Energy use in the chilled food sector

Case study – Air blast chilling of solid/liquid food mixtures (pie fillings)

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Summary

A study has been carried out of the pie filling air blast chilling operation at a pie manufacturing plant in the UK. The aim of the case study was to provide data on energy consumption in the air blast chilling of hot solid/liquid food mixtures (specifically pie fillings) post cooking under real use conditions in a manufacturing environment. Detailed data was also required for verification of the LSBU/FRPERC refrigeration model, which required trials under more controlled conditions (not during normal production).

The mean specific energy consumption over the sampled production period was 173.3 kWh/tonne. Specific energy consumption was lowest (143.1 kWh/tonne) on the day of highest production, indicating that once the chiller is switched on and cooled down at the beginning of the day (fixed overhead) efficiency will be improved the longer it can be used to usefully chill pie fillings – i.e. short production runs are less efficient in terms of blast chiller energy consumption.

The mean energy coefficient (EC) of the air blast chilling process was 0.44, which is poor compared to values up to 1.5 for forced air coolers published in 2001.

A comprehensive set of data for validating the LSBU/FRPERC refrigeration model is presented, which were obtained under controlled conditions in the factory. It is anticipated that the model will aid system optimisation of the existing air blast system.

The baseline power consumption required just to keep the air blast chiller cold, without any food product load was approximately 5 kW. Evaporator fans alone consumed up to 30% of the baseline power consumption.

Analysis of the recorded temperature data revealed lower than expected evaporating temperatures for a blast chilling process (saturation temperature approximately -15°C). Increasing the evaporation temperature would offer significant energy savings.

Removing the evaporator fan power (direct and indirect) from the process of cooling hot products would make a significant contribution to increasing overall energy efficiency. Both vacuum cooling and some form of direct contact cooling system are two alternative methods that offer this advantage. However, there appears to be little hard evidence of direct measurements related to the energy efficiency of food cooling (especially solid/liquid food mixtures) that can be used with any certainty to provide guidance to the food industry.

The predicted rate of temperature fall, using the refrigeration model, closely follows the measured data. The maximum difference between the predicted and measured mean centre tray temperature at any time is 5.9°C, the average difference is 2.3°C.

The difference between the predicted (58.9 kWh) and measured (64 kWh) overall energy consumption is 5.1 kWh, an 8 % difference. The base load i.e. the average power used without any food product was predicted to be 5.1 kW and the measured value 5.6 kW, a 9 % difference.

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Introduction

The cooked chilled food sector is a major and growing user of energy for refrigeration in the food industry. After cooking the air blast chilling of hot solid/liquid food mixtures is common to many processes within the food manufacturing industry, not least the ready meal and pie manufacturing sectors. However, there is little, if any detailed data available on the energy consumed by air blast chilling systems under real use conditions in the UK.

In the first part of this study, the primary aim was to provide data on energy used in the air blast chilling of hot solid/liquid food mixtures (more specifically a range of hot pie fillings) post cooking under real use conditions (typical production) in a manufacturing environment. The data gathered provides a benchmark for comparison with other blast chilling operations.

In the second part of this study, the primary aim was to collect detailed data of the same air blast chilling operation to validate the LSBU/FRPERC refrigeration computer model under more controlled conditions.

The site was chosen for the study as it is an example of an air blast chilling operation of solid/liquid food mixtures that require cooling post cooking. FRPERC has also a built up a good relationship with the pie manufacturing company providing the benefit of unrestricted access to plant and manufacturing data.

Process description

The specification of the pie filling blast chilling operation requires that trays of hot pie filling mix are cooled immediately post cooking, having reached a minimum temperature of 75°C, down to a final chilled temperature of below 5°C.

Batches (approximately 60 kg) of a range of different pie fillings are cooked and then transferred into stainless steel trays, covered with cling film and stacked into trolleys. Each trolley accommodates two columns of 14 trays. Each tray is filled with approximately 8 kg of cooked product (mean weight of empty tray = 1.25 kg). Once each trolley is fully loaded with 28 trays of hot product, it is wheeled into the air blast chiller for cooling to below 5°C (taking approximately 6 h). The chiller can accommodate up to three trolleys at a time. Trolleys enter the air blast chilling tunnel through the entrance door at one end (Figure 1) and are incremented through in single file until they are removed through the exit door at the other end. Note evaporator coil and fans (covered by mesh) on left hand side of trolley.

Figure 1. Pie filling air blast chiller entrance door end view

Components of blast chiller

The air blast chiller is a modified Foster unit of a type that is no longer manufactured and its original specification is unknown. A plan view of the chiller and fan/evaporator coil configuration are shown in Figure 2. Refrigeration is provided by a remote compressor (Figure 3), housed in an outside enclosure below the wall-mounted condenser (Figure 4).

Compressor

Prestcold semi-hermetic, R1500/0138 S/D, 380/420VAC, 3-phase, 32 FLA, 40 LRA

Condenser

Dry air cooled condenser unit with a single constant speed fan

Width = 66 cm
Depth = 36 cm
Coil length = 30 rows by 6 deep
Mean face velocity (Air on) = 3.4 m.s^{-1}

Height = 77 cm
Coil pipe = 9.7 mm O/D
Fin spacing = 8 per inch (Aluminium)

Evaporator dimensions

Width = 66 cm
Depth = 30 cm
Coil length = 60 rows by 4 deep
Mean face velocity (Air on) = 2.1 m.s^{-1}

Height = 162.5 cm
Coil pipe = 6.4 mm O/D
Fin spacing = 8 per inch (Aluminium)

Pipe lengths

Evaporator to compressor = 38.5 m x 28.6 mm O/D (Armaflex insulation = 15 mm thick)
Compressor to condenser = 3 m x 28.6
Condenser to receiver = 3 m x 19.1 mm O/D
Receiver to evaporator = 38.5 m x 19.1 mm O/D

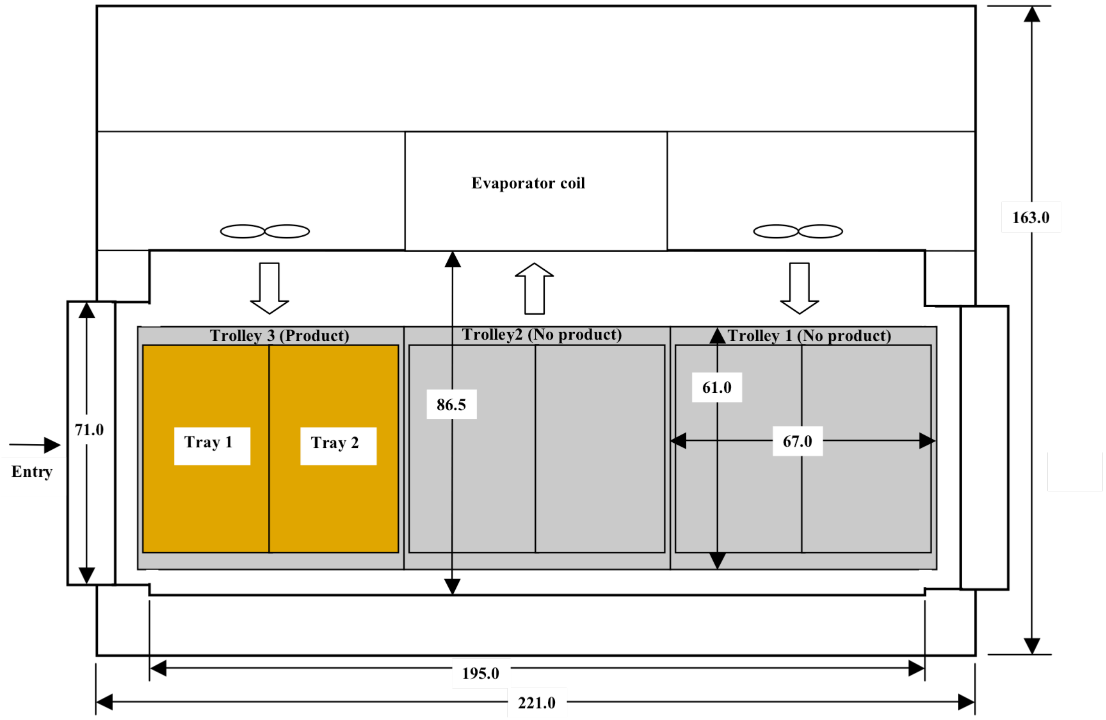

Figure 2. Schematic of blast chiller for pie fillings

Figure 3. Top view of the compressor

Figure 4. Compressor and wall mounted condenser fan unit

Method

Specific energy consumption

To obtain the specific energy consumption of the air blast chilling of solid/liquid food mixtures (pie fillings) the total energy consumption, product throughput and temperature reduction achieved over the corresponding period are required.

