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Design and development of apparatus to provide repeatable surface temperature–time treatments on inoculated food samples

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Abstract

The majority of data relating heat treatments to thermal death kinetics has previously been obtained by carrying out in vitro tests on small samples of microorganisms in growth medium or food slurries. However, strong evidence exists that suggests microbial death on heat-treated food surfaces cannot be predicted accurately from such systems. An apparatus was therefore designed to enable microbial death on food surfaces to be quantified.

The apparatus uses hot air to provide a 'dry' heat treatment to raise the surface of a food sample to a given temperature, up to 100 °C, hold and then cool it. The surface temperature was measured using an infra-red (IR) thermometer and the air heater was controlled to give a specified surface temperature history. Steam was also used to provide a 'wet', but less controlled heating cycle.

Keywords: Food poisoning; Surface decontamination; Microbial models; Heating and cooling equipment; Surface temperature measurements

1. Introduction

In this journal, James and Evans (2005) have covered the background behind the 'Bugdeath' project and the requirement for apparatus to produce controlled heating and cooling cycles on the surface of foods. This paper describes the design and construction of the apparatus, which was used by microbiologists in the Bugdeath project to gather data on thermal death kinetics.

2. Specification

To provide data to model microbial death during heating and cooling, the test apparatus had to control the sample's surface temperature in a pre-defined manner. The test apparatus was therefore designed to (1) heat the sample from a set starting temperature, at a set rate, until a set end of heating temperature was reached, (2) hold the sample at the end of heating temperature for a defined period then (3) cool the sample in a controlled manner to a temperature at which no microbial growth can occur. At least 10 sampling points were required within each heating–holding–cooling regime to allow sufficient data for the microbial modelling work, and so the apparatus was designed such that samples could be removed at predefined points in the cycle. Samples that were removed for analysis during the treatment needed to be cooled immediately to prevent any further microbial activity.

The original specification of the apparatus was that it should be able to produce repeatable temperature cycles, with an average error of less than ±2 °C, on food

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surfaces over any temperature profile, encompassed by the 'slow' and 'rapid' cycles. The extremes of these cycles are represented by, for the slow treatment, a surface temperature rise from 5 to 60 °C in 600 s, dwell time at 60 °C of 600 s followed by cooling to 5 °C in 600 s, and for the rapid treatment, surface temperature rise from 5 to 120 °C in 5 s, a 0 s dwell time at 120 °C followed by cooling to 5 °C in 5 s. The apparatus should also be able to produce wet (condensing steam) and dry (evaporating) environments.

There was also the requirement to develop methods for accurately measuring food surface and process temperatures. The specification stated that temperatures should be measured to an accuracy of better than ±1 °C during the slow heating, holding and cooling processes. The temperatures in the 'rapid' heating and cooling process should be measured with an accuracy better than ±2 °C throughout the process.

Prototype apparatus was manufactured and tested at the Food Refrigeration and Process Engineering Research Centre, University of Bristol (FRPERC). Four more of the systems were manufactured and delivered to the project partners. The apparatus needed to be simple to operate, safe and reliable, since microbiologists, food technologists and engineers from three different EU countries would use it. It was designed so that researchers and technicians in the institutions would be able operate the equipment with little training.

The following sections explain in detail the development of each part of the system.

3. Development of system

After initial discussions with the project partners, a number of changes were made to the initial specifications. The maximum temperature of the rapid cycle was set at 100 °C since it was not expected that bacteria would survive above this temperature. The minimum time for the rapid heating cycle was lengthened to allow single-phase heaters to be used. The minimum time for the cooling was increased since rapid cooling to temperatures where further microbial activity would be inhibited was more easily carried out by placing the sample into a stomacher bag immediately after it came out of the system (McGovern, McCann, & Sheridan, 2005) containing cold diluent.

At an early stage of development, studies were carried out to ensure that the high air velocities achieved over the surface of the sample would not detach an excessive number of microorganisms from the sample surface. Loss of microorganisms could reduce the final counts (and so cause a non-thermal reduction in the bacterial numbers) and lead to safety problems, as many of the bacteria used were pathogenic or genetically modified. The outlet air was also filtered to ensure that no bacteria left the treatment chamber in the air stream. This filter is described in detail in Section 4.4.

The studies showed that a very small number of bacteria were removed from the sample, but that the filter prevented them from leaving the process chamber.

The apparatus was designed to repeatably produce controlled surface temperature–time treatments on samples during rapid heating and cooling cycles and accurate measurement of surface temperatures during the process. Samples had to be easy to produce and inoculate and have a known surface area exposed to the heating and cooling environment. The heating and cooling system had to produce rapid but uniform treatment of the whole sample surface. The main options considered were: (1) whether to have separate dry, wet and cooling chambers or carry out the whole cycle in one chamber; (2) use a contact or non-contact method of measuring and hence controlling the surface temperature of the food sample; and (3) deliver the heating and cooling environment across the surface of the sample or directly impinge it onto the surface. These different options were investigated using a combination of direct experimentation, mathematical heat transfer modelling and computational fluid dynamics (CFD).

The design that was chosen from these options was to automatically introduce the inoculated sample into a single chamber and carry out all of the process cycles in that chamber. Having multiple chambers would have increased the size of the apparatus and its complexity. It would have required surface temperature measurement in each chamber, movement of the sample between chambers and filtration of each chamber.

A non-contact method of measuring surface temperature (IR thermometer) that would not interact with the microorganisms on the surface was chosen because it was felt that any contact may affect the bacterial numbers on the surface and measuring true, rapidly changing surface temperatures by any other method was extremely difficult (Hoke, Housska, Kyyhos, Landfeld, & Pipekb, 2003; James, Goksoy, Corry, & James, 2000).

It was not practical to introduce all of the treatment streams (heating, cooling and steam) directly from above and measure the surface temperature using an IR thermometer due to lack of space. This was especially the case with one of the systems since the project partner using it needed to view the product surface from above with a light sensitive camera. The treatment streams were, therefore, delivered across (parallel to) the surface of the sample.

A control system with a graphical user interface (GUI) was employed to ensure that the apparatus was safe, repeatable and easy to use.

