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2 Design and development of apparatus to provide repeatable 3 surface temperature–time treatments on inoculated food samples

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10 Abstract

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

15 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
16 100 °C, hold and then cool it. The surface temperature was measured using an infra-red (IR) thermometer and the air heater was
17 controlled to give a specified surface temperature history. Steam was also used to provide a 'wet', but less controlled heating cycle.
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19 *Keywords:* Food poisoning; Surface decontamination; Microbial models; Heating and cooling equipment; Surface temperature measurements

21 1. Introduction

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

29 2. Specification

30 To provide data to model microbial death during
31 heating and cooling, the test apparatus had to control

the sample's surface temperature in a pre-defined man- 32
ner. The test apparatus was therefore designed to (1) 33
heat the sample from a set starting temperature, at a 34
set rate, until a set end of heating temperature was 35
reached, (2) hold the sample at the end of heating tem- 36
perature for a defined period then (3) cool the sample 37
in a controlled manner to a temperature at which no 38
microbial growth can occur. At least 10 sampling points 39
were required within each heating–holding–cooling re- 40
gime to allow sufficient data for the microbial modelling 41
work, and so the apparatus was designed such that sam- 42
ples could be removed at predefined points in the cycle. 43
Samples that were removed for analysis during the treat- 44
ment needed to be cooled immediately to prevent any 45
further microbial activity. 46

The original specification of the apparatus was that it 47
should be able to produce repeatable temperature cycles, 48
with an average error of less than ± 2 °C, on food 49

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

60 There was also the requirement to develop methods
61 for accurately measuring food surface and process tem-
62 peratures. The specification stated that temperatures
63 should be measured to an accuracy of better than
64 ± 1 °C during the slow heating, holding and cooling pro-
65 cesses. The temperatures in the 'rapid' heating and cool-
66 ing process should be measured with an accuracy better
67 than ± 2 °C throughout the process.

68 Prototype apparatus was manufactured and tested at
69 the Food Refrigeration and Process Engineering Re-
70 search Centre, University of Bristol (FRPERC). Four
71 more of the systems were manufactured and delivered
72 to the project partners. The apparatus needed to be sim-
73 ple to operate, safe and reliable, since microbiologists,
74 food technologists and engineers from three different
75 EU countries would use it. It was designed so that
76 researchers and technicians in the institutions would
77 be able operate the equipment with little training.

78 The following sections explain in detail the develop-
79 ment of each part of the system.

80 3. Development of system

81 After initial discussions with the project partners, a
82 number of changes were made to the initial specifica-
83 tions. The maximum temperature of the rapid cycle
84 was set at 100 °C since it was not expected that bacteria
85 would survive above this temperature. The minimum
86 time for the rapid heating cycle was lengthened to allow
87 single-phase heaters to be used. The minimum time for
88 the cooling was increased since rapid cooling to temper-
89 atures where further microbial activity would be inhib-
90 ited was more easily carried out by placing the sample
91 into a stomacher bag immediately after it came out of
92 the system (McGovern, McCann, & Sheridan, 2005)
93 containing cold diluent.

94 At an early stage of development, studies were carried
95 out to ensure that the high air velocities achieved over
96 the surface of the sample would not detach an excessive
97 number of microorganisms from the sample surface.
98 Loss of microorganisms could reduce the final counts
99 (and so cause a non-thermal reduction in the bacterial
100 numbers) and lead to safety problems, as many of the
101 bacteria used were pathogenic or genetically modified.
102 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 bac-
teria 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 sam-
ples during rapid heating and cooling cycles and accu-
rate measurement of surface temperatures during the
process. Samples had to be easy to produce and inocu-
late and have a known surface area exposed to the heat-
ing 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 experimenta-
tion, mathematical heat transfer modelling and compu-
tational 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 temper-
ature (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 num-
bers on the surface and measuring true, rapidly chang-
ing 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

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

164 The sample dish was held (friction fit) on an alumin-
165 ium support connected to a motor that rotated the sam-
166 ple at a frequency of 0.8 Hz. The purpose of the rotation
167 was to create a more even heating and cooling at the sur-
168 face. Without rotation the leading edge of the sample
169 would be subjected to higher heating and cooling rates.
170 To keep the heating as one dimensional as possible
171 (from the top surface only), a nickel ring was placed
172 around the sample, with the cavity inside the ring pro-
173 viding the insulation. A schematic of the complete sam-
174 ple and its holder is shown in Fig. 1.