The total energy consumption of the air blast chiller was recorded at two locations; the blast chiller junction box (in the factory) and the compressor enclosure (outside factory) using portable energy monitors (Sinergy e-Tracker Mk2, Stockport, UK). The three phase supply was recorded (Figure 5) using a 1 minute integration period providing a log of true RMS voltage and current ±2% of reading, Hz, kW, kVAr and power factor.

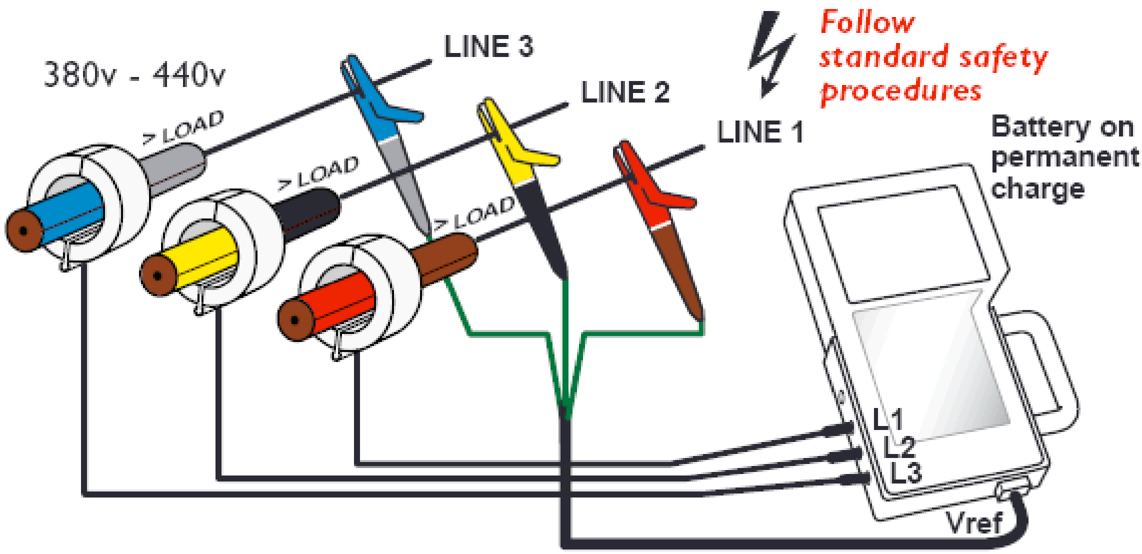

Figure 5. Three phase energy monitor attachment setup using direct voltage measurement and three clamp on current transformers (Source: Sinergy, UK)

In order to calculate the specific energy consumption of the air blast chilling operation, a record of the throughput of product during the energy recording period was maintained. The quantity and time of transferring trolleys of trays of pie filling in and out of the air blast chilling tunnel were noted for the monitored production period.

Efficiency of air blast chilling process

One measure of the efficiency of the blast chilling process is the ratio of the heat removed from the product being cooled to the electrical energy supplied to the entire refrigeration system - also referred to as energy coefficient (EC). Under production conditions it is impractical to directly measure the heat removed from the hot pie filling. Therefore, the heat removed during the cooling process was calculated using a computer model (FoodProp) (James et al., 2009), based on the 'COSTHERM' program (Miles et al., 1983). The model predicts the enthalpy change during cooling, based on calculations using the products chemical composition. Using this method and the assumption that the pie filling is cooled from an average initial temperature of 75°C to an average final temperature of 5°C, the enthalpy change for each sample days production was calculated.

Recording of air blast chiller details

The air blast chiller refrigeration system comprises of a single compressor, vertical wall mounted condenser unit and a Foster designed push through rack tunnel with two vertical banks consisting of three axial electric motor/fan units. The dimensions and specification details of the blast chiller required by the LSBU/FRPERC refrigeration model developers were determined and recorded where possible. As the system was built up from some second hand components (many of which were no longer in production) the manufacturers specifications were not always available.

Data collection for model validation

In an effort to obtain operational data under more controlled conditions suitable for the model validation, the factory offered the sole use of the air blast chiller for the trial. Before starting the trial, all the data loggers were synchronised and set to start recording all the parameters detailed in Table 1 at one minute intervals. Prior to loading the trolleys, the blast chiller was switched on and left to cool down and stabilise to a steady state condition to provide a baseline dataset (no product load), with the doors closed. Due to logistical constraints the trial was limited to chilling one fully loaded trolley. In order to reproduce typical air flow conditions of a fully loaded chiller two trolleys (trolley 1 and trolley 2) containing a full complement of empty trays were also placed into the tunnel (Figure 6). Six trays out of the 28 trays containing pie filling in the test trolley (trolley 3) were fitted with multipoint thermocouple probes (T-type copper-constantan) to determine the slowest cooling point near the geometric centre of each tray. Trays 1 and 2 on the top shelf of the trolley, trays 3 and 4 on the shelf halfway down and trays 5 and 6 on the bottom shelf. All thermocouple and RH sensors were recorded at 1-minute intervals using Comark 2014 loggers. Table 1 provides a list of the parameters measured throughout all the trials.

Figure 6. View of a full trolley instrumented with multi-point thermocouple temperature probes and data loggers in position at entry end of air blast chiller

Table 1. Parameters measured throughout trials

Parameter measured	*Units*
Air-off evaporator coil	°C
Air-on evaporator coil	°C
Evaporator liquid temperature	°C
Evaporator saturation temperature	°C
Evaporator suction temperature	°C
Air relative humidity inside chiller	%RH
Air temperature outside chiller	°C
Air relative humidity outside chiller	%RH
Compressor suction temperature	°C
Compressor discharge temperature	°C
Compressor crankcase temperature	°C
Air-off condenser	°C
Air-on condenser	°C
Condenser refrigerant temperature in	°C
Condensing temperature	°C
Condenser refrigerant temperature out	°C
External air relative humidity	%RH
External air temperature	°C

Results and discussion

The energy consumption and all parameters listed in Table 1 of the air blast chiller was monitored during selected daily and weekly production cycles during a 4 month period from May to August 2008. Results are presented that cover a typical range of production conditions observed, from low to high throughput per day.

Specific energy consumption

The mean specific energy consumption, calculated over a daily production cycle, for air blast cooling hot pie fillings at the factory was 173.3 kWh/tonne and ranged from a minimum of 143.2 kWh/tonne to a maximum of 208.2 kWh/tonne (Table 2).

The mean daily throughput of product was 708 kg/day ranging from a minimum throughput of 540 kg/day to a maximum of 900 kg/day.

Energy consumption of the refrigeration system including the compressor, evaporator fans, condenser fans and defrost heaters ranged from a minimum of 99.1 kWh/day to a maximum of 137.6 kWh/day with a mean of 120.5 kWh/day over the sample production period.