A borosilicate glass Petri dish (part no. 402/0060/01, Merck Ltd., Dorset, UK) with an external diameter of 55 mm and height of 19 mm was chosen as the sample holder. Food samples could be readily inserted into

the dish with a known surface area exposed at the top. The size provided a good compromise between a small sample, whose surface temperature would be easier to change and a large sample that would allow easier inoculation and recovery of microorganisms for analysis.

The sample dish was held (friction fit) on an aluminium support connected to a motor that rotated the sample at a frequency of 0.8 Hz. The purpose of the rotation was to create a more even heating and cooling at the surface. Without rotation the leading edge of the sample would be subjected to higher heating and cooling rates. To keep the heating as one dimensional as possible (from the top surface only), a nickel ring was placed around the sample, with the cavity inside the ring providing the insulation. A schematic of the complete sample and its holder is shown in Fig. 1.

The sample dish was automatically raised into the treatment chamber immediately after insertion. The chamber was of dimensions $210 \times 210 \times 226$ mm high and was constructed from an angle iron frame and aluminium side panels. The top of the chamber housed a plate of clear safety glass ($160 \times 160 \times 6$ mm thick, Pilkington plc, St. Helens, UK) with a 12 mm diameter hole in the centre for mounting the IR thermometer. Nozzles to deliver hot air, cold air and steam to the surface of the sample protruded through and were held in place by the side panels.

The main apparatus was designed to be small enough to pass through a standard laboratory doorway and had overall dimensions of $0.7 \times 1.0 \times 2.0$ m. A separate refrigeration system, of external dimensions $0.8 \times 0.8 \times 1.2$ m, was used to provide cold air for cooling the sample surface. A desktop computer was used to control and monitor system performance. The only services required were: (1) a 230 V, 32 A electrical supply for the main unit, (2) a 230 V, 13 A supply for the refrigeration system and (3) a low flow rate of dry, clean, compressed air at a pressure of 4.0 bar. The air supply could come from either a compressed air line or a compressed air cylinder with regulator.

The glass panel in the top was provided to allow one partner to use a light sensitive camera to view bioluminescent bacteria on the surface of the sample (Lewis, Baldwin, O'Neill, Alloush, & Nelson, 2005). The apparatus used by this partner was also modified in a number of ways, including the provision of a matt black internal finish to reduce reflections that would interfere with the camera's ability to measure light emissions from the bacteria on the product surface.

Each apparatus was CE marked and provided to the partners with full operating instructions.

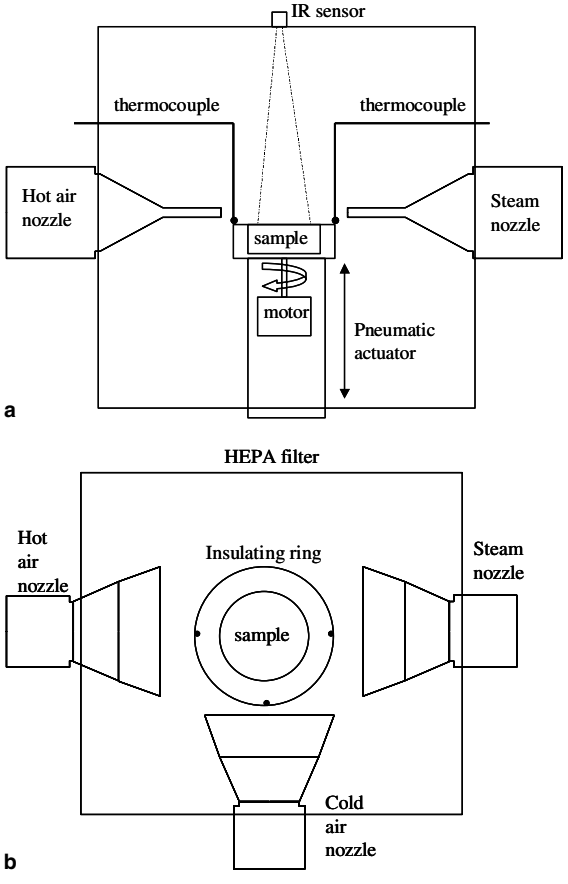

Fig. 1. (a) Vertical section of chamber and (b) plan view of chamber.

4. Process and control

Fig. 2 shows a schematic of the chamber and treatment processes. There were three different treatment processes, hot air, cold air and steam.

4.1. Hot air 'dry' treatment

Air was taken from ambient and blown through a high-pressure regenerative blower into a 3.3 kW heater (Robust and Heater 3000, respectively, Leister Process Technologies, Sarnen, Switzerland) via a 25 mm diameter PVC hose. The hot air from the heater was exhausted through a flat nozzle (70×4 mm). The nozzle was positioned 30 mm away from the edge of the sample and 5 mm above the surface of the sample. The hot air was blown over the sample parallel to its surface and the temperature of the air controlled to give the correct temperature at the product surface at any point in the experiments (explained in more detail in Section 4.6).

4.2. Steam 'wet' treatment

A domestic wallpaper stripper (SS76-CE, Earlex Ltd., Surrey, UK), with a 2 kW element was used to generate steam at atmospheric pressure. The outlet of the steam generator was connected to a three-way L-port 1/4 in. brass ball valve with pneumatic actuation (Everyvalve

