THERMAL INSULATION PACKAGING FOR COLD-CHAIN DELIVERIES MADE FROM FEATHERS

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ABSTRACT

This paper reports on new thermal insulation packaging materials made from feathers. Clean and disinfected feathers from the poultry industry have been processed into fibres and air laid using commercial pilot-plant facilities to form non-woven feather fibre composite mats. This process can produce materials with different thickness and density by varying the processing conditions and mat composition. The thermal performance of non-woven feather fibre packaging liners has been compared to expanded polystyrene (EPS) to assess the potential for use in temperature-controlled deliveries. Experiments involved monitoring the time-temperature profile of meat substitute materials and coolants stored inside cardboard boxes lined with thermal insulation. The results show that feather fibre composite insulation has comparable thermal performance to EPS and may out-perform EPS under some conditions. It is concluded that low-cost, lightweight and sustainable non-woven feather fibre liners have potential to displace the materials currently used for delivering chilled and frozen foods and other products susceptible to degradation by high temperatures during delivery.

Keywords: feathers; thermal insulation; packaging; cool box; cold-chain

1. Introduction

Life-style changes and time constraints on urban populations in many economically developed countries have led to an increase in home delivery food subscription kits and frozen foods. This requires an effective cold chain to deliver products in good condition (Jackson & Viehoff, 2016). Meal-kit subscriptions combine pre-portioned fresh ingredients, which are conveniently delivered to the doorstep. The global market for these is expected to be between 3 and 5 billion US $ by 2022 (Meal kit industry statistics, facts and history, 2018). The deliveries usually contain fresh dairy products, fish and meat, and this requires temperature-controlled transport and storage systems from the upstream supplier to the consumer (Montanari, 2008).

Cold chain failure can be caused by poor practices of suppliers, faulty design of refrigeration equipment and, in some cases, the position of products and packages in storage containers (Ndraha, Hsiao, Vlajic, Yang, & Lin, 2018). Ineffective cold chains result in food waste, increased costs and adverse environmental impacts. The increasing demand for household delivery meal-kits requires temperature-control during the last few miles of delivery to the customer. Refrigerated vehicles are used, but these have high running costs. To overcome this problem, many companies have started to use conventional non-refrigerated vehicles but with insulated delivery parcels to provide thermal protection. This allows greater flexibility in delivery, as insulated products can remain appropriately cooled even in hot weather conditions, when they are dropped at the customer's house. Thermally insulating packaging is also critical for maintaining the low temperatures required for the delivery of pharmaceutical products and temperature sensitive bio-materials, such as organs for transplant (Singh, Gaikwad, Lee, & Lee, 2018).

Expanded polystyrene (EPS), polyurethane-foam (PU) and expanded polyethylene-foam (PE-Foam) are typically used for deliveries of chilled products. The type and weight of coolants used, the geometry of the delivery container, the weight of the transported goods and their specific heat capacity all influence the thermal efficiency of the packaging. Fresh meat and fish deliveries need to be controlled to legally pre-defined temperature thresholds, which must not be exceeded during any stage of the cold chain. For meat products, legal temperature thresholds range from 4 to 8 °C and the recommended storage temperature during transport of frozen fish is between -1 and +1 °C (New Zealand Food Safety Authority, 1995). Exposure to temperatures above these limits accelerates product deterioration by initiating exponential bacterial growth that jeopardises food safety.

EPS is low cost, has excellent thermal properties, appropriate mechanical strength and is compliant with the requirements for food contact. There have been several investigations that have characterised the thermal performance of EPS in cool box applications. The thermal resistance (R-value) of several box configurations containing additional aluminium linings have been reported (Burgess, 1999). Multilayered packaging products have been tested and a mathematical model for R-value prediction derived (Choi & Burgess, 2007). Further studies have investigated the use of EPS for transporting fish and a mathematical model was developed to predict performance under different delivery conditions (Froese, 1998; Mai et al., 2012; Laguerre et al., 2013). The core-temperature of fish was studied in relation to the position inside EPS containers (Navaranjan, Fletcher, Summers, Parr, & Anderson, 2013). A multi-factor evaluation of packaging functionality in cold chains has been used to identify the parameters that influence packaging performance (Defraeye et al., 2015).

Although EPS is widely used for chilled deliveries of meal-kits, a number of issues are becoming of increasing concern. There is significant negative publicity associated with single use plastics. The high volume of EPS combined with contamination from transporting food makes the cost of recycling thermal packaging EPS high, currently ~$3000 per tonne (Merrington, 2011). It is reported that ~80% of EPS produced in the USA is currently landfilled (Chandra, Kohn, Pawlitz, & Powell, 2016). Consumers are increasingly aware of the end-of-life disposal issues associated with packaging materials, and as a result there is a need to develop more sustainable alternatives (Schumann & Schmid, 2018). New biodegradable, sustainable thermally insulating packaging is required. This should ideally be low cost, resistant to moisture, mechanically strong, visually attractive and easy to manufacture (Schumann & Schmid, 2018).

Feathers may offer an effective alternative. They are a unique material with a combination of properties that gives them the potential to be processed into new, sustainable high-performance products. They are predominantly composed of the protein keratin, but have a complex structure consisting of a hollow shaft (quill) and rachis, with vanes consisting of barbs and barbules, as shown in Figure 1. This provides feathers with high tensile strength and toughness, extreme lightweight, and excellent thermal insulation properties.

Feathers are a problematic waste that is generated in significant quantities by the poultry processing industry. Annual waste feather production in the EU is ~3.1 million tonnes (Karma 2020). Applications for waste chicken feathers are currently limited, particularly compared to other natural fibres such as wool, hemp and sisal. Specific types of down feathers are used for filling duvets, garments and upholstery, but these applications can only ever use a very small percentage of the total feathers generated. At present, much of the waste poultry feathers produced in the UK are processed using an autoclave to form feather-meal, a low-value, low-grade protein feed that is mainly exported to Eastern Europe and Russia (Campos et. al, 2017).

The air laid manufacturing process enables short fibres to be formed into a range of non-woven mat-type products with different density and thickness using minimal additional binder materials. It is commonly used to process synthetic fibres into a range of consumer products including wipes, house insulation and personal hygiene products. This research has used air laid technology to produce novel non-woven mats using feather fibres, a natural material readily available through food waste streams that is fully biodegradable. The performance of the feather fibre mats is compared to the performance of commercially available EPS packaging panels.