Table 2. Daily throughput and energy data for pie filling air blast chilling operation

Sample No.	*Pie filling throughput (kg/day)*	*Daily energy consumption (kWh/day)*	*Specific energy consumption (kWh/tonne)*
1	780	137.6	176.4
2	780	132.2	169.5
3	660	110.2	167.0
4	900	128.9	143.2
5	540	105.5	195.4
6	720	122.3	169.9
7	600	124.9	208.2
8	540	99.1	183.5
9	840	123.6	147.1
Mean	708	120.5	173.3
SD	130	12.8	20.8

The most efficient production cooling cycle occurred on the day of highest product throughput. The least efficient cooling cycle occurred on a day of low production coinciding with the blast chiller being operated for a prolonged period. This indicates that the scheduling of the batch cooking operation can have a significant knock-on effect on the subsequent efficiency of the blast cooling operation. It should also be obvious that turning on the blast chiller too early before the first complete trolley of hot product is fully assembled will have a detrimental effect on the efficiency of the operation. Equally, failing to promptly remove trolleys once sufficient cooling has been achieved and immediately switching off the chiller will increase the specific energy consumption. Therefore, it is recommended that once the chiller is switched on and cooled down at the beginning of the day (fixed overhead) efficiency will be improved the longer it can be used to usefully chill pie fillings – i.e. short production runs are less efficient in terms of blast chiller energy consumption.

Efficiency of air blast chilling process

The measure of the efficiency of the blast chilling process used was the ratio of the heat removed from the product being cooled to the electrical energy supplied to the entire refrigeration system - also referred to as energy coefficient (EC). Assuming that the pie filling is cooled from an average initial temperature of 75°C to an average final temperature of 5°C, the enthalpy change for each sample days production was calculated and is shown in Table 3.

Table 3. Product throughput, enthalpy change and energy coefficient for sample production days

Sample No.	*Pie filling throughput (kg/day)*	*Enthalpy change from 75 to 5°C (kWh)*	*Enthalpy change/ energy consumption (kWh/kWh)*
1	780	58.8	0.43
2	780	58.8	0.44
3	660	49.7	0.45
4	900	67.8	0.53
5	540	40.7	0.39
6	720	54.3	0.44
7	600	45.2	0.36
8	540	40.7	0.41
9	840	63.3	0.51
Mean	708	53.3	0.44
SD	130	9.8	0.05

The mean ratio of enthalpy change of cooled product to electrical energy supplied (EC) is 0.44. The EC value ranged from a minimum of 0.36 to a maximum value of 0.53. These are comparable to values of 0.40 and 0.52 obtained by authors Thompson and Chen (1988) and Chen (1986). However, they appear to be poor in comparison with EC values of 1.4 to 1.5 for forced air coolers published by one of the same authors more recently

(Thompson, 2001). There is insufficient detail in those publications to determine the precise source of the efficiency improvement by 2001, other than the indication that more efficient fans and fan control strategies should be used as fans or pumps are the highest heat load other than the product load itself. This was also the conclusion of other studies including those concerning primary air blast chilling of meat carcasses. However, unlike discreet solid products, solid/liquid food mixtures should lend themselves to more direct methods of cooling with the potential for energy saving.

Data obtained from validation trial

Figure 7 to Figure 14 provide plots of the blast chiller, refrigeration system, ambient temperatures and relative humidities throughout the trial period from cool down, steady state operation and product cooling.

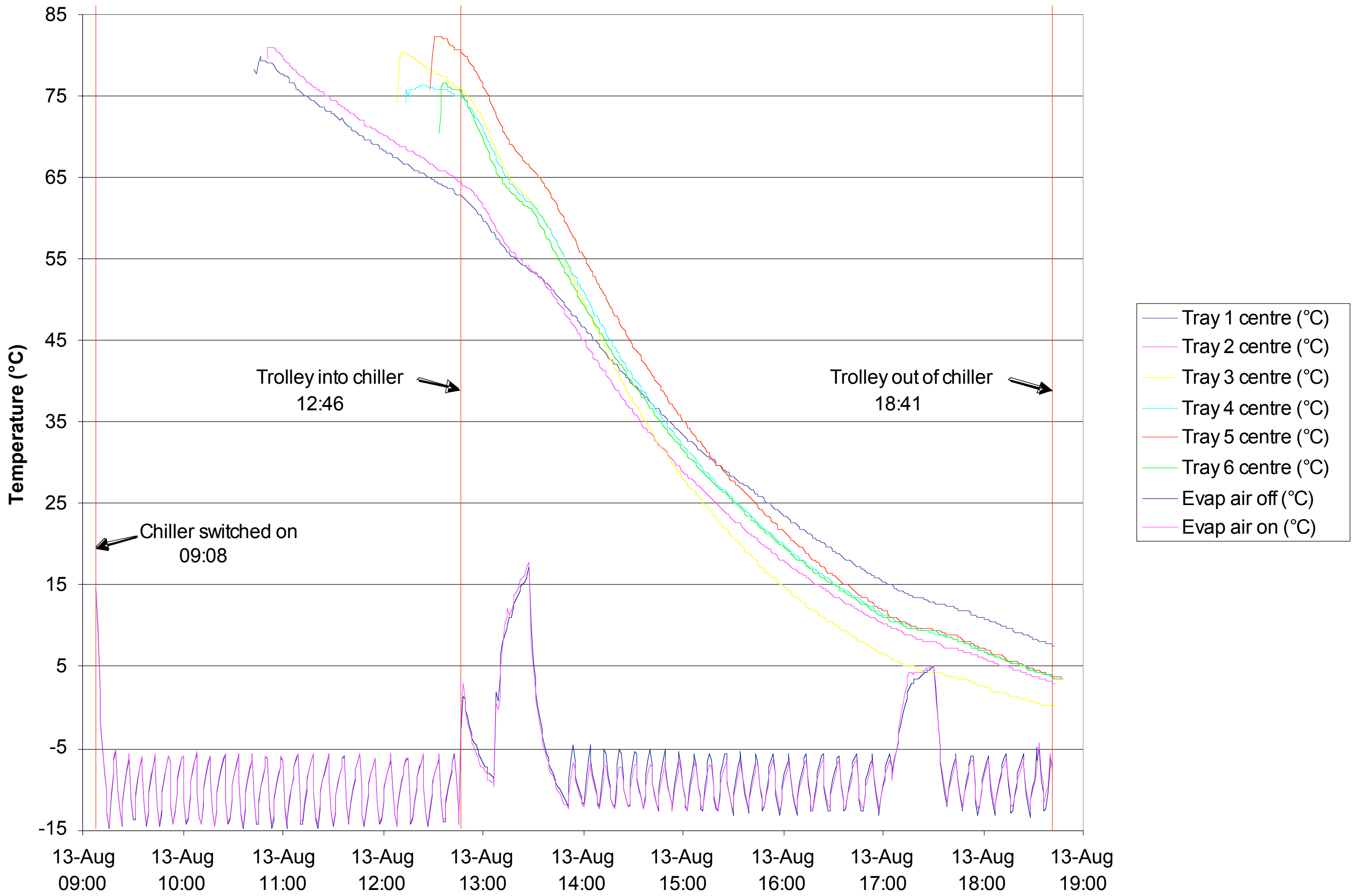

Figure 7. Plot of pie filling temperatures cooled in Foster blast chiller (centre of trays 1 to 6) and chiller temperatures (air on and air off)