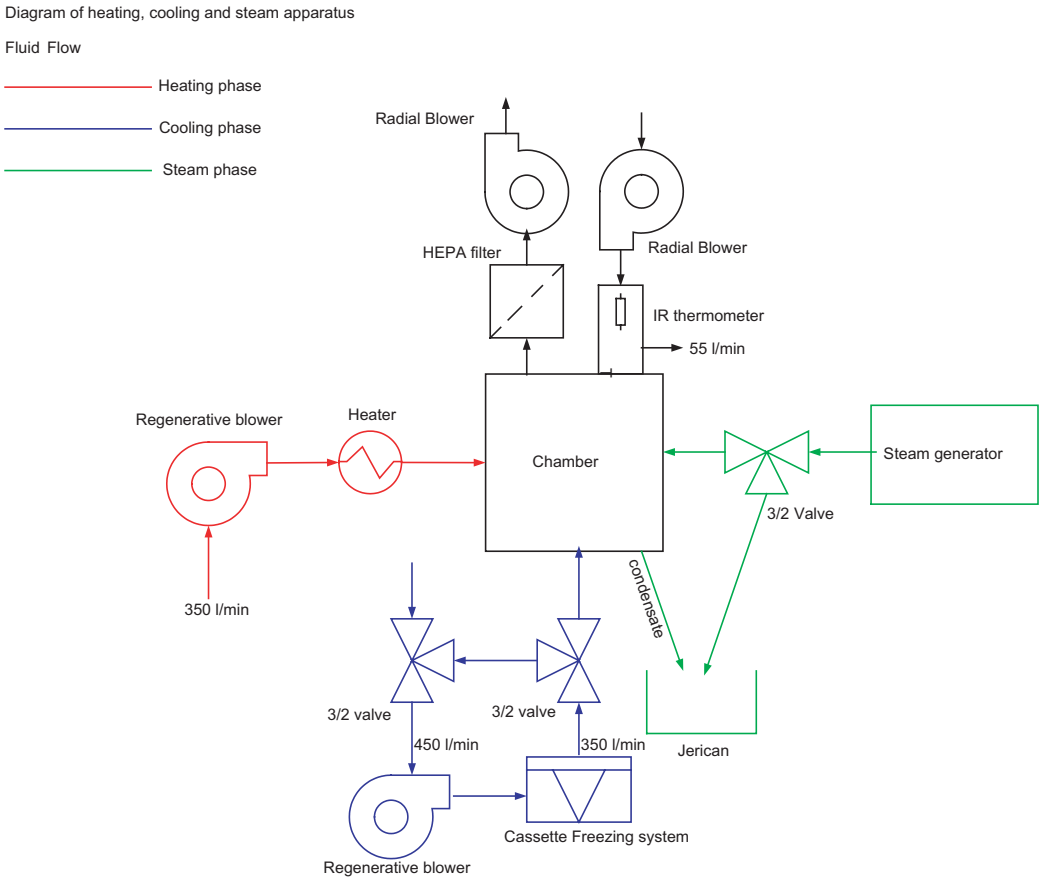

Fig. 2. Schematic of the apparatus showing the treatment equipment.

Ltd., Hertfordshire, UK) by a 10 mm diameter polyurethane tube. The valve outlets were connected to: (1) a nozzle, positioned 30 mm from the edge and 5 mm above the surface of the sample and (2) a PVC tube acting as a vent for the steam when the steaming process was off. The steam exited the nozzle under the slight pressure from the steam generator and was exhausted over the sample parallel to its surface.

The chamber and filter were heated using the hot air system (using air at up to 100 °C for a period of 2 min) prior and subsequent to the steam being introduced to avoid condensation in the filter, which could block it and reduce its effectiveness or lead to damage as a result of the high back pressure caused by the blockage. The steam treatment was restricted to 60 s to keep the build up of moisture in the filter to an insignificant level.

4.3. Cold air treatment

Cold air was accumulated by re-circulating it through the evaporator of a refrigeration cassette mounted on top of a chest freezer. The cassette was designed to cool air in an upright freezer (560FP, Sadia Refrigeration, Sheffield, UK). The chest freezer (AFG 522, Whirlpool UK Ltd., Surrey, UK) was used as an insulated box (refrigeration was not used) to accumulate the cold air for the cooling system. The cassette was positioned above the chest freezer and the top of the chest freezer cut so that air from the chest freezer re-circulated through the evaporator of the cassette, and was cooled. An aluminium frame was used to seal the connection between chest freezer and cassette.

Fig. 2 shows the refrigeration circuit. Two holes were cut in the top of the cassette, one just before the evaporator and one just after, and ports were connected to these holes. A 25 mm inside diameter PVC hose was attached to each of the two ports; these holes were wrapped with 13 mm thick rubber pipe insulation (Armaflex, Armstrong Insulation products, Lancs., UK). Cold air from the refrigeration unit was drawn into the treatment chamber using a high-pressure regenerative blower (Robust, Leister Process Technologies, Sarnen, Switzerland). Two three-port air operated valves (VGA342-10A, SMC UK Ltd., Buckinghamshire, UK) allowed air to either recycle through the pipes and blower (this was to allow pre-cooling of the system) or be discharged through a nozzle positioned 15 mm in front of the sample and 5 mm above the surface of the sample.

The cooling treatment could only be selected in combination with (and after) a hot air treatment. Cooling was not possible after a wet heat treatment due, to increased condensation problems. The programme produced a 15 min pre-cooling phase before the treatment was started, in order to pre-cool as much of the cooling system and pipework as possible, so that the cooling air would be as cold as possible when the cooling phase was initiated.

4.4. Filtration

A filtration system was attached to the chamber to contain any bacteria that may have been blown off the samples during the treatments. Air from the chamber was drawn through a high efficiency particulate air (HEPA) filter (SSA/H13/2FL/2Gr, Absolair Filtration Ltd.) of dimensions $210 \times 223 \times 150$ mm. This was attached to a vertical side of the chamber.

A fan, of the type used in domestic gas fired central heating systems (WFFB1701-035:AMP8778, Sifan Systems Ltd., Oxon, UK), was attached to the other side of the filter to draw air from the chamber through the filter. The extraction fan drew a larger volume of air out of the chamber than any of the treatments put into the chamber, maintaining a slight negative pressure in the chamber. This meant that the chamber did not need to be air tight, to avoid bacteria leaving the chamber in the air stream, as any leakage air would be into the chamber and would pass through the filter before leaving the chamber.

4.5. Sample entry

When the start button on the GUI was pressed, a warning buzzer sounded for a period of 5 s before a pneumatic actuator (C95KB32-350, SMC Ltd.) raised the sample into the chamber through a hole in the bottom plate of the chamber. When the sample was fully inserted into the chamber, a microswitch was triggered, which sent a signal to the control program to start the treatment.