2. Experimental work

2.1 Materials

Chicken feathers were obtained from a major UK poultry facility that processes ~1.6 million chickens a week. This produces ~160 tonnes of wet soiled by-product feathers. The as-received feathers were washed, disinfected, dried and shredded (Rapid 2040 granulator, Sweden) to produce fine feather fibres.

The chicken feather fibres were processed into liners using a commercial pilot plant facility to form non-woven feather fibre composite mats. This process was chosen because it produces a low-density product that captures air for insulation and only requires the addition of a simple binder material. In this case, the feather fibres were mixed with a bi-component fibre consisting of polyethylene (PE) with a polypropylene (PP) core (LMF-Bico, Fipatec, 32 mm, 4 dtex). The materials were mixed in a 1:10, LMF-Bico: feather fibre ratio.

A schematic diagram of the pilot scale air laid process used to manufacture non-woven textile samples is shown in Figure 2. The mixed fibres fall under gravity to form a loose bed on a conveyor belt, the speed of which determines the bed thickness. As the fibre bed forms it continuously moves on the conveyor belt into a zone where it is simultaneously heated and pressed between two belts. Non-woven feather fibre mats form when the sheath of the bi-component fibres softens at the applied temperature in the air laid process, bonding the feather fibres into a coherent isotropic product with the microstructure shown in Figure 3. Varying the spacing between the moving belts controls the density and thickness of the feather fibre mats formed.

A typical air laid non-woven feather fibre composite mat produced is shown in Figure 4. This was cut to an appropriate size and sealed inside 20μm thick biodegradable film (Novamont, Mater-Bi), to improve the handling characteristics of the mat. After several manufacturing trials and extensive laboratory testing, the composition of the feather fibre mats was optimised for composition, density and thickness. The optimised feather fibre mat had an average thickness of 28 mm and density of 25 kg/m^3. The thermal performance of this non-woven feather fibre mat has been compared to commercially available 25 mm thick EPS with a density of 22 kg/m^3.

2.2 *Characterisation of non-woven feather fibre mats*

The thermal conductivity and thermal resistance of the feather textile and EPS panels were determined using a heat flow meter (Netzsch, HFM 446 Lambda Heat Flow Meter). This applies a temperature gradient across a test sample and the heat flow is determined. The thermal conductivity (λ) is defined as the rate of steady state heat flow through a unit area of homogeneous material induced by a unit of temperature gradient in a direction perpendicular to the unit area. λ has units of W/mK and is given by:

$$\lambda = q\frac{d}{\Delta T}$$

where d is the sample thickness (m), ΔT is the temperature difference across the sample (K) and q is the heat flow rate (W/m^2). When a state of equilibrium is reached the heat flow is constant and the thermal conductivity can be calculated. The thermal resistance can be determined by dividing the sample thickness by the thermal conductivity. A high thermal resistance R (m^2K/W) is required to reduce the rate of heat flow across the material, as this enables the material to maintain a high temperature differential.

$$R = \frac{\Delta T}{q} = \frac{d}{\lambda}$$

The test samples had an area of 20 x 20 cm and these were tested at four different mean temperatures ranging from -0.5 °C to 10 °C. This temperature range was selected to cover typical operating conditions during food product deliveries. All tests in the heat flow meter used a small compressive load of 1.8 kPa to ensure contact. The test data is provided in section 3.

2.3 *Cool box thermal insulation testing*

Cool box trials used corrugated double-walled cardboard boxes with dimensions of 30 x 30 x 30 cm. This allowed uniform directional heat transfer as the products and coolants were placed at the centre of the box base. Schematic diagrams of the side and plan view of the test boxes are shown in Figure 5. The aim was to record the temperature variation with respect to time at the core of the product, under typical delivery conditions for chilled and frozen meat products. The external conditions were controlled using an environmental chamber (Weiss Technik UK, WIR66-5H) programmed to subject the trial boxes to a typical temperature profile of a summer day in London, UK.

Tylose meat substitute test packs were used (EN23953:2005). These are made from sodium carboxyl methylcellulose and have similar thermo-physical properties to lean beef (James, Lejay, Tortosa, Aizpurua, & James, 2005). The tylose was chilled down to 2 °C for the chilled product testing and -9 °C for frozen meat testing.

The temperature inside the boxes was measured using t-type thermocouples inserted between the tylose packs. Thermocouples were mounted using thermo-conductive gel onto the surface of the tylose packs.

An additional tylose pack was placed onto the thermocouples so that the temperature was measured at the core of the meat substitute product. Two thermocouples were used in each of the tests so that any errors could be identified and the average between the two values taken. Cold chain temperature loggers (RC-5) were also placed on the surface of the meat substitute packs to provide additional time-temperature data. These temperature loggers are used in commercial cold-chain testing and have 0.1 °C resolution and ± 0.5 °C accuracy. Each sensor logged the temperature every 5 minutes. The experiments were repeated several times and the averages temperature values calculated and plotted against time elapsed. The RC-5 data loggers were diagonally located on two corners inside each box. The thermocouples and data loggers were calibrated and tested in the chamber for 24 hours (Eiltech Ltd.) before testing.

Sorba-freeze silica gel sheets (www.sorbafreeze.com) were used as the coolant. These were soaked in water for 48 hours and frozen at -20 °C for 48 hours. Each sheet weighed between 740 and 810g and these were placed on top and bottom of the tylose packs. The insulation materials inside the box formed a complete thermal envelope. The test boxes, one with the non-woven feather fibre composite mats insulation and one with the conventional EPS insulation, together with a control box with no insulation were then placed in the middle of the environmental chamber.

Table 1 summarises the test conditions used to compare the thermal performance of the novel non-woven feather fibre composite mats insulation and EPS packaging insulation. Three tests used chilled tylose and one used frozen tylose. The three chilled tests used 4kg of tylose with varying amounts of coolant. For the frozen test the amount of tylose was reduced to 3kg and the coolant reduced to 0.7kg. The weight of the coolant was reduced because the frozen tylose had sufficient cooling-capacity to retain low temperatures without needing significant additional coolant. Deliveries of frozen products often use very little or no coolant, depending on the ambient temperature.