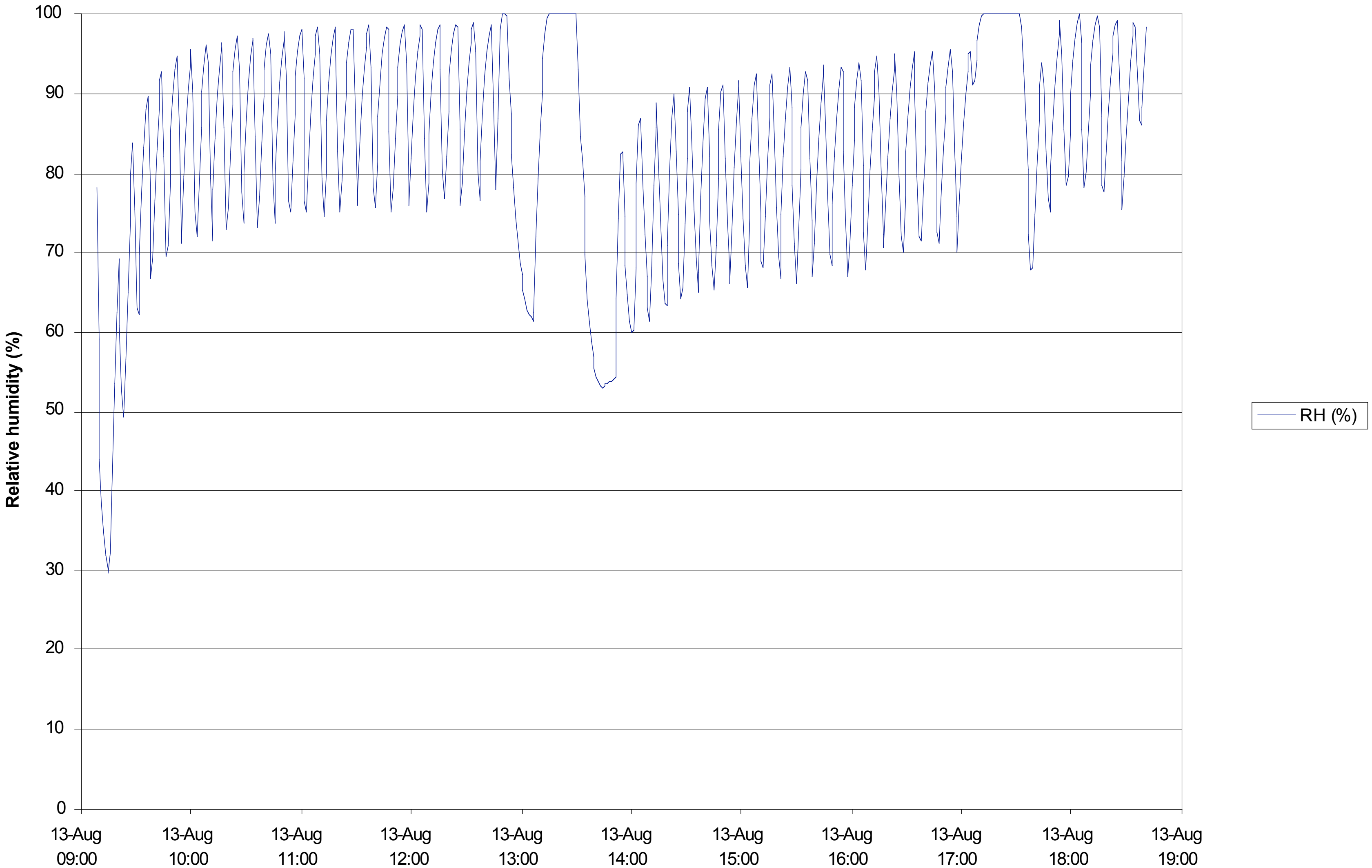

Figure 8. Plot of relative humidity (%) in blast chiller from switch on at 09:08 to switch off at 18:41 on 13-Aug-08

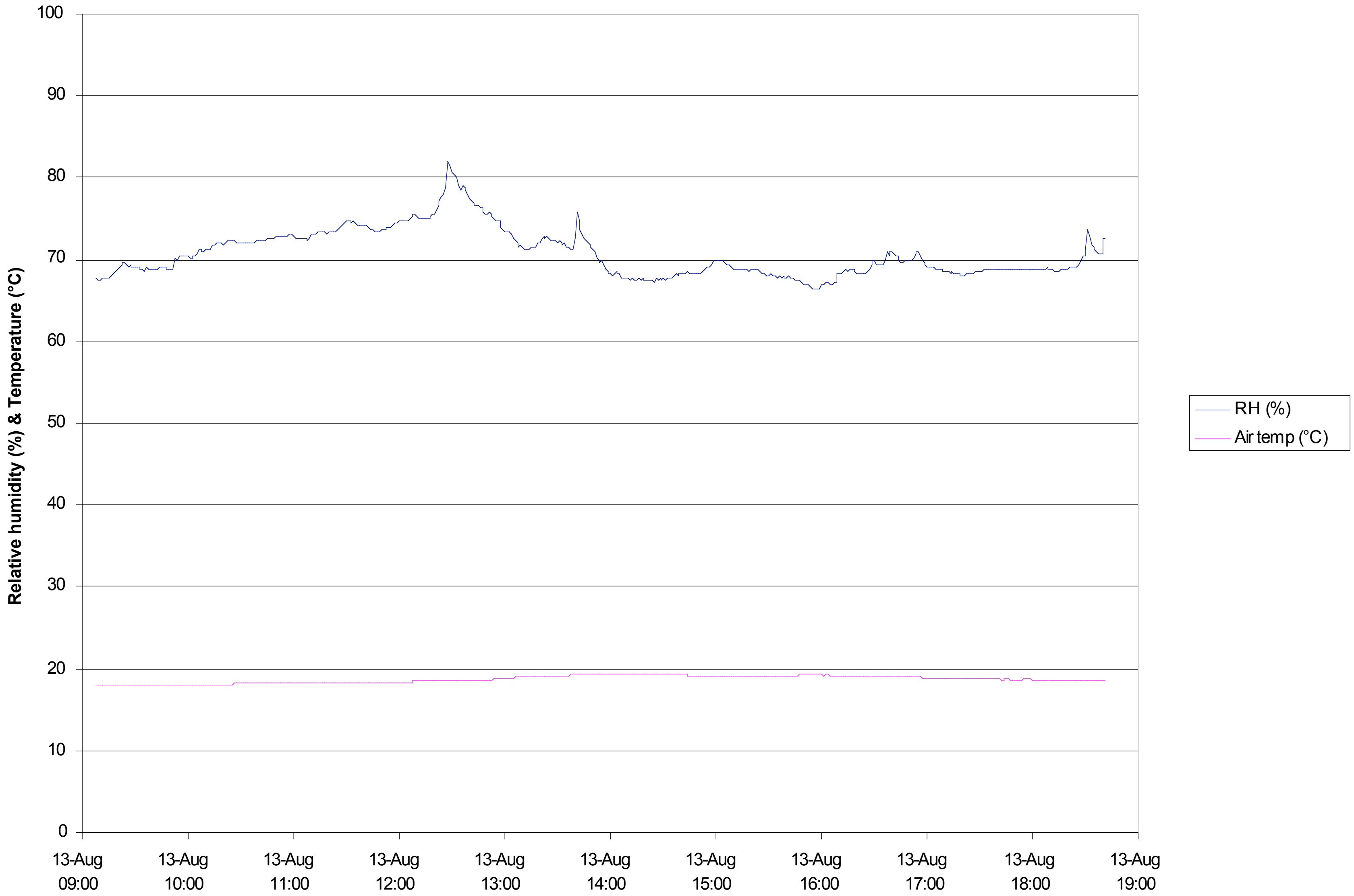

Figure 9. Plot of air temperature (°C) and relative humidity (%) in factory production area outside blast chiller during trial