4.6. Temperature control

For 'dry' heating the user entered values for 'temperature at start of heating', 'temperature at end of heating', 'heating duration' and 'holding duration' into the GUI (Fig. 3). The control and logging programme converted this into a heating and holding ramp as shown in Fig. 4. This ramp defined the desired surface temperature history of the sample. The control and logging programme compared the actual surface temperature (measured by an IR thermometer) with the desired surface temperature at 0.5 s intervals. If the measured temperature was below the desired temperature the heater was switched on, if it was below, the heater was switched off. The

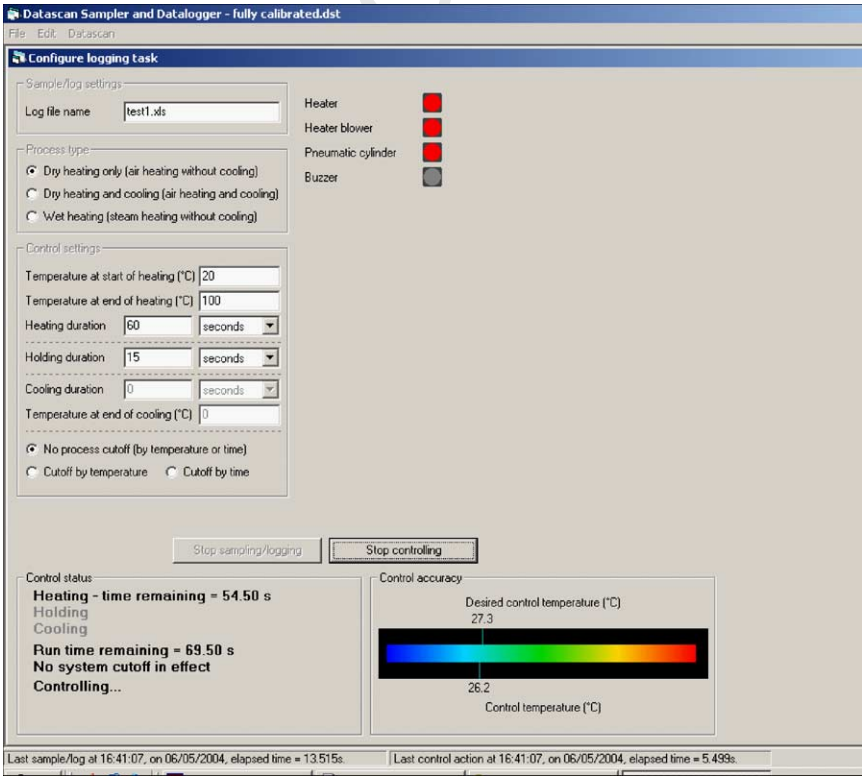

Fig. 3. Screenshot of GUI during a treatment.

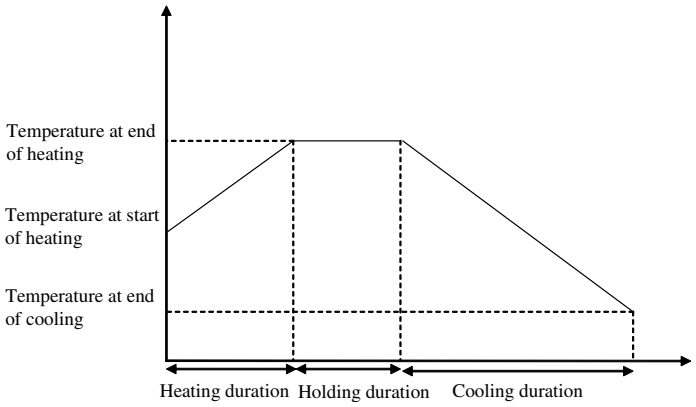

Fig. 4. Desired temperature history given input parameters.

blower remained on during the entirety of the heating and holding periods.

If cooling was specified in the GUI, the user was also required to enter values for 'temperature at end of cooling' and 'cooling duration'. This defined a cooling ramp in the same way as the heating profile. The temperature was controlled at the same interval as the heating process but in the opposite manner (a high temperature turned the cooling on and a low temperature turned it off). If cooling was required, the two pneumatic valves were actuated, allowing cold air to blow into the chamber. If not required, the valves were de-activated, preventing cold air from entering the chamber, but allowing the air to re-circulate around the cooling circuit, keeping as much of it as cold as possible. Unlike during the heating and holding periods, air only passed over the sample when cooling was required.

4.7. Safety

An emergency stop button and safety relay were used in the apparatus to allow shutdown and avoidance of all potential hazards. The relay cut power to the heater, blower and released pneumatic pressure to the system removing energy from the actuator. To avoid the apparatus being reset automatically (e.g. after power fluctuations) and potentially becoming hazardous, the emergency stop circuit included a manual start button which had to be pressed after either a cut in power or the emergency stop button being pressed.

A thermal fuse was connected to the wall of the chamber, which would cut the power to the heater if the chamber wall rose above 125 °C. This would be reset automatically when the temperature of the fuse had dropped below 125 °C.

4.8. Measurement of process conditions

A 16-channel analogue input measurement processor (Datascan 7320, Measurement Systems Ltd.) measured the temperature of the streams flowing out of the treatment nozzles, the humidity and temperature of the ambient air (outside the rig) and also the temperature of the product surface every 0.5 s and logged the values in an output file during every treatment. Temperatures of the streams flowing out of the hot air, steam and cold air nozzles were measured at a distance of 1 mm above the circumference of the insulating ring using Type K mineral insulated thermocouples with an outside diameter of 3 mm. A combined sensor (Carel ASWC110000, Padova, Italy), situated adjacent to the chamber measured the ambient air temperature and relative humidity.

The prototype rig also had a dew-point temperature transmitter (HMP240, Vaisala Ltd., Suffolk, UK) fitted inside the chamber. This was used to measure the dew point of the air within the chamber during dry and wet treatments.

The surface temperature was measured using a miniature IR thermometer (MID02LT, Raytek UK, Buckinghamshire, UK) with a system accuracy of ±1 °C and repeatability of ±0.5 °C. The IR thermometer was fixed to the top of the chamber at a height of 90 mm from the sample surface. Due to its 2:1 optics, the surface temperature was measured over a circle of 45 mm diameter. The sensor head had to be maintained at a constant temperature to maintain the accuracy of the measurements. A housing was made to fit the sensor, which had inlet and outlet ports that allowed ambient air to be blown through the housing using a radial blower (MVL RG130, Air Control Industries Ltd., Somerset, UK) to stabilise the sensor head temperature. The blower was operated for 30 min before the treatments to ensure temperature stabilisation stabilise the sensor head temperatures before the start of a treatment.