3.0 Results

Table 2 shows the thermal conductivity and thermal resistance data for non-woven feather fibre composite mats and EPS tested at -5, 0, 5 and 10 °C. The change in test temperature does not significantly change the thermal conductivity of either material. Both materials have similar thermal conductivity. However the EPS has higher thermal resistance because the feather fibre mats compress under the imposed load applied during thermal conductivity testing much more than the EPS boards. The compressive strain (Δd/d) of 49% for the feather fibre textiles is much greater than the compressive strain under the same load (16%) for the EPS boards.

Figures 6 to 9 show the temperature inside the product as a function of time. Figures 6, 7 and 8 show the temperature variation at the core of the tylose samples over 48 hours for the chilled tests and for varying ratio of delivery to coolant weight. Figure 9 shows the temperature variation at the core of the tylose samples over a 72 hour period in the frozen test. In all tests the time taken for the temperature at the core of the product to reach the 4 °C temperature limit is indicated. The RC-5 temperature loggers gave consistent data to the thermocouples, as they displayed on average a breach of the set temperature at between 3 and 4 hours before the thermocouples positioned in the middle of the tylose blocks.

Figure 6 shows the time-temperature data of the tylose for the test run 1, using 1.1 kg sorba-freeze, frozen at -20 °C and 4 kg tylose, chilled at 2 °C. The 4 °C limit inside the core of the tylose blocks was exceeded after 10 hours for EPS while the temperature remained below the limit for 15 hours using the feather fibre mats. The control test without insulation reached 4 °C temperature after just 5 hours. The feather textile therefore outperformed the control samples by a factor of 3 and EPS by a factor of 1.5 under these test conditions.

Figure 7 shows the results for test run 2 using 1.4 kg of sorba-freeze. EPS and the feather textile show very similar performance under these test conditions, with the tylose core temperature only exceeding 4 °C after 25 hours. The control box sample with no insulation reached 4 °C after just 8 hours.

Figure 8 compares the performance of feather mat and EPS using 2.2 kg of coolant. The result shows that under these conditions EPS outperforms the feather fibre mat by ~3 hours. The feather textile breaches the temperature threshold after 28 hours, whereas the EPS box reaches the temperature limit after 31.5 hours. This change in performance is believed to be related to the reduced thermal resistance R caused by the reduction in thickness of the feather fibre mat due to the increased load in this test.

Figure 9 shows the time-temperature data for the test run using frozen tylose. EPS and the feather textile both maintain the tylose below 4 °C for in excess of 40 hours compared to the control value of ~22 hours. Under these test conditions the feather fibre mat maintained the tylose temperature below 4 °C for an additional 4 hours compared to EPS.

4. Discussion

This research has investigated the use of non-woven feather fibre mats as thermal packaging for meal-kit subscriptions. The time taken for the temperature of chilled meat substitutes to reached 4 °C when exposed to typical summer conditions in a Northern European city was recorded. Feathers have desirable properties for thermal packaging. They are lightweight, they are biodegradable, their structure contains large amounts of air in hollow fibres and the structure of non-woven products produces a low thermal conductivity material. The results indicate that feather textiles with a specific density of 25 kg/m^3 and a thickness of 28 mm can outperform commercially available EPS. However, different conditions during use can also adversely influence the insulation properties of feather mats.

The test results show that contact pressure induced by the delivery weight can create local thermal bridges at the base and even on the sides of the boxes. Table 1 shows that test run 3 had the highest pressure on the bottom insulation panel because the overall package weight was highest. As a result, the bottom mat suffered greater compression, resulting in reduced thickness and increased density. As the weight increases the feather fibres become more compacted, resulting in air loss within the mat structure from the chambers of the barbules and barbs. Compression of natural fibre insulating materials usually decreases thermal conductivity and air permeability as density increases (Kosínski et al. 2017). This applies to the feather textile. Compression of the mat results in a decrease in thickness and because the thermal resistance is the ratio of thickness to the thermal conductivity there is an overall reduction in thermal resistance. Overall these effects caused the bottom load-bearing insulating feather fibre mat to have reduced thermal resistance compared to the sides and top. This influences the overall thermal performance of the box if it contains high loads. Synthetic rigid insulation foams are, in comparison, much more resistant to compression loading and therefore this effect is not apparent for the EPS containing boxes. As a result, EPS outperforms the feather fibre mat in test run 3. The rigid properties of EPS are favourable in some applications, but the flexibility of the feather fibre textiles can also be an advantage as it allows temperature sensitive products to be wrapped by insulation to produce more space effective thermal packaging.

Absorption of water onto the feather fibres is also a potential issue because this can replace air pockets in the material leading to an increase in thermal conductivity. Water leaking from melting coolants or condensation could infiltrate the feather textile due to the high permeability, while the performance of EPS is unlikely to be influenced by water in the same way.

There is scope for the specification of the feather mat to be adapted to the operational parameters of the cold chain, such as delivery weight, delivery times and specific heat capacity of the delivery contents. However, the thermal and mechanical performance of the feather textile are linked and understanding the relationship under complex operational conditions is part of on-going research.

An additional practical issue with feather fibre insulation is the potential for increased bacterial growth. Feathers are inherently biodegradable compared to biologically inert materials such as EPS and this may be a factor in some applications. However, the end of life options for feather fibre textiles are improved by the biodegradability of feathers. Fully bio-derived and biodegradable bonding fibres could replace the polypropylene-polyethylene bi-component fibre used in these samples. Packaging that is inherently biodegradable fits with the circular economy concept of products mimicking nature at end of life by biodegrading to add nutrients to the eco-system. Further comparative multi-dimensional characterisation is required to fully understand the performance, feasibility and potential opportunities associated with using feather textiles for thermal packaging.

5. Conclusion

There are new challenges and opportunities associated with cold chain logistics arising from the growth in meal-kit subscriptions and increased consumer awareness concerning the end of life options for packaging materials. A change in packaging material may be the least disruptive and most flexible way to improve cold chain performance under these dynamic conditions. Cool box insulating packaging is critical because meal kit customers see, touch and manage this material.