175 The sample dish was automatically raised into the
176 treatment chamber immediately after insertion. The
177 chamber was of dimensions 210 × 210 × 226 mm high
178 and was constructed from an angle iron frame and alu-
179 minium side panels. The top of the chamber housed a
180 plate of clear safety glass (160 × 160 × 6 mm thick, Pil-
181 kington plc, St. Helens, UK) with a 12 mm diameter
182 hole in the centre for mounting the IR thermometer.
183 Nozzles to deliver hot air, cold air and steam to the sur-

184 face of the sample protruded through and were held in
185 place by the side panels.

186 The main apparatus was designed to be small enough
187 to pass through a standard laboratory doorway and had
188 overall dimensions of 0.7 × 1.0 × 2.0 m. A separate
189 refrigeration system, of external dimensions
190 0.8 × 0.8 × 1.2 m, was used to provide cold air for cool-
191 ing the sample surface. A desktop computer was used to
192 control and monitor system performance. The only ser-
193 vices required were: (1) a 230 V, 32 A electrical supply
194 for the main unit, (2) a 230 V, 13 A supply for the refrig-
195 eration system and (3) a low flow rate of dry, clean,
196 compressed air at a pressure of 4.0 bar. The air supply
197 could come from either a compressed air line or a com-
198 pressed air cylinder with regulator.

199 The glass panel in the top was provided to allow one
200 partner to use a light sensitive camera to view biolumi-
201 nescent bacteria on the surface of the sample (Lewis,
202 Baldwin, O'Neill, Alloush, & Nelson, 2005). The appa-
203 ratus used by this partner was also modified in a number
204 of ways, including the provision of a matt black internal
205 finish to reduce reflections that would interfere with the
206 camera's ability to measure light emissions from the bac-
207 teria on the product surface.

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

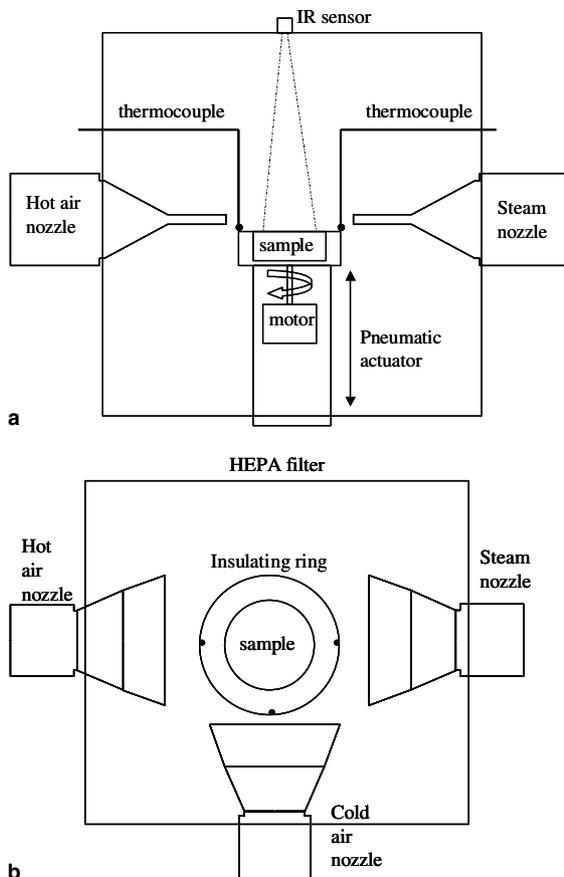


Fig. 1. (a) Vertical section of chamber and (b) plan view of chamber.

4. Process and control

211 Fig. 2 shows a schematic of the chamber and treat-
212 ment processes. There were three different treatment
213 processes, hot air, cold air and steam.