4.9. Control and logging

A 16-channel digital output expansion module (Datascan 7035, Measurement Systems Ltd.) was connected to the measurement processor, enabling it to switch de-

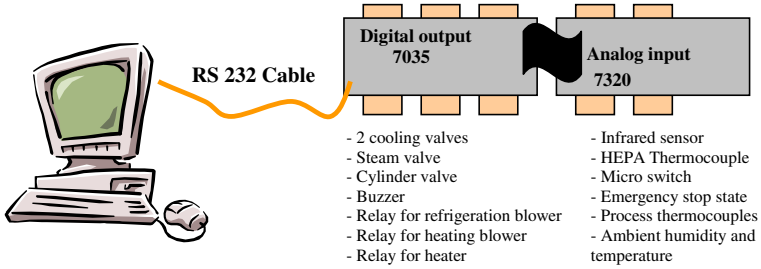

Fig. 5. Connection of control modules.

vices connected to each channel on or off, as shown in Fig. 5.

The control and logging program was written in Visual Basic 6 (Microsoft) and compiled into an executable file. The executable file was installed on a personal computer (PC) and used to control the processes. The programme controlled all of the process treatments, the movement of the sample, the safety of the system and logged the measured data to disk. The programme received information on the state of the process from the analogue input processor and controlled the process by setting the state of switches on the digital output processor. A simplified flow diagram of the control procedure is given in Fig. 6.

The PC (Pentium 4/1.6 GHz, Viglen Ltd.) was connected to the analogue input digital and output processors (situated inside the apparatus) via an RS232 cable. This meant that the PC could be separated from the apparatus, simplifying delivery and positioning of the apparatus.

4.10. Calibration

4.10.1. Calibration of process thermocouples

The thermocouples used to measure temperatures during the treatments were calibrated in a stirred water bath between 25 and 100 °C against a platinum

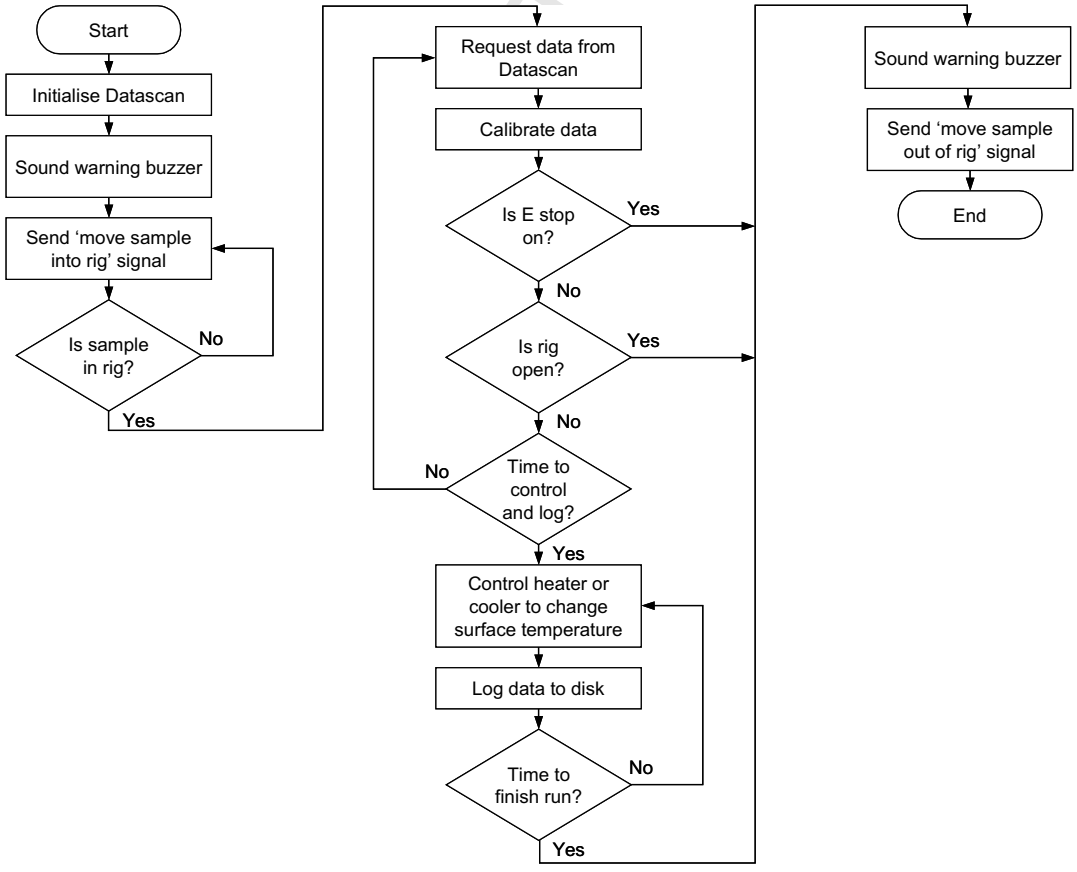

Fig. 6. Simplified flow diagram of control procedure.

resistance thermometer (Fluke 2180A), calibrated to national standards.

4.10.2. Calibration of IR thermometer in a dry environment

Experiments were carried out to evaluate an accurate way of calibrating the IR thermometer in a dry environment. These experiments showed that a uniform temperature could be achieved over the surface of a high conductivity sample if it was placed in the sample holder and heated slowly (from 20 to 100 °C in 900 s). A thermocouple was positioned just below the surface of the high conductivity sample and it was demonstrated that this gave an accurate measurement of surface temperature at these heating rates. This method of achieving a slowly changing, accurately measured surface temperature enabled accurate calibration of the IR sensor. The IR thermometer was calibrated in this way using a sample manufactured from aluminium and its top surface painted matt black. The sample used a type-K thermocouple (calibrated as with the process thermocouples, above) placed in the centre, just below the top surface to measure surface temperatures during the heating. Rotation of the sample was unnecessary, as it had been established that the surface would be of uniform temperature during this calibration process. To avoid twisting and breakage of the thermocouple the rotation was therefore stopped by turning off the motor. The IR thermometer was calibrated against the thermocouple in the aluminium sample during the treatment. The emissivity of the matt black surface was assumed to be 1.0 and the settings of the IR thermometer set appropriately.