Non-woven air laid feather fibre textiles have potential to be an effective, sustainable and lightweight natural material for thermally insulating chilled and frozen food. The thermal performance of these materials was assessed and compares favourably with commercially available EPS packaging panels, except when high packaging loads are used. Under these conditions the feather fibre mats reduce in thickness and this decreases the thermal resistance R. In order to reduce the environmental burden of single use packaging, it is important to promote the use of more sustainable materials with improved end-of-life characteristics. Reporting the performance of sustainable alternatives such as feather-fibre packaging allows decision makers in the cold chain industry to assess the performance of alternative materials. However, further work is needed to understand the full life cycle implications of how alternatives can be managed at end of life, to understand their impact on sustainability. This research demonstrates the potential for using feather-based products in cold chain food delivery. Additional markets for thermal insulating feather fibre mats may include use in pharmaceutical cold chains and biotechnology logistics.

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Table 1. Test conditions used to compare the thermal performance of expanded polystyrene (EPS) and feather fibre textile thermal insulation packaging. Control tests were run using boxes contained no thermal insulation. Delivery weight is the amount of meat substitute and coolant used in the test.

	Test run 1 chilled tylose	Test run 2 chilled tylose	Test run 3 chilled tylose	Test run 4 frozen tylose
Total delivery weight (kg)	5.1	5.4	6.6	3.7
Test duration (hours)	48	48	48	72
Coolant weight (kg)	1.1	1.4	2.2	0.7
Tylose mass (kg)	4	4	4	3
Tylose temperature (°C)	2	2	2	-9
Coolant temperature (°C)	-20	-20	-20	-6
Pressure on bottom insulation panel (kPa)	2.5	2.7	3.2	1.8

Table 2. Thermal conductivity and thermal resistance of the non-woven feather fibre composites and EPS panels determined using a heat flow meter (Netzsch, HFM 446 Lambda Heat Flow Meter). The samples are tested under a low compressive load and this reduces the sample thickness, which reduces the thermal resistance, particularly for the feather fibre composite.

Material	Mean Temperature °C	Thickness (mm)	Strain (%)	Thermal Conductivity (λ) W/mK	Thermal Resistance m^2K/W
Non-woven feather fibre composite	-5	14.4	48.6	0.030	0.481
	0	14.1	49.6	0.030	0.469
	10	14.3	48.9	0.032	0.448
	15	14.0	50	0.033	0.424
Expanded polystyrene (EPS)	-5	21.0	16.0	0.033	0.637
	0	21.2	15.2	0.034	0.623
	10	20.9	16.4	0.034	0.614
	15	21.1	15.6	0.035	0.603

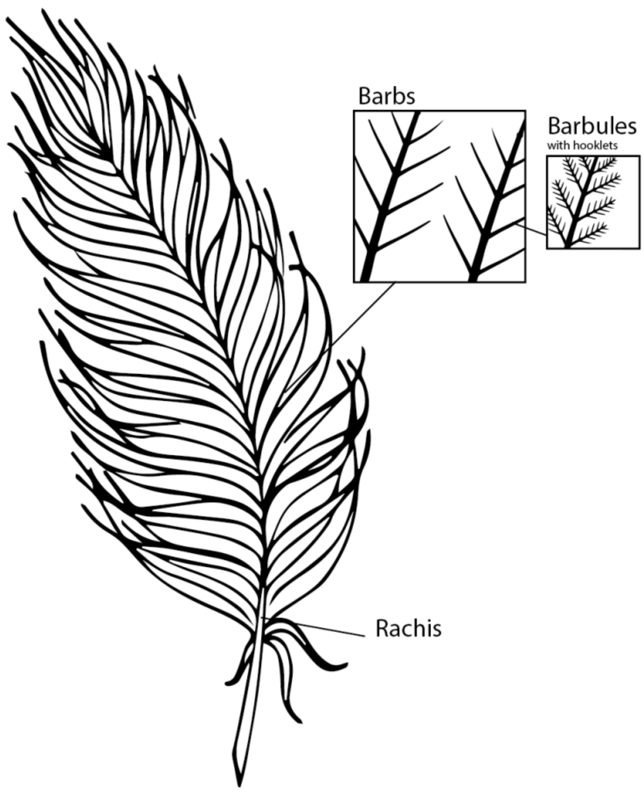


Fig. 1. Feather structure consisting of a hollow shaft (quill) and rachis, with the vane consisting of barbs and barbules.

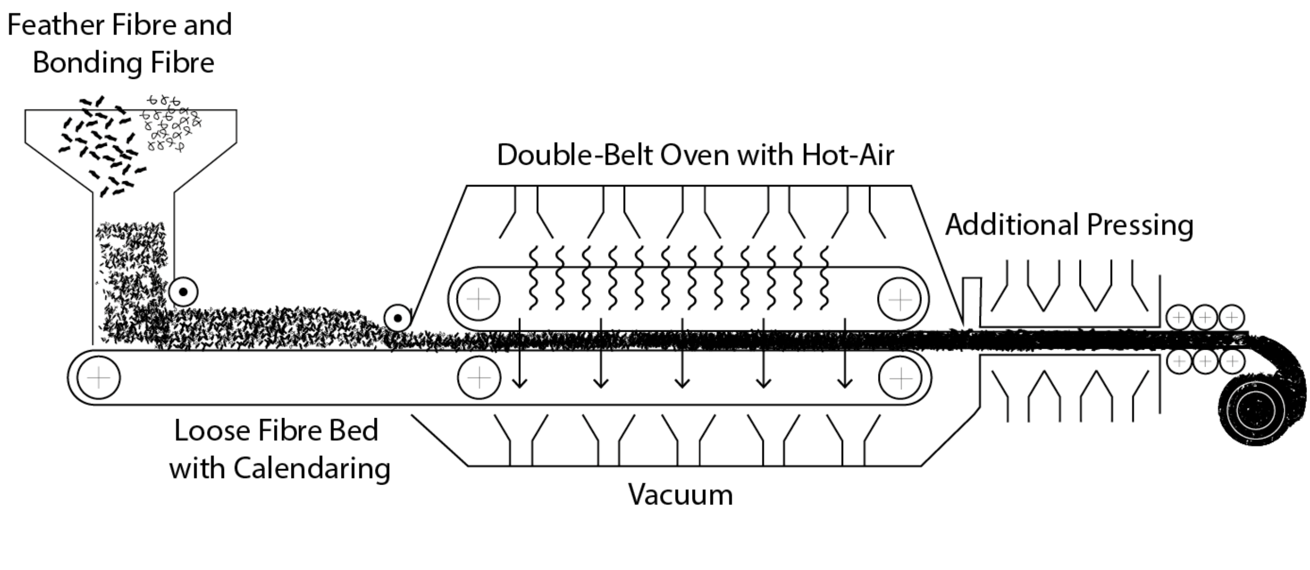


Fig. 2. Schematic diagram showing the air laid process used to form non-woven feather fibre composites.