4.1. Hot air 'dry' treatment

215 Air was taken from ambient and blown through a
216 high-pressure regenerative blower into a 3.3 kW heater
217 (Robust and Heater 3000, respectively, Leister Process
218 Technologies, Sarnen, Switzerland) via a 25 mm diame-
219 ter PVC hose. The hot air from the heater was exhausted
220 through a flat nozzle (70 × 4 mm). The nozzle was posi-
221 tioned 30 mm away from the edge of the sample and
222 5 mm above the surface of the sample. The hot air was
223 blown over the sample parallel to its surface and the
224 temperature of the air controlled to give the correct tem-
225 perature at the product surface at any point in the exper-
226 iments (explained in more detail in Section 4.6).

4.2. Steam 'wet' treatment

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

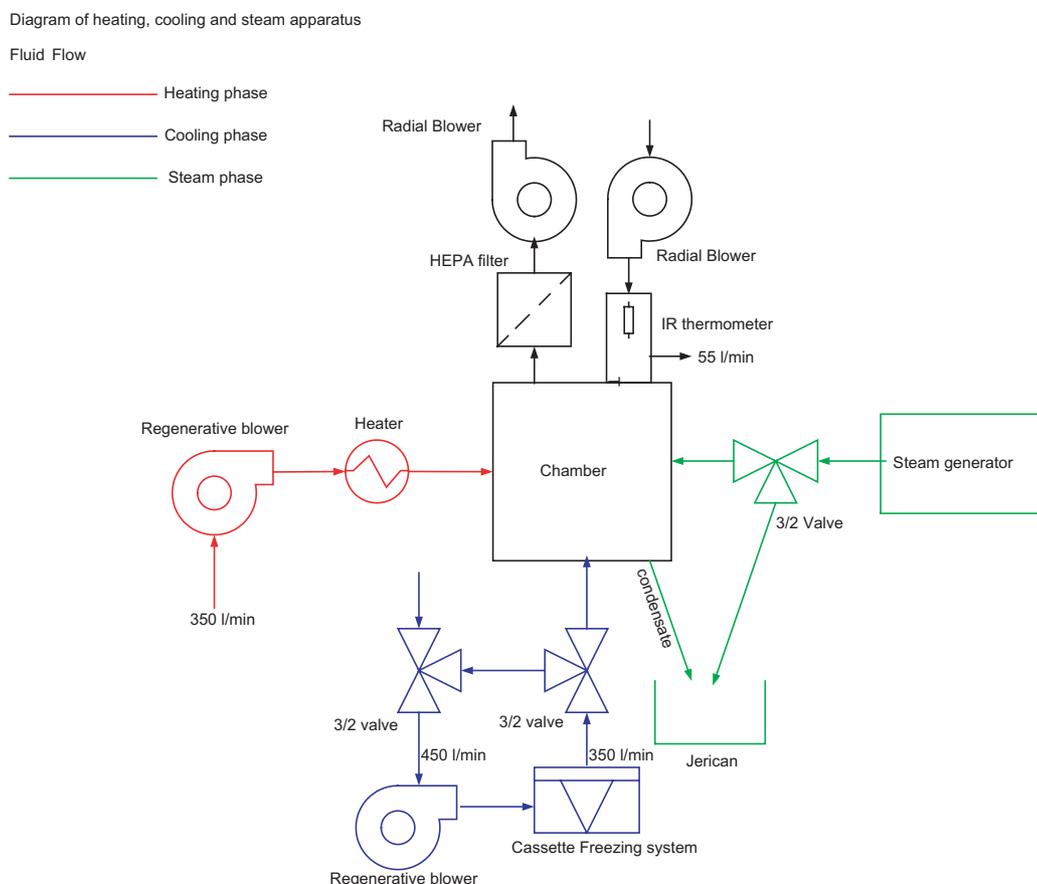


Fig. 2. Schematic of the apparatus showing the treatment equipment.