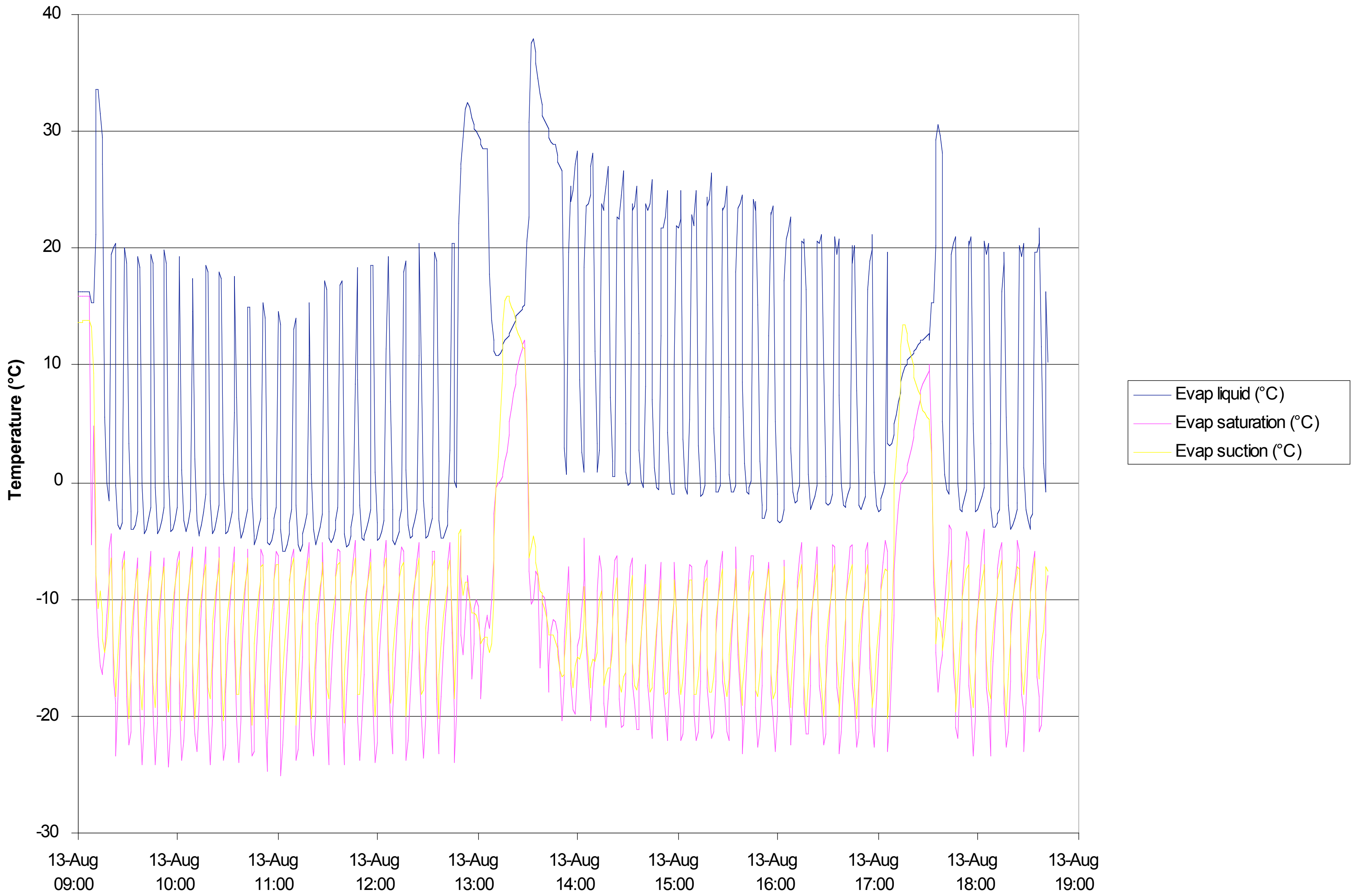

Figure 10. Evaporator liquid, saturation and suction temperatures (°C) during trial