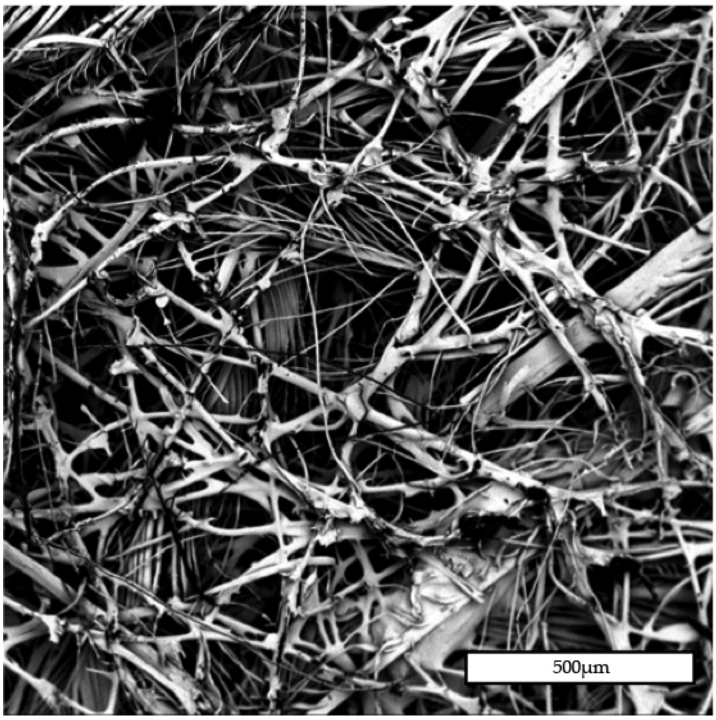
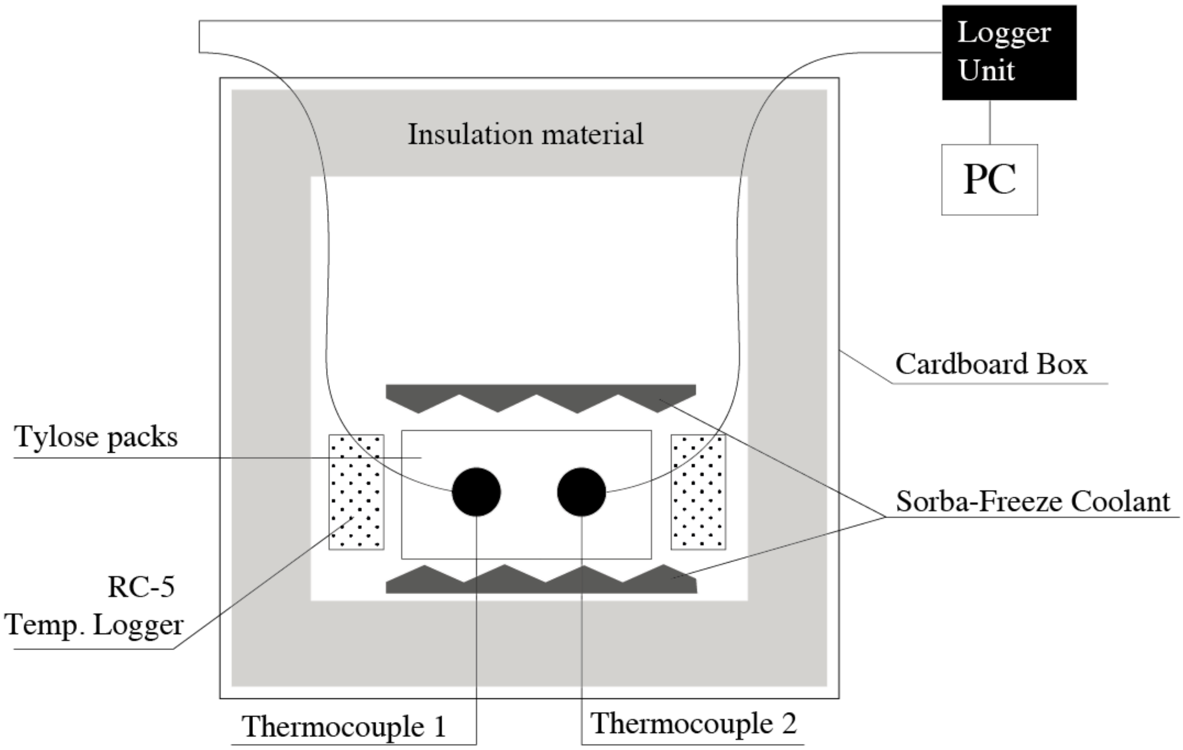


Fig. 3. SEM image showing the typical microstructure of air laid non-woven feather fibre composites.

Fig. 4. Typical air laid non-woven feather fibre composite material.

a)