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

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

249 4.3. Cold air treatment

250 Cold air was accumulated by re-circulating it through
 251 the evaporator of a refrigeration cassette mounted on
 252 top of a chest freezer. The cassette was designed to cool
 253 air in an upright freezer (560FP, Sadia Refrigeration,
 254 Sheffield, UK). The chest freezer (AFG 522, Whirlpool
 255 UK Ltd., Surrey, UK) was used as an insulated box

(refrigeration was not used) to accumulate the cold air 256
 for the cooling system. The cassette was positioned 257
 above the chest freezer and the top of the chest freezer 258
 cut so that air from the chest freezer re-circulated 259
 through the evaporator of the cassette, and was cooled. 260
 An aluminium frame was used to seal the connection be- 261
 tween chest freezer and cassette. 262

263 Fig. 2 shows the refrigeration circuit. Two holes were 264
 cut in the top of the cassette, one just before the evaporator 265
 and one just after, and ports were connected to these holes. 266
 A 25 mm inside diameter PVC hose was attached to each of the 267
 two ports; these holes were wrapped with 13 mm thick rubber 268
 pipe insulation (Armaflex, Armstrong Insulation products, 269
 Lancs., UK). Cold air from the refrigeration unit was drawn 270
 into the treatment chamber using a high-pressure regenerative 271
 blower (Robust, Leister Process Technologies, 272
 Sarnen, Switzerland). Two three-port air operated 273
 valves (VGA342-10A, SMC UK Ltd., Buckinghamshire, 274
 UK) allowed air to either recycle through the pipes and blower 275
 (this was to allow pre-cooling of the system) or be discharged 276
 through a nozzle positioned 15 mm in front of the sample and 277
 5 mm above the surface of the sample. 278
 279

280 The cooling treatment could only be selected in com-
 281 bination with (and after) a hot air treatment. Cooling
 282 was not possible after a wet heat treatment due, to in-
 283 creased condensation problems. The programme pro-
 284 duced a 15 min pre-cooling phase before the treatment
 285 was started, in order to pre-cool as much of the cooling
 286 system and pipework as possible, so that the cooling air
 287 would be as cold as possible when the cooling phase was
 288 initiated.

289 4.4. Filtration

290 A filtration system was attached to the chamber to
 291 contain any bacteria that may have been blown off the
 292 samples during the treatments. Air from the chamber
 293 was drawn through a high efficiency particulate air
 294 (HEPA) filter (SSA/H13/2FL/2Gr, Absolair Filtration
 295 Ltd.) of dimensions 210 × 223 × 150 mm. This was at-
 296 tached to a vertical side of the chamber.

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

307 chamber and would pass through the filter before leav-
 308 ing the chamber.

4.5. Sample entry

310 When the start button on the GUI was pressed, a
 311 warning buzzer sounded for a period of 5 s before a
 312 pneumatic actuator (C95KB32-350, SMC Ltd.) raised
 313 the sample into the chamber through a hole in the bot-
 314 tom plate of the chamber. When the sample was fully in-
 315 serted into the chamber, a microswitch was triggered,
 316 which sent a signal to the control program to start the
 317 treatment.

4.6. Temperature control

319 For 'dry' heating the user entered values for 'temper-
 320 ature at start of heating', 'temperature at end of heating',
 321 'heating duration' and 'holding duration' into the GUI
 322 (Fig. 3). The control and logging programme converted
 323 this into a heating and holding ramp as shown in Fig. 4.
 324 This ramp defined the desired surface temperature his-
 325 tory of the sample. The control and logging programme
 326 compared the actual surface temperature (measured by
 327 an IR thermometer) with the desired surface tempera-
 328 ture at 0.5 s intervals. If the measured temperature was
 329 below the desired temperature the heater was switched
 330 on, if it was below, the heater was switched off. The