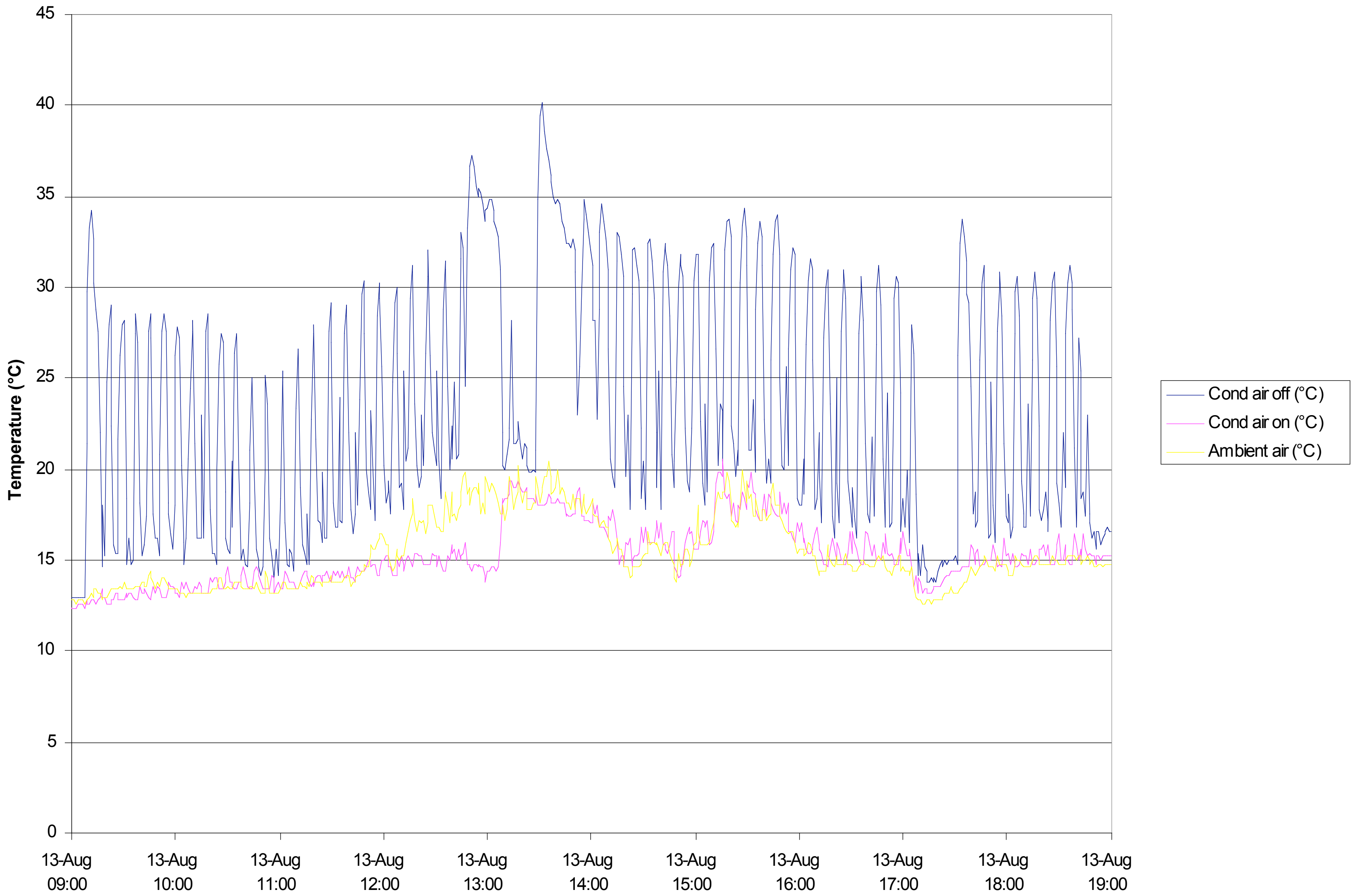

Figure 11. Condenser air on, air off and ambient temperatures during trial

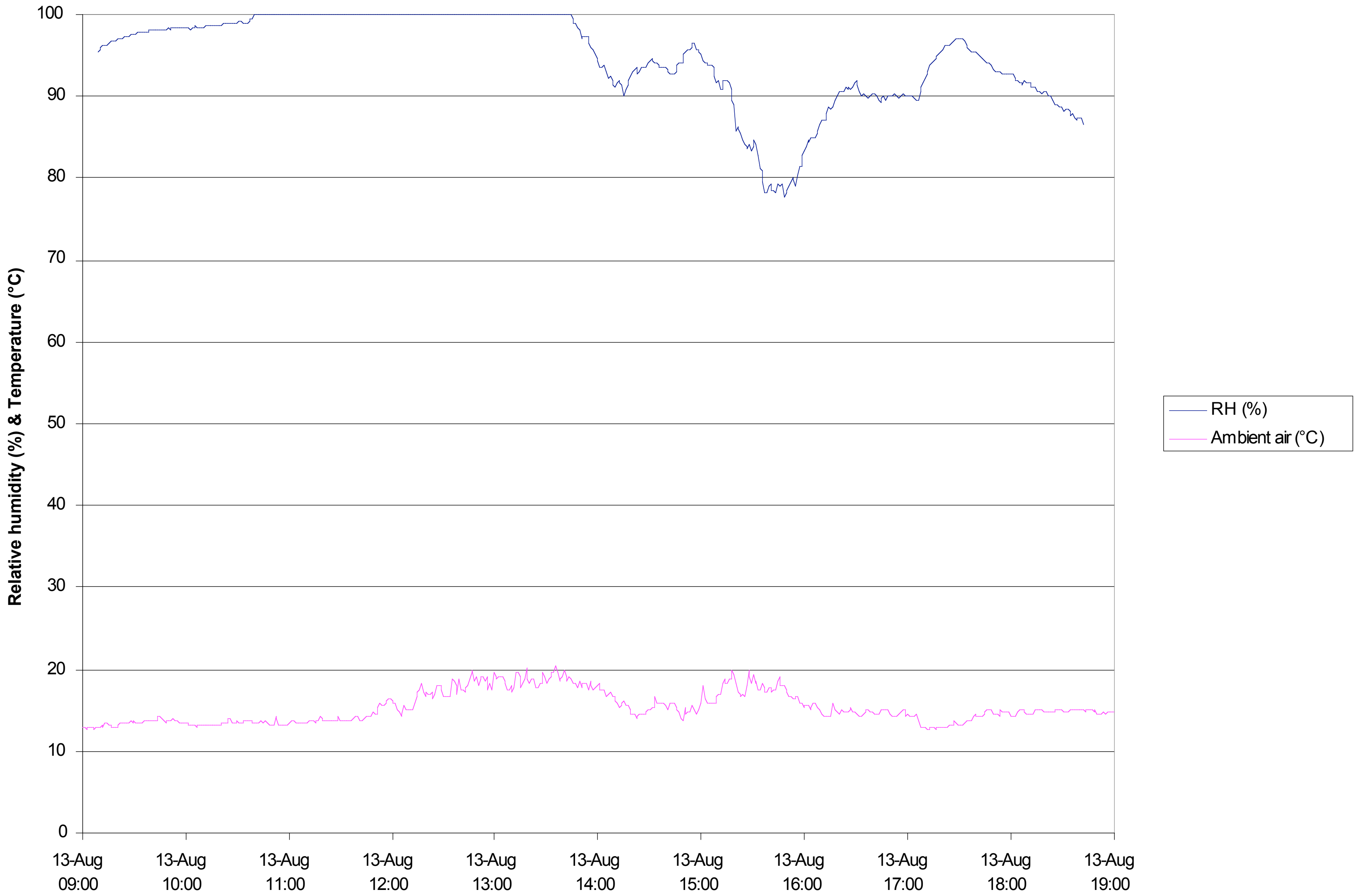

Figure 12. Outside ambient temperature (°C) and relative humidity (%) during trial

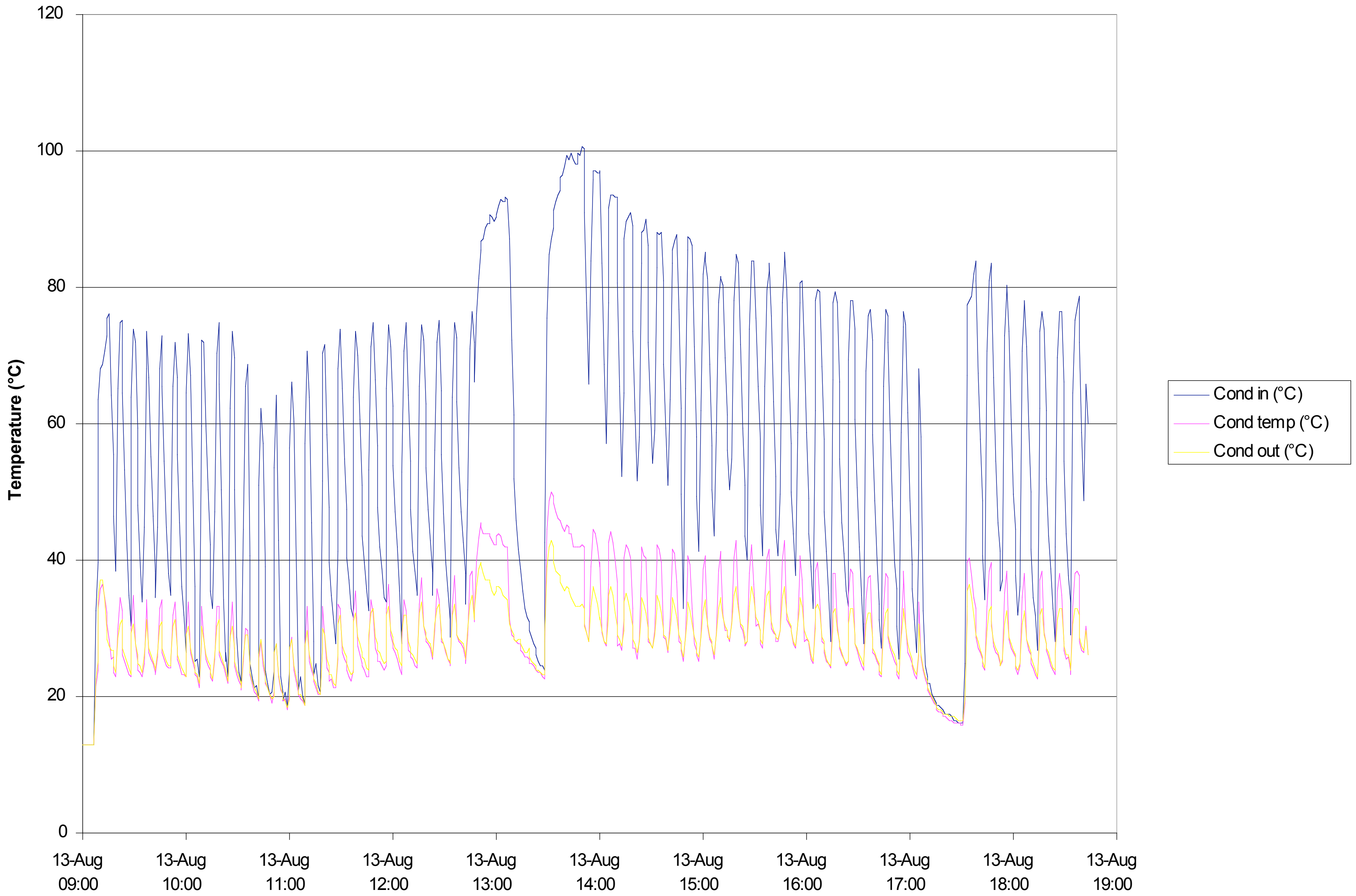

Figure 13. Refrigerant temperature in to condenser, condensing temperature and refrigerant temperature out of condenser during trial