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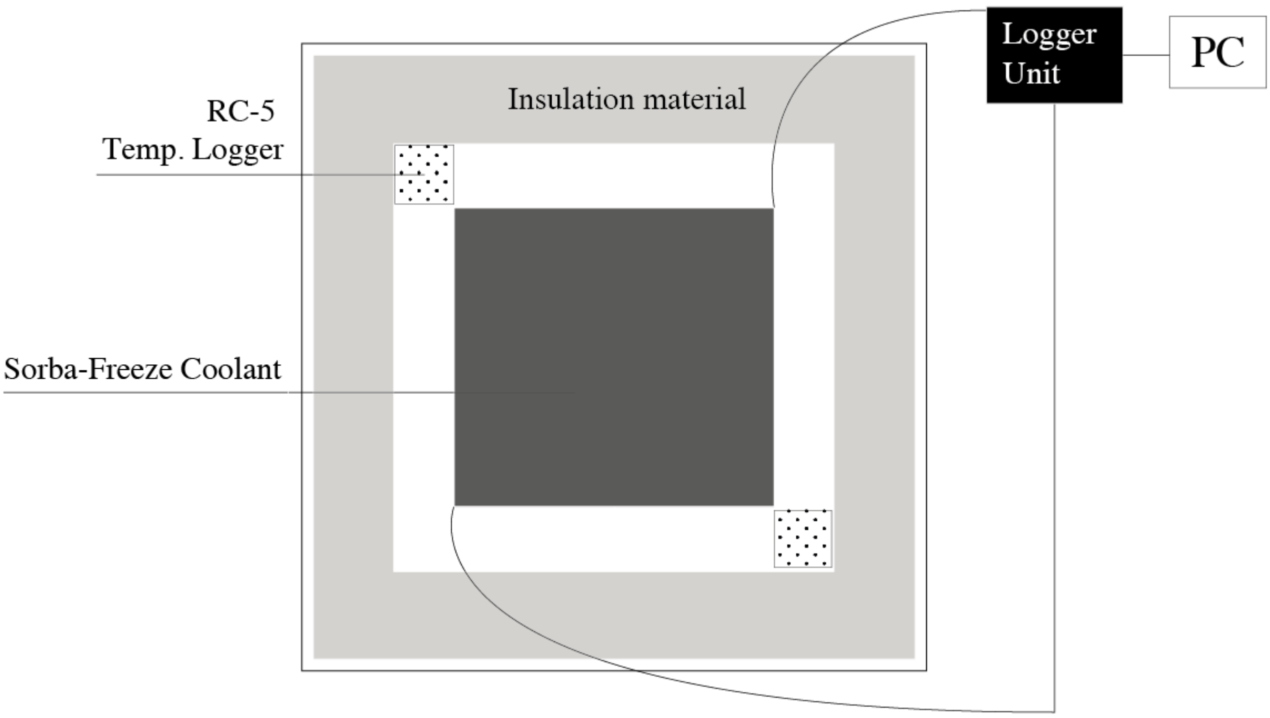

Fig. 5. Test box configuration for simulated delivery run in environmental chamber a) side view and b) plan view

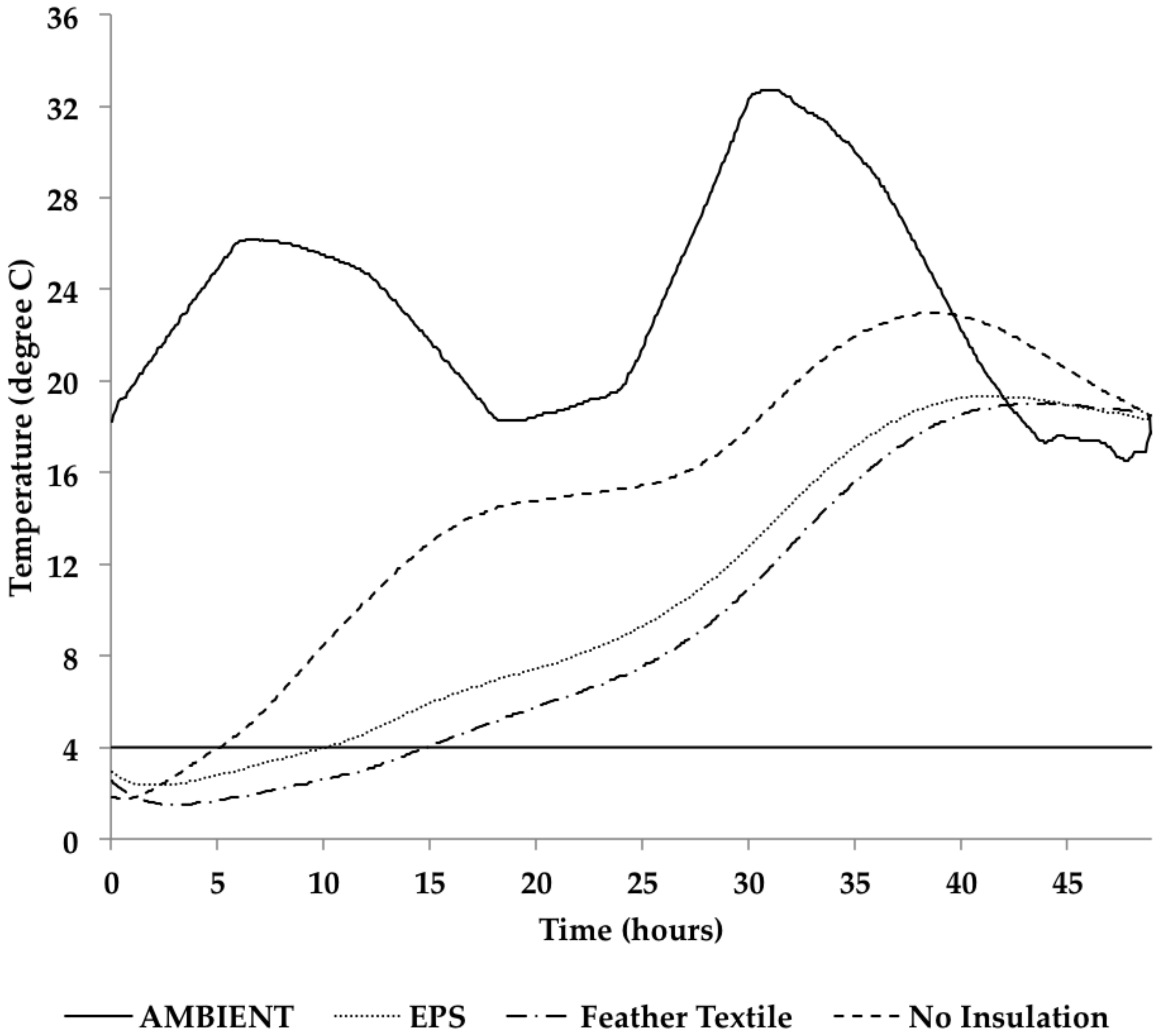

Fig. 6. Simulated delivery Test run 1. The total delivery weight was 5.1kg (1.1kg coolant at -20 °C, 4kg tylose chilled at 2 °C). The test ran for 48 hours in the environmental chamber. The error in the temperature measurement was +/- 0.5 °C.

