"
MSFlexGrid2.CellAlignment = flexAlignLeftCenter
'Labels
'Assign Labels
LBL2(1) = "CpAIR"
LBL2(2) = "CpMASS"
LBL2(3) = "CpLOAD"
LBL2(4) = "K1"
LBL2(5) = "K2"
LBL2(6) = "Kheat"
LBL2(7) = "Ksun"
LBL2(8) = "Kload"
LBL2(9) = "dt"
LBL2(10) = ""
LBL2(11) = ""

```

```

'Place Labels
MSFlexGrid2.Col = 0
For i = 1 To 11
MSFlexGrid2.Row = i
MSFlexGrid2.Text = LBL2(i)
Next i

```

```

End Sub

```

```

Private Sub read_datafile()
Open "MAFdata.dat" For Input As #1
Input #1, dt 'time interval seconds
Input #1, Nmax 'max allowed number of iterations
Input #1, MaxTime 'max allowed elapsed time
Input #1, RecordInterval 'minutes - used when weather data is not read in. The weather data
' interval is used when it is.

```

```
'Actual Parameters
```

```

Input #1, Pyrocal 'Pyranometer Cal kW/m2V
Input #1, Absorptivity 'absorptivity of container surface
Input #1, Kheat 'kW heat in from heater
Input #1, K1 'kW/m2K ambient<->mass CHTC
Input #1, K2 'kW/m2K mass<->air in container CHTC

```

```

Input #1, A1 'm2 surface area of container for heat transfer
Input #1, A2 'm2 surface area of container absorbing sun
Input #1, V 'm3 volume of air in container
Input #1, Tare 'kg tare weight of container

```

```

Input #1, AL 'm2 surface area of load exposed to air
Input #1, CpLOAD 'kJ/kgK 'average heat capacity of load
Input #1, Load 'kg mass of load
Input #1, Kload 'kW/m2K air<->load overall transfer coefficient

```

```

Input #1, CpAIR 'kJ/kgK 'heat capacity of air
Input #1, AirDensity 'kg/m3 air density
Input #1, CpMASS 'kJ/kgK 'average heat capacity of container

```

```

Input #1, Tmax 'maximum control temp
Input #1, Tmin 'minimum control temp
Input #1, Charge 'cost of power $
Input #1, G$ 'weather data file

```

```
Close #1
```

```
End Sub
```

```
Private Sub reader()
```

```
Open G$ For Input As #1
```

```
Input #1, N
```

```
For i = 1 To N
```

```
Input #1, a(i, 1), a(i, 2), a(i, 3), a(i, 4)
```

```
'Print a(i, 1), a(i, 2), a(i, 3), a(i, 4)
```

```
Next i
```

```
Close #1
```

```
End Sub
```

```
Private Sub writer()
```

```
If rff% = 1 Then Print #1, a(dpoint, 1), a(dpoint, 2), a(dpoint, 3), Tmass, a(dpoint, 4), Tair,
Tload, kWhr, Heater%
```

```
If rff% = 0 Then Print #1, t / 3600, Tamb, Pyro, Tmass, Tair, Tload, kWhr, Heater%
```

```
End Sub
```

```
Private Sub diskopen()
```

```
Open "c:\HOLD\mafmodel.sve" For Output As #1
```

```
Open "c:\HOLD\mafdiagnostic.sve" For Output As #2
```

```
If rff% = 1 Then Print #1, " Time", "Tamb", "Pyro", "Tmass", "Tair", "Tair(model)", "Tload",
kWhr
```

```
If rff% = 0 Then Print #1, " Time", "Tamb", "Pyro", "Tmass", "Tair(model)", "Tload", "kWhr"  
End Sub
```

```
Private Sub result1()
```

```
Open "mafresult.sve" For Output As #1
```

```
Print #1, "Output from MAFmodel "; VER$; " on "; Date$; " at "; Time$
```

```
Print
```

```
Print #1, "Weather data file "; G$
```

```
Print #1, "Read from file "; rff%
```

```
Print #1, "Temp control enabled "; TControl%
```

```
Print #1, "Pyrocal", Pyrocal 'Pyranometer Cal kW/m2V
```

```
Print #1, "Absorptivity", Absorptivity 'absorptivity of container surface
```

```
Print #1, "Kheat", Kheat 'kW heat in from heater
```

```
Print #1, "K1", K1 'kW/m2K ambient<->mass CHTC
```

```
Print #1, "K2", K2 'kW/m2K mass<->air in container CHTC
```

```
Print #1, "Kload", Kload 'kW/m2K air<->load HTC
```

```
Print #1, "A1", A1 'm2 surface area of container for heat transfer
```

```
Print #1, "A2", A2 'm2 surface area of container absorbing sun
```

```
Print #1, "AL", AL 'm2 surface area of load exposed to air
```

```
Print #1, "V", V 'm3 volume of air in container
```

```
Print #1, "Tare", Tare 'kg tare weight of container
```

```
Print #1, "Load Wt", Load 'kg mass of load
```

```
Print #1, "CpAIR", CpAIR 'kJ/kgK 'heat capacity of air
```

```
Print #1, "CpLOAD", CpLOAD 'kJ/kgK 'average heat capacity of load
```

```
Print #1, "CpMASS", CpMASS 'kJ/kgK average heat capacity of container"
```

```
Print #1, "Air Density", AirDensity 'kg/m3 air density
```

```
Print #1, "Tmax", Tmax 'maximum control temp
```

```
Print #1, "Tmin", Tmin 'minimum control temp
```

```
Print #1, "Charge", Charge 'cost of power $
```

```
Close #1
```

```
End Sub
```

```
Private Sub result2()
```

```
Open "c:\HOLD\mafresult.sve" For Append As #1
```

```
Print #1,
```

```
Print #1,
```

```
Print #1, "End of Run Data"
```

```
Print #1,
```

```
Print #1, "N ", N
```

```
Print #1, "t ", Format(t / 3600, "###0.000")
```

```
Print #1, "Tamb ", Format(Tamb, "####0.0")
```

```
Print #1, "Tmass", Format(Tmass, "####0.0")
```

```
Print #1, "Tair", Format(Tair, "####0.0")
```

```
Print #1, "Tload", Format(Tload, "####0.0")
```

```
Print #1, "Psun ", Format(Psun, "####0.0")
```

```
Print #1, "kWhr ", Format(kWhr, "####0.0")
```

```
Print #1, "Cost ", Format(Cost, "###0.00")
```

```
Close #1
```

```
End Sub
```