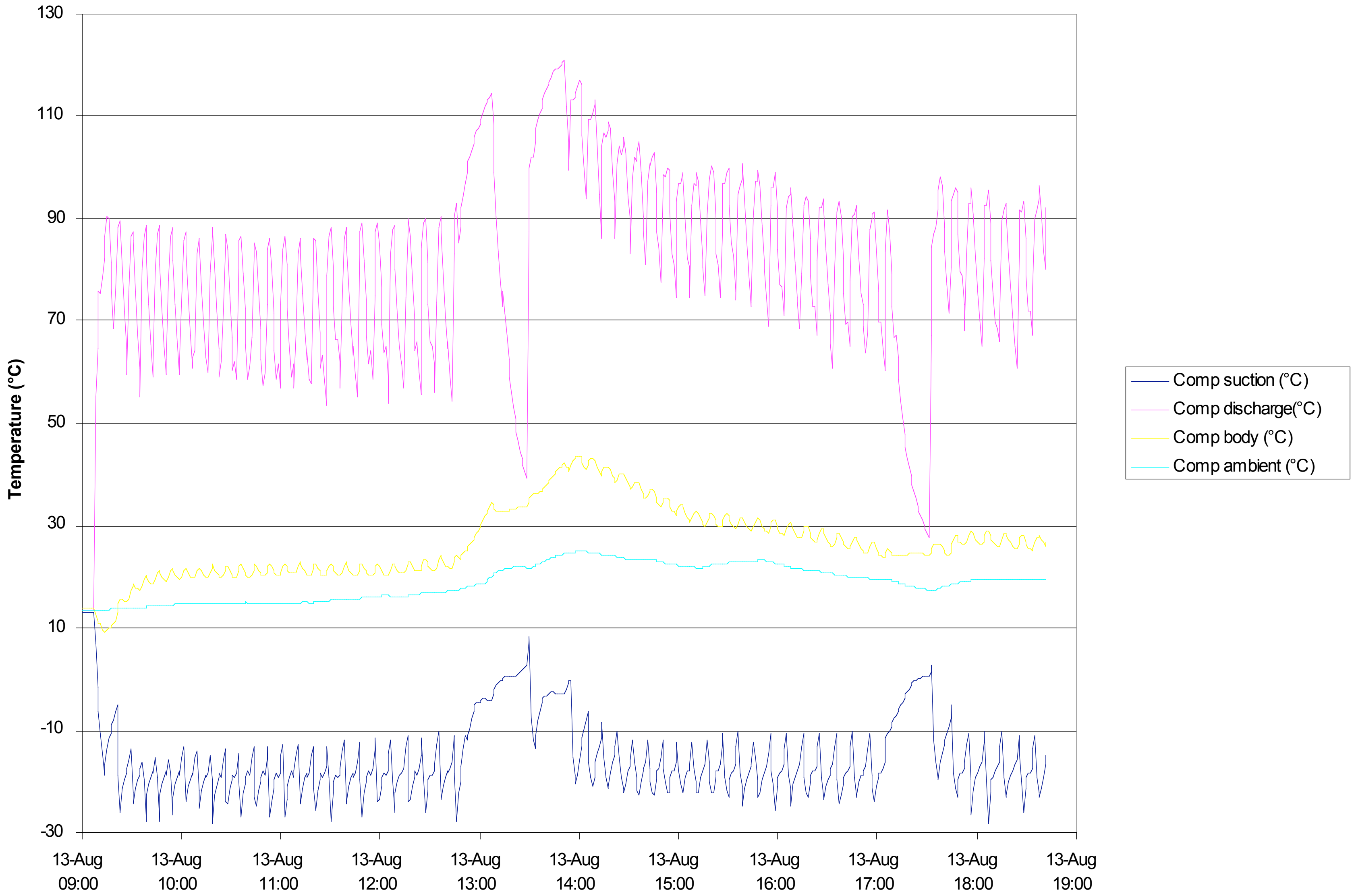

Figure 14. Compressor suction, discharge and compressor body temperatures and air temperature surrounding compressor during trial

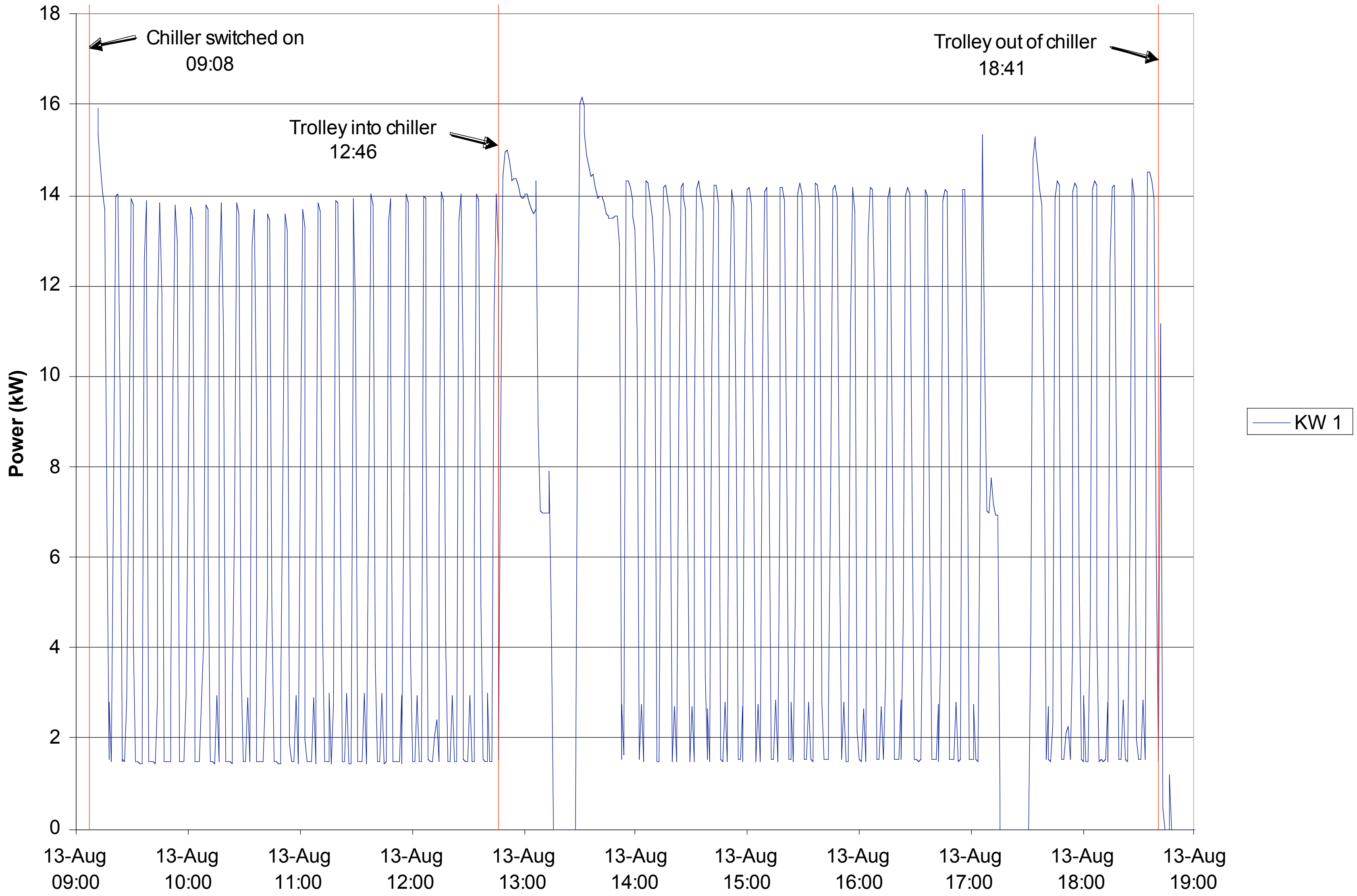

Figure 15. Blast chiller power (kW) during trial

Figure 15 shows the power consumption over the corresponding period, with the time that the blast chiller was switched on (9:08), the time the entry door opened and the trolleys pushed in and the time the exit door opened and the trolleys rolled out overlaid on to it. Note that there were two electric defrost periods, activated by timer at 4 hourly intervals (13:08 and 17:08). During defrost the fans and compressor are de-activated, the 7 kW heating elements activated for 7 minutes followed by a variable length holding period (about 15 minutes in this instance) with no heaters, fans or compressor power.

Baseline power consumption (steady state)

The baseline power consumption required just to keep the air blast chiller cold, without any food product load was approximately 5 kW. The evaporator fans alone were consuming almost 1.5 kW and run continuously at full power (except during defrost), accounting for up to 30% of the baseline power consumption. In addition to this direct electrical power consumption they also contribute to an additional heat load on the refrigeration system.

It is clear that minimising (or eliminating) evaporator fan power is key to increasing energy efficiency.

Evaporating temperature

Analysis of the recorded temperature data reveals that the evaporating temperature appears to be lower than expected for a blast chilling process (saturation temperature approximately -15°C). Increasing the evaporation temperature would offer significant energy savings as long as the product cooling specification could still be maintained. Freezing of the surface and edges of the pie fillings was noticed on removal of trolleys at the end of the cooling period. This indicated that the thickness of the product in the trays was probably excessive for optimum rapid cooling in trays under these conditions. The practicality of using thinner product and alternative (higher) processing temperatures in the blast chiller are worth considering.

Validation

London South Bank University have developed a computer based, dynamic simulation software of a D-X type, air-to-air, vapour compression refrigerator combined with cold-space and ambient weather model, with the working title of ‘VCRmodel’. This is the type of system most commonly found in batch chilling and freezing systems in the food industry and is also found in many chilled and frozen storage rooms.