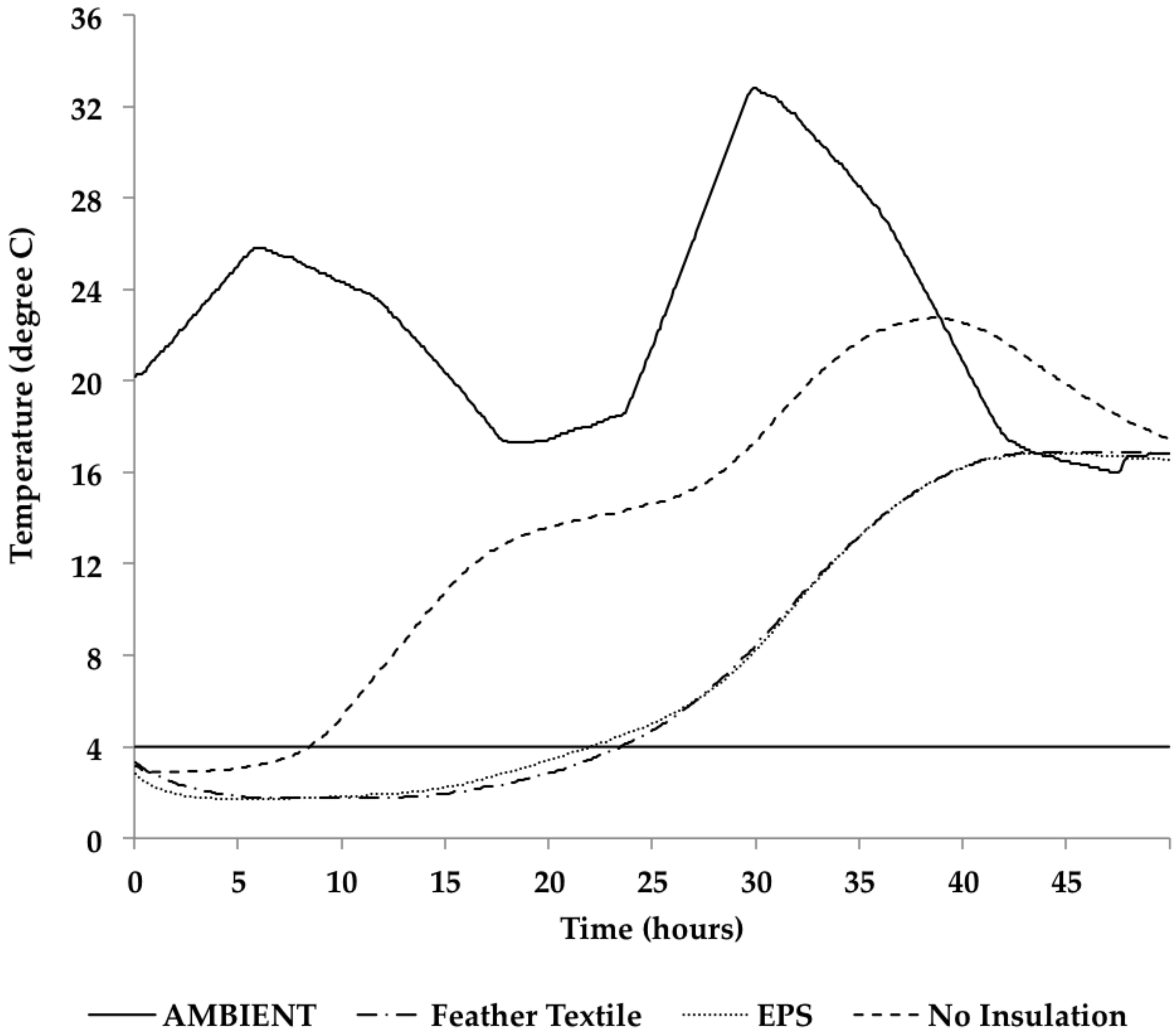

Fig. 7. Simulated delivery Test run 2. The total delivery weight was 5.4kg (1.4kg coolant at -20 °C, 4kg tylose chilled at 2 °C). The test ran for 48 hours in the environmental chamber. The error in the temperature measurement was +/- 0.5 °C.