4.10.3. Calibration of IR thermometer in a wet environment

IR thermometers can accurately measure the product surface temperatures through air. Water in the environment between the product surface and IR thermometer, both in the form of droplets in the treatment stream and condensed on the surface (as happens during a steam treatment), lead to inaccurate temperature readings.

Experiments were carried out to evaluate an accurate way of calibrating the IR thermometer in a wet environment. There was not a consistent correlation between the surface temperatures measured by the thermocouple in the high conductivity sample and the IR thermometer, making calibration impossible.

It was found that condensation on the sample surface was dependent on initial surface temperature but there was also a highly variable element introduced by formation of water droplets on the surface (Ulloa, Rouaud, Foster, Kondjoyan, & Havet, in preparation).

5. Performance

5.1. Surface temperature treatment

5.1.1. Dry heating/cooling

The apparatus heated the surface of a sample from 5 to 100 °C in a duration that was settable by the user. There was also an option to hold the surface temperature at up to 100 °C for a duration that was settable by the user.

There was no minimum heating duration that could be entered into the GUI. If a duration was entered which was too small for the heating equipment to raise the temperature of the surface to the required temperature in the required time, the heater would heat the product surface at the maximum rate until the end of the heating duration. In these cases, it could be seen from the output file that the 'control temperature' lagged behind the 'desired control temperature'.

Heating tests were carried out in the apparatus using a sample made from a test substance (hydroxyethylmethylcellulose, Gutschmidt, 1960; Riedel, 1960), commonly known as Tylose, a food simulant with similar thermal properties to lean beef. When set to 'maximum heating', the apparatus was able to heat the surface of a Tylose sample from 9 to 100 °C in 25 s (Fig. 7), a heating rate of 3.6 K s^{-1}. This 'maximum heating' setting heated the sample as quickly as possible to a target temperature, instead of in a straight-line ramp. The temperature of the air exiting the hot air nozzle rose to a maximum of 250 °C at the end of heating.

When set to 'maximum cooling' (again, cooling as rapidly as possible and so not a straight line ramp), the apparatus was capable of cooling the surface of a Tylose sample from 100 to 40 °C in 51 s (1.2 K s^{-1})

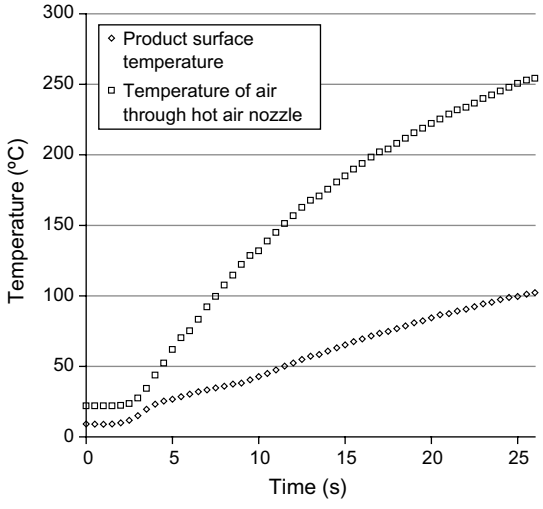

Fig. 7. Temperatures measured on the surface of Tylose and the air exiting the process nozzle for a maximum heating (uncontrolled) treatment.

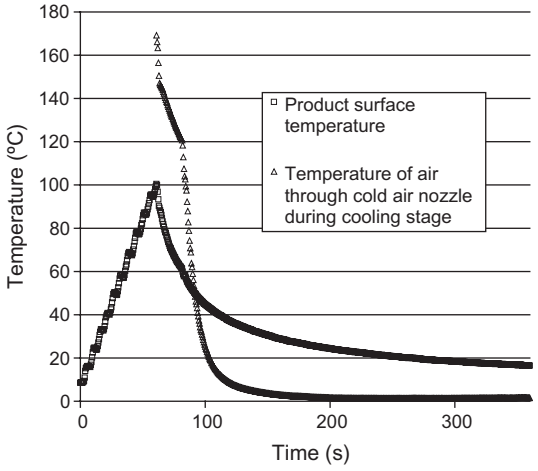

Fig. 8. Temperatures measured on the surface of Tylose and the air exiting the process nozzle for a maximum cooling (uncontrolled) treatment.

and to 16.4 °C in 5 min (0.3 K s^{-1}) (Fig. 8). These data were for a sample that had been heated from 5 to 100 °C in 60 s (in a controlled, straight line ramp, without holding at 100 °C).

The rate of cooling was significantly lower than the rate of heating. The reason for the slow cooling is shown by the temperature history of the air exiting the cold nozzle. The cold air was 170 °C at the start of cooling and took a further 31 s to fall below the surface temperature of the sample (51 °C). The main reason for this was that the temperature of the cooling nozzle rose significantly during the heating treatment as it was heated by the hot air from the heating nozzle. This in turn heated the cold air as it was blown into the chamber. The air from the cold air nozzle reached a minimum of 1 °C during the cooling treatment.

Fig. 9 shows the temperature history of a sample of Tylose, with a heating treatment of 5–60 °C in 30 s, followed by holding at 60 °C for 30 s and then a cooling treatment of 60–5 °C in 30 s. The temperatures of the air at the exit of both the heating and cooling nozzles are also shown during their respective treatments. The temperature of the sample can be seen to fluctuate above and below the desired control temperature as the heater switches on and off. The average absolute errors were 1.7 °C during the heating ramp and 2.4 °C during the holding period. The surface temperature was, on average, higher than the desired control temperature because the rate of heating was much higher than the rate of cooling, meaning that one 0.5 s control increment of heating increased the temperature more than one increment of cooling reduced it. For the first 5 s after holding, the cooling valves cycled on and off to keep the surface at the desired temperature. After this point the actual cooling rate was less than the desired rate and so the cooling was always on.