The interactive software allows data to be entered into the model which calculates the time dependent transient responses of a refrigerator and cold-space to variations in outdoor and indoor air temperatures and humidity. Transmission and infiltration heat loads through the structure and doors, internal loads from lighting, people and food-product are all taken into account. The food-product load is calculated using a food thermal model 'FoodTemp' (James et al., 2009) developed by FRPERC that takes as input the air temperature and flow determined by the VCRmodel. These data are used to determine the amount of heat removed from food in the refrigerated space and the rate of cooling in the food. The amount of heat released by the food is returned as input to the VCRmodel, so that the total energy consumed at each stage of the process can be determined.

The model was then run after inputting all of the component design data and the measured parameters, and the predictions in terms of food temperatures and energy used compared with the measured values.

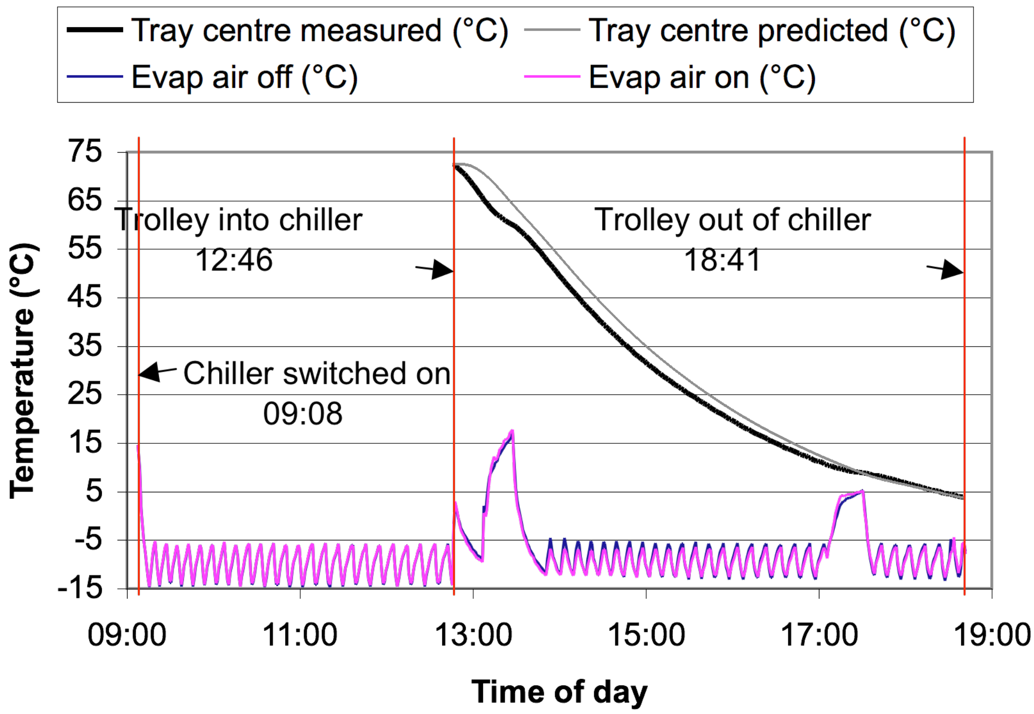

Figure 16. Plot of measured and predicted pie filling temperatures cooled in Foster blast chiller (Average of centre of trays 1 to 6) and chiller temperatures (air on and air off).

The average measured and predicted pie filling temperatures during the chilling operation are shown in Figure 16. It can be seen that the predicted rate of temperature fall closely follows the measured data. The maximum difference between the predicted and measured mean centre tray temperature at any time is 5.9°C, the average difference is 2.3°C. The measured and predicted energy consumptions over 15 minute intervals are shown in Figure 17. The difference between the predicted (58.9 kWh) and measured (64 kWh) overall energy consumption is 5.1 kWh, an 8 % difference. The base load i.e. the average power used without any food product was predicted to be 5.1 kW and the measured value 5.6 kW, a 9 % difference.

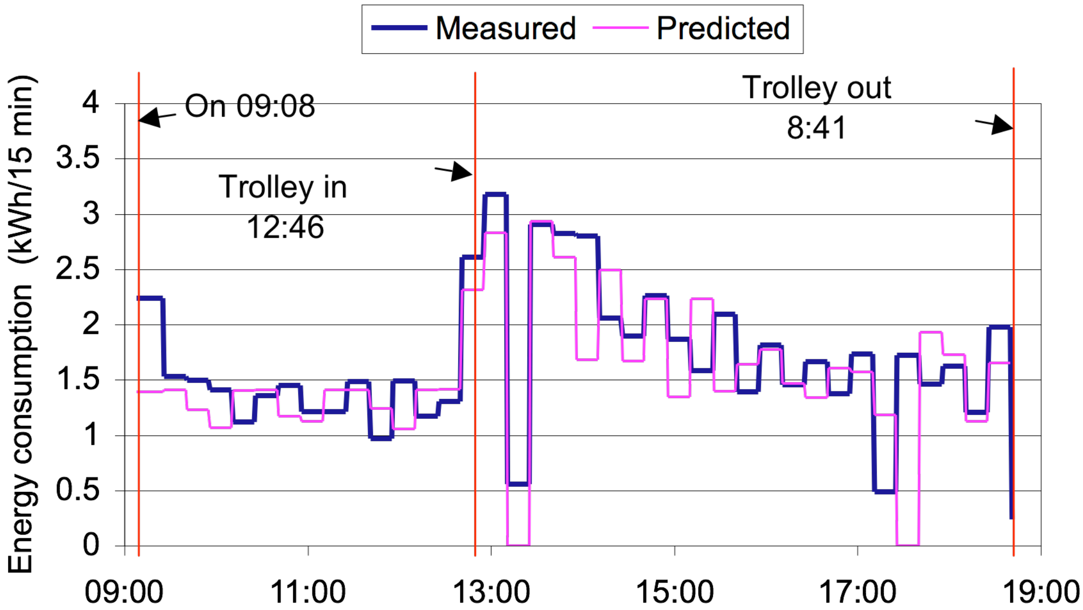

Figure 17. Predicted and measured energy consumption over 15 minute intervals.

It is exciting that the initial validation has produced such small errors in the prediction of food temperatures and energy consumption. During the verification process information gained from the comprehensive monitoring exercise were available to refine the model. These data would not normally be available and a considerable amount of time and effort is now being invested in further verification and development to produce a robust, fully tested model and to identify its limits of application.

Conclusion

This case study provides a benchmark specific energy consumption value for the air blast cooling of hot solid/liquid food mixtures (specifically hot pie fillings) under ‘actual use’ conditions in a small scale UK chilled pie manufacturing plant.

Specific energy consumption

The mean specific energy consumption over the sampled production period was 173.3 kWh/tonne and ranged from a minimum of 143.1 kWh/tonne to a maximum of 208.2 kWh/tonne.

Specific energy consumption was lowest (143.1 kWh/tonne) on the day of highest production, indicating that once the chiller is switched on and cooled down at the beginning of the day (fixed overhead) efficiency will be improved the longer it can be used to usefully chill pie fillings – i.e. short production runs are less efficient in terms of blast chiller energy consumption.

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Validation data

A comprehensive set of data for validating the LSBU/FRPERC refrigeration model was obtained under controlled conditions in the factory. It is planned to use the validated model to aid the optimisation of the existing air blast chilling system.

Baseline power consumption (steady state)

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Evaporating temperature

Analysis of the recorded temperature data revealed lower than expected evaporating temperatures for a blast chilling process (saturation temperature approximately -15°C). Increasing the evaporation temperature would offer significant energy savings as long as the product cooling specification could still be maintained. Product surface freezing highlighted the problem of using too cold air temperatures with too thick a product.

Comparison with model

The predicted rate of temperature fall closely follows the measured data. The maximum difference between the predicted and measured mean centre tray temperature at any time is 5.9°C, the average difference is 2.3°C.

The difference between the predicted (58.9 kWh) and measured (64 kWh) overall energy consumption is 5.1 kWh, an 8 % difference. The base load i.e. the average power used without any food product was predicted to be 5.1 kW and the measured value 5.6 kW, a 9 % difference.

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