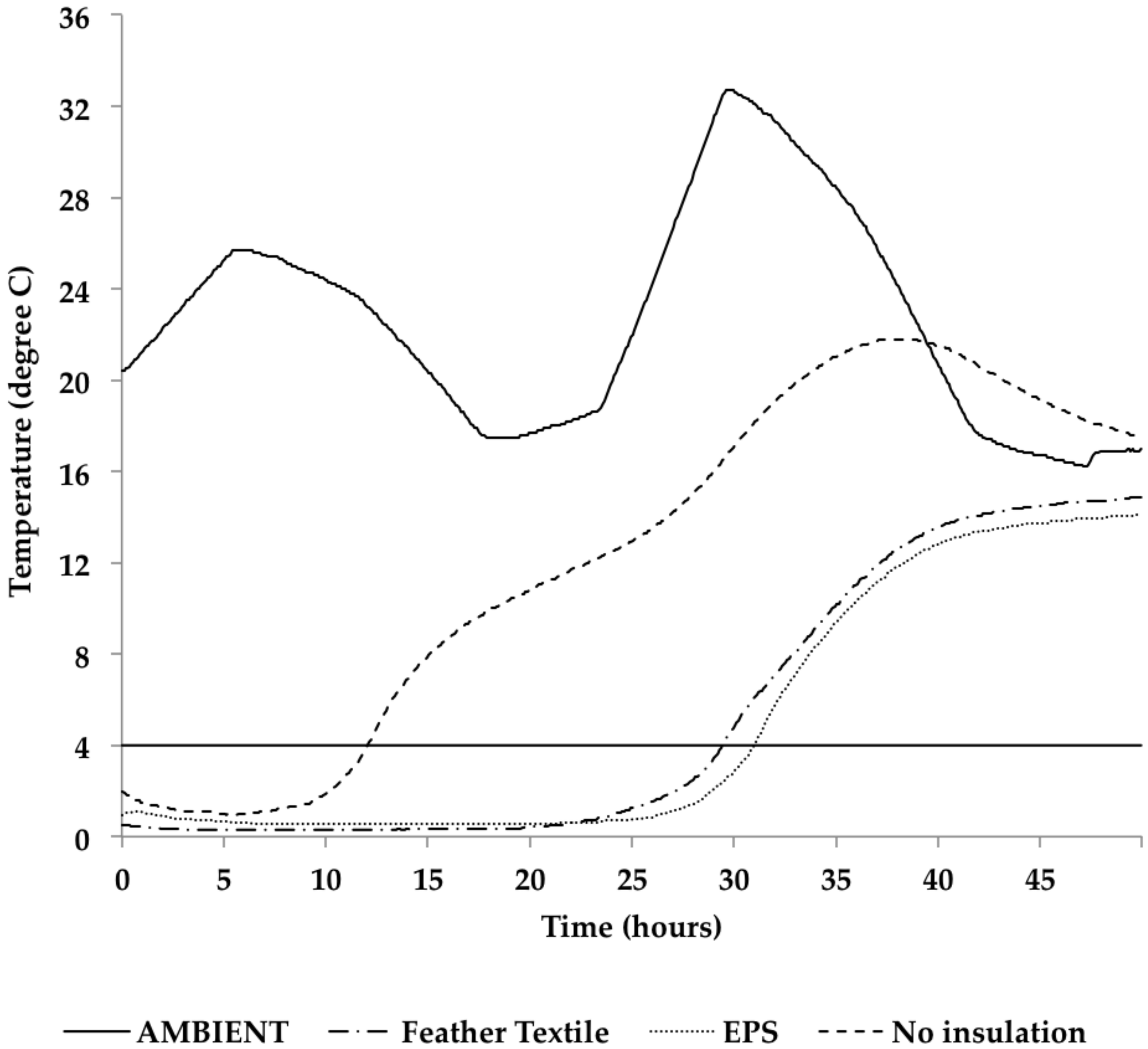

Fig. 8. Simulated delivery Test run 3. The total delivery weight was 6.6kg (2.2kg coolant at -20 °C, 4kg tylose chilled at 2 °C). The test ran for 48 hours in the environmental chamber. The error in the temperature measurement was +/- 0.5 °C.

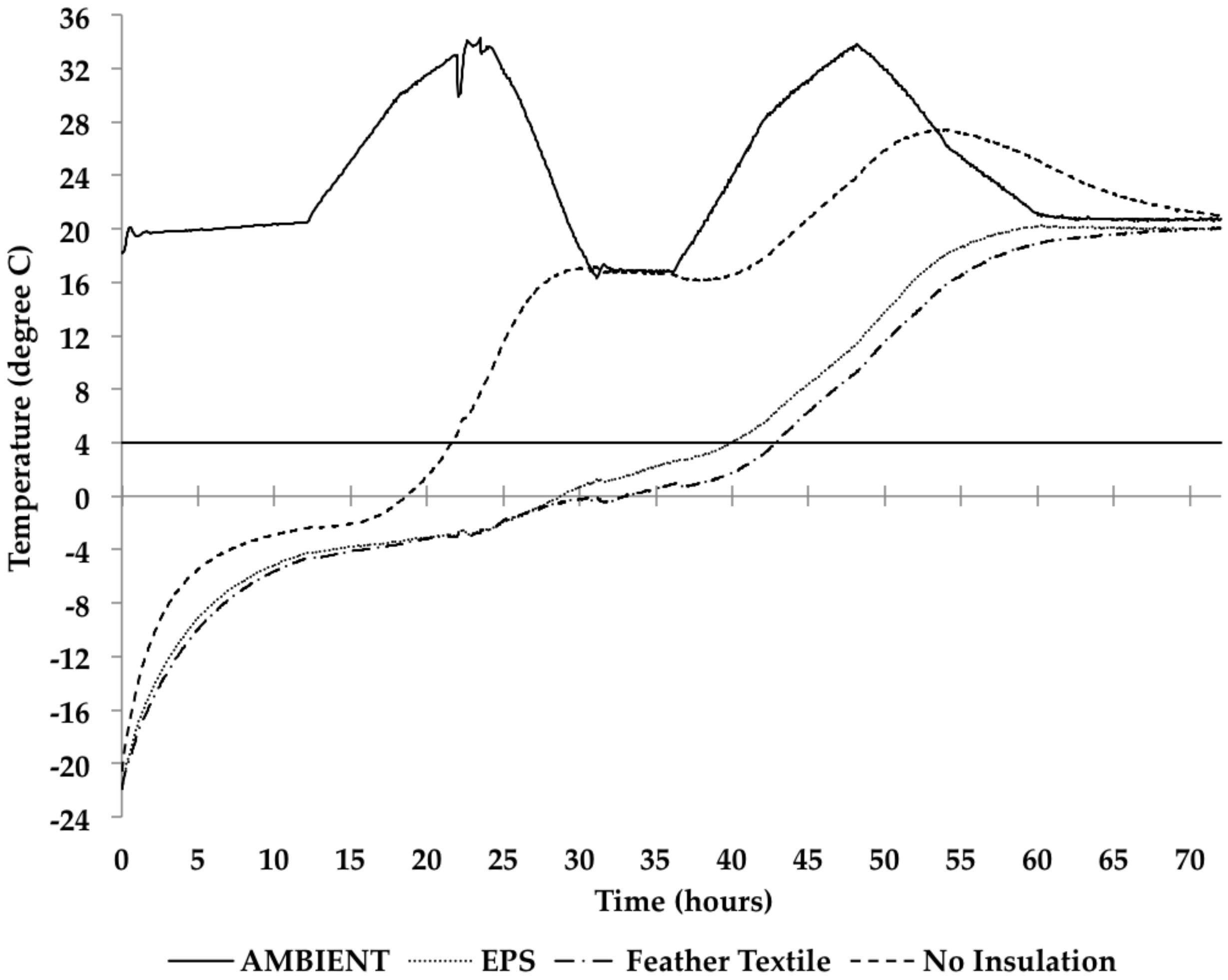

Fig. 9. Simulated delivery Test run 4. The total delivery weight was 3.7kg (0.7kg coolant at -6 °C, 3kg frozen tylose at -9 °C). The test ran for 72 hours in the environmental chamber. The error in the temperature measurement was +/- 0.5 °C.