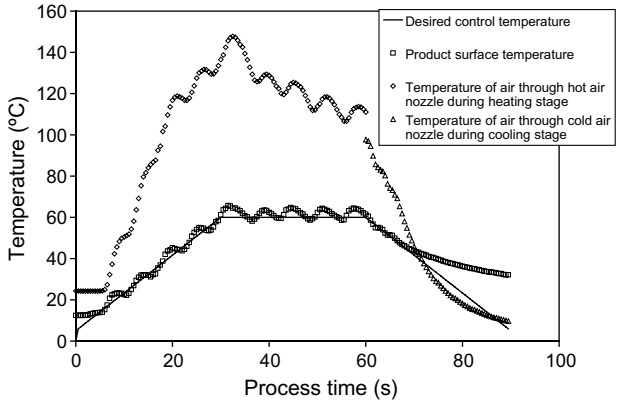

Fig. 9. Temperature history for a Tylose sample with a 5–60 °C in 30 s heating treatment followed by a 30 s holding period and a 60–5 °C in 30 s cooling treatment.

5.2. Steam

It is not possible to show the temperature history of the surface during a wet heat experiment, as the IR thermometer did not provide a meaningful surface temperature. This is explained in Section 4.10.3.

5.3. Humidity measurements

During hot air treatments on moist products, the dew point temperature inside the chamber did not change by more than 2 °C (the accuracy of the dew point sensor at those conditions). This showed that the moisture evaporated from the sample surface was expelled from the chamber.

Fig. 10 shows the temperature history during a wet heat treatment. The dew point temperature quickly rose to a temperature just below the dry bulb temperature at

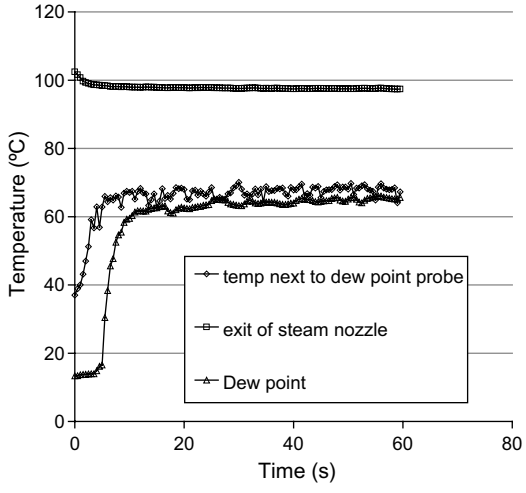

Fig. 10. Temperature history during a wet heat treatment on a Tylose sample.

the position of the dew point probe, giving a relative humidity (RH) of nearly 100%. As the product sample was closer to the wet heating stream than the dew point sensor, it was assumed that the RH over the sample was 100%.

5.4. Uniformity of heating

Two methods were used to measure the uniformity of heating. The first was using thermocouples just under the surface of an aluminium sample and the second was using an IR thermal imaging camera.

5.5. Thermocouple method

The aluminium sample used in these experiments was similar to that used in Section 4.10, except that it had a second thermocouple placed 16 mm from the centre, just under the surface. This thermocouple was used to measure either leading or trailing edge temperatures, depending on the orientation of the sample to the hot air nozzle. To avoid breakage of the thermocouples during these experiments the sample rotation was disabled as in Section 4.10.

The advantage of this method was that a history of the temperature uniformity was measured during the entire heating process. However, this method was not very comparable to the process that the food samples underwent, as the aluminium sample would have had very different thermophysical properties to the foods that were processed in the apparatus and the rotation of the sample was disabled, which would have caused larger temperature differences on the surface than if it had been rotating.

5.6. Thermal imaging method

A thermal imaging camera (ThermaCam E4, FLIR Systems AB, Sweden) was used to determine the temperatures on the surface of a Teflon sample, after a rapid, high temperature dry heating treatment (20–100 °C in 60 s). The camera had been calibrated using radiation sources that are traceable to National Standards. The emissivity of the camera was set to 0.95. It was not possible to take the image to measure temperatures whilst the sample was in the chamber and therefore the sample was removed from the apparatus directly after heating and the thermal image taken as soon as possible. The duration between end of heating and taking the image was 9 s. The same heating treatment was applied to Tylose samples with and without sample rotation.

The advantage of this method was that real surface temperatures were measured at all positions on the surface of a sample that had similar properties on a food product. The only disadvantage was that it was not possible to measure temperature data using the camera during the heating process or immediately afterwards.

5.7. Dry air treatment

Fig. 11 shows the temperature history during a rapid hot air treatment followed by a holding period using the thermocouple method. The heater was unable to maintain the specified heating gradient and therefore gave maximum heating until the holding period. The difference between the leading and trailing edge temperatures reached a maximum of 10 °C, 25 s after the treatment started.

Fig. 12 shows the thermal image 9 s after a rapid hot air treatment with no sample rotation. It can be seen that there is a temperature gradient from top to bottom, representing the leading and trailing edge of the sample. The maximum and minimum surface temperatures of

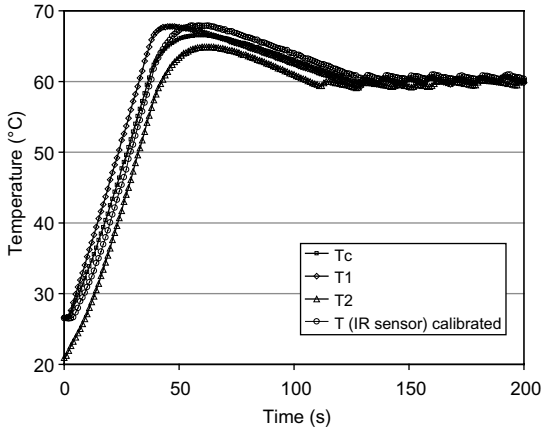

Fig. 11. Temperature history during a fast hot air treatment. Centre thermocouple (Tc), leading edge thermocouple (T1), IR sensor temperature (T(IR sensor)) and trailing edge thermocouple (T2) are plotted.