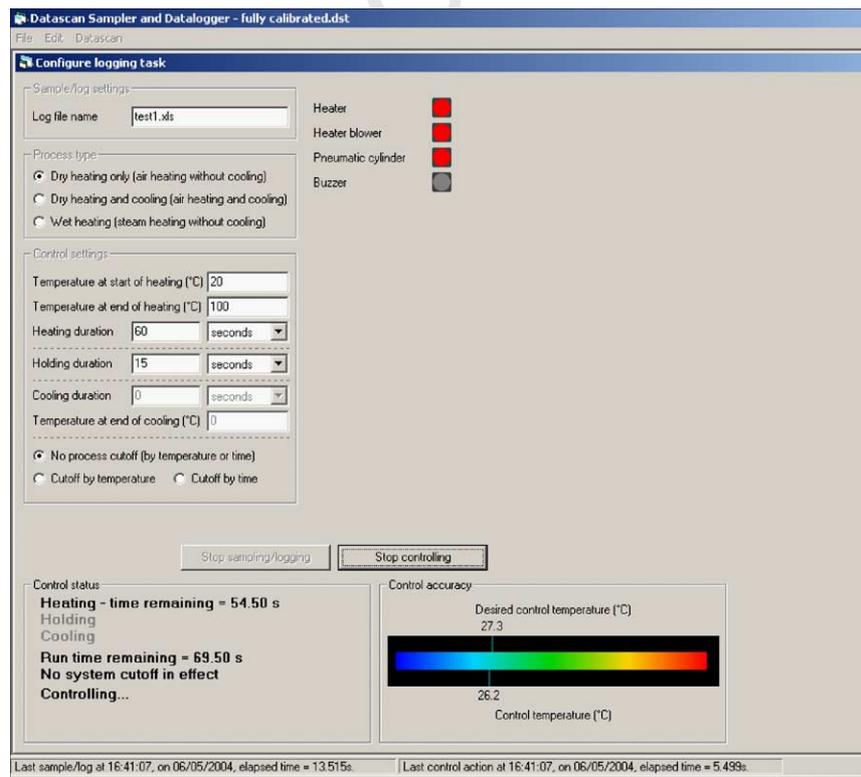


Fig. 3. Screenshot of GUI during a treatment.

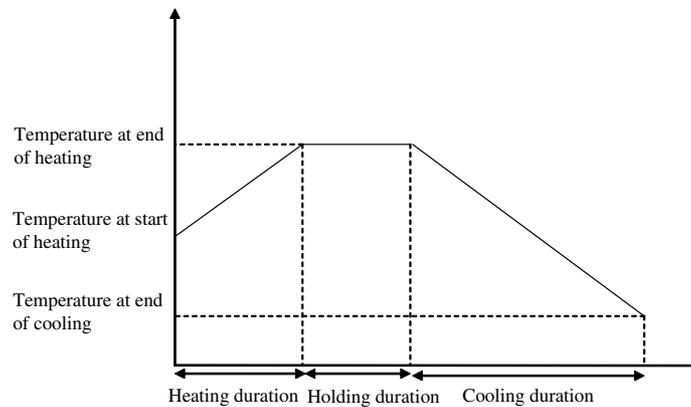


Fig. 4. Desired temperature history given input parameters.

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

333 If cooling was specified in the GUI, the user was also
334 required to enter values for ‘temperature at end of cool-
335 ing’ and ‘cooling duration’. This defined a cooling ramp
336 in the same way as the heating profile. The temperature
337 was controlled at the same interval as the heating pro-
338 cess but in the opposite manner (a high temperature
339 turned the cooling on and a low temperature turned it
340 off). If cooling was required, the two pneumatic valves
341 were actuated, allowing cold air to blow into the cham-
342 ber. If not required, the valves were de-activated, pre-
343 venting cold air from entering the chamber, but
344 allowing the air to re-circulate around the cooling cir-
345 cuit, keeping as much of it as cold as possible. Unlike
346 during the heating and holding periods, air only passed
347 over the sample when cooling was required.

348 4.7. Safety

349 An emergency stop button and safety relay were used
350 in the apparatus to allow shutdown and avoidance of all
351 potential hazards. The relay cut power to the heater,
352 blower and released pneumatic pressure to the system
353 removing energy from the actuator. To avoid the appa-
354 ratus being reset automatically (e.g. after power fluctua-
355 tions) and potentially becoming hazardous, the
356 emergency stop circuit included a manual start button
357 which had to be pressed after either a cut in power or
358 the emergency stop button being pressed.

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

364 4.8. Measurement of process conditions

365 A 16-channel analogue input measurement processor
366 (Datascan 7320, Measurement Systems Ltd.) measured

the temperature of the streams flowing out of the treat- 367
ment nozzles, the humidity and temperature of the 368
ambient air (outside the rig) and also the temperature 369
of the product surface every 0.5 s and logged the values 370
in an output file during every treatment. Temperatures 371
of the streams flowing out of the hot air, steam and cold 372
air nozzles were measured at a distance of 1 mm above 373
the circumference of the insulating ring using Type K 374
mineral insulated thermocouples with an outside diam- 375
eter of 3 mm. A combined sensor (Carel ASWC110000, 376
Padova, Italy), situated adjacent to the chamber mea- 377
sured the ambient air temperature and relative humidity. 378

The prototype rig also had a dew-point temperature 379
transmitter (HMP240, Vaisala Ltd., Suffolk, UK) fitted 380
inside the chamber. This was used to measure the dew 381
point of the air within the chamber during dry and 382
wet treatments. 383

The surface temperature was measured using a mini- 384
ature IR thermometer (MID02LT, Raytek UK, Buck- 385
inghamshire, UK) with a system accuracy of $\pm 1^\circ\text{C}$ 386
and repeatability of $\pm 0.5^\circ\text{C}$. The IR thermometer was 387
fixed to the top of the chamber at a height of 90 mm 388
from the sample surface. Due to its 2:1 optics, the sur- 389
face temperature was measured over a circle of 45 mm 390
diameter. The sensor head had to be maintained at a 391
constant temperature to maintain the accuracy of the 392
measurements. A housing was made to fit the sensor, 393
which had inlet and outlet ports that allowed ambient 394
air to be blown through the housing using a radial 395
blower (MVL RG130, Air Control Industries Ltd., 396
Somerset, UK) to stabilise the sensor head temperature. 397
The blower was operated for 30 min before the treat- 398
ments to ensure temperature stabilisation stabilise the 399
sensor head temperatures before the start of a treatment. 400

4.9. Control and logging 401

A 16-channel digital output expansion module (Data- 402
scan 7035, Measurement Systems Ltd.) was connected 403
to the measurement processor, enabling it to switch de- 404

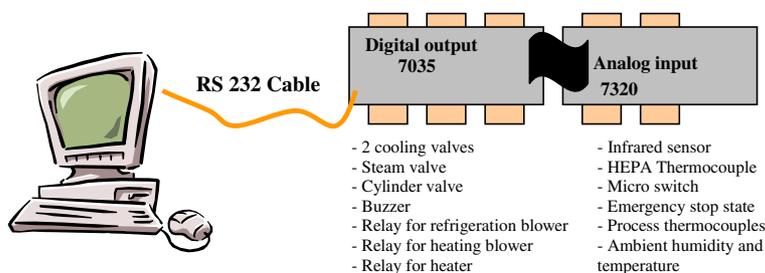


Fig. 5. Connection of control modules.

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

407 The control and logging program was written in
408 Visual Basic 6 (Microsoft) and compiled into an execut-
409 able file. The executable file was installed on a personal
410 computer (PC) and used to control the processes. The
411 programme controlled all of the process treatments,
412 the movement of the sample, the safety of the system
413 and logged the measured data to disk. The programme
414 received information on the state of the process from
415 the analogue input processor and controlled the process
416 by setting the state of switches on the digital output pro-
417 cessor. A simplified flow diagram of the control proce-
418 dure is given in Fig. 6.

419 The PC (Pentium 4/1.6 GHz, Viglen Ltd.) was con-
420 nected to the analogue input digital and output proces-
421 sors (situated inside the apparatus) via an RS232 cable.
422 This meant that the PC could be separated from the
423 apparatus, simplifying delivery and positioning of the
424 apparatus.

425 4.10. Calibration

426 4.10.1. Calibration of process thermocouples

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