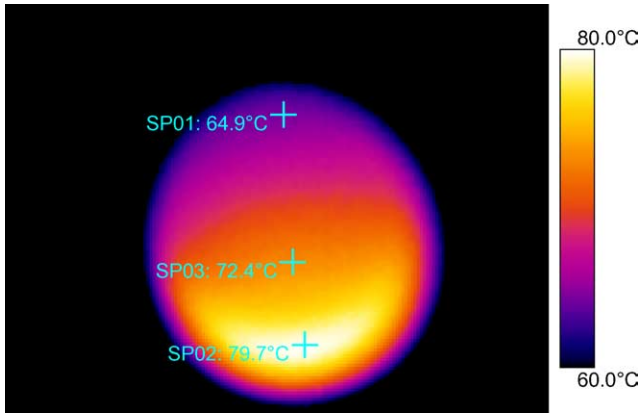

Fig. 12. Temperature uniformity taken by a thermal imaging camera, 9 s after heating to 100 °C in 60 s. Sample rotation was disabled.

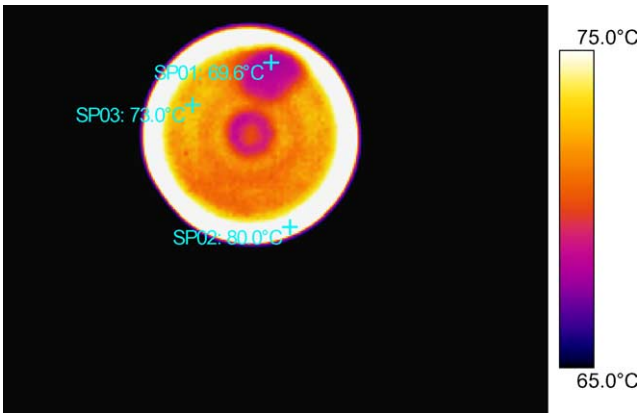

Fig. 13. Temperature uniformity taken by a thermal imaging camera, 9 s after heating to 100 °C in 60 s.

the bulk of the sample were 79.7 and 64.9 °C respectively.

Fig. 13 shows the thermal image 9 s after a rapid hot air treatment with sample rotation. A hot ring (80 °C) can be seen around the edge of the sample, representing the glass and perhaps the outer edge of the sample. The maximum and minimum temperatures of the bulk of the sample (inside the hot ring) were 73.0 and 69.6 °C respectively.

The reduced average temperature of the sample (approximately 70 °C) represents the rapid cooling of the surface that occurs by conduction from the bulk of the sample to the surface and heat exchange with the environment during the 9 s between the end of heating and taking the thermal image.

5.7.1. Wet treatment

Fig. 14 shows the temperature history during a 60 s steam treatment using the thermocouple method. The temperature exiting the steam nozzle reached 100 °C after 2 s. There was a difference between leading and trailing edge temperatures that reached a maximum of 18 °C, 7 s after the treatment started.

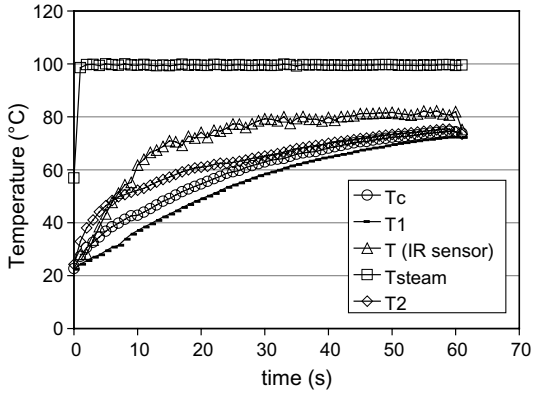

Fig. 14. Temperature history during a 60 s steam treatment. Steam temperature (Tsteam) centre thermocouple (Tc), trailing edge thermocouple (T1), IR sensor temperature (T(IR sensor)) and leading edge thermocouple (T2) are plotted.

6. Discussion and conclusion

Test apparatus to heat a sample from a given surface temperature at a given rate, hold the sample at a given temperature for a defined period and cool the sample in a controlled manner has been built and its performance evaluated. Four more versions of these apparatus were built, CE marked, shipped to project partners and used to obtain bacterial death data.

The apparatus can either heat in a dry (hot air) or wet (steam) manner. The apparatus included a HEPA filtration system to contain bacteria and the ability to view the sample from above during treatments with a light sensitive camera. The apparatus has proved to be simple to use, safe and reliable.

Surface temperatures were controlled using temperatures measured by a calibrated IR thermometer during the dry experiments. It was not possible to obtain reliable measurements from the IR thermometer during wet heating treatments and so these treatments were controlled on duration only.

The apparatus was shown to heat a Tylose (meat simulant) sample from 9 to 100 °C at a rate of up to 3.6 K s^{-1} and cool it to 40 °C at a rate of up to 1.2 K s^{-1} then to 16.6 °C at a rate of up to 0.3 K s^{-1}. Temperature control to a defined ramp was achieved at an average accuracy of 1.7 °C and 2.4 °C on the sample surface, during heating and holding periods, respectively.

It was not possible to measure temperature uniformity during a real treatment on real food. A maximum surface temperature difference of 10 °C and 18 °C were recorded (with thermocouples) for air and steam respectively, just under the surface of an aluminium sample without sample rotation. Thermal imaging allowed temperatures across the surface of a Tylose sample to be measured 9 s after a rapid heating treatment. These showed a large temperature difference of 14.8 °C between the leading and trailing edge without sample rotation, but a much smaller temperature difference of 3.4 °C with sample rotation.

Delivering the treatment streams across (parallel to) the surface of the sample allowed the space above the sample to be used for surface temperature measurement using an IR thermometer and viewing with a light sensitive camera. However, delivering the treatment streams across the surface was not ideal, as it led to uneven surface temperatures. Temperature uniformity was greatly increased by sample rotation although this did not allow measurement of sample temperatures with thermocouples.

Carrying out both the cooling and heating in the same chamber caused the cooling to be less effective than originally intended. The slow rate of cooling was due to delivery of cold air into the chamber through a nozzle that had been previously heated by the air exiting the heating nozzle during the heating/holding treatment. The air also absorbed heat as it passed through the blower.

An improved apparatus which addresses many of these issues has been built and tested and is described in another publication in this Journal Special Edition (Foster et al., 2005).

7. Uncited references

Soto and Borquez (2001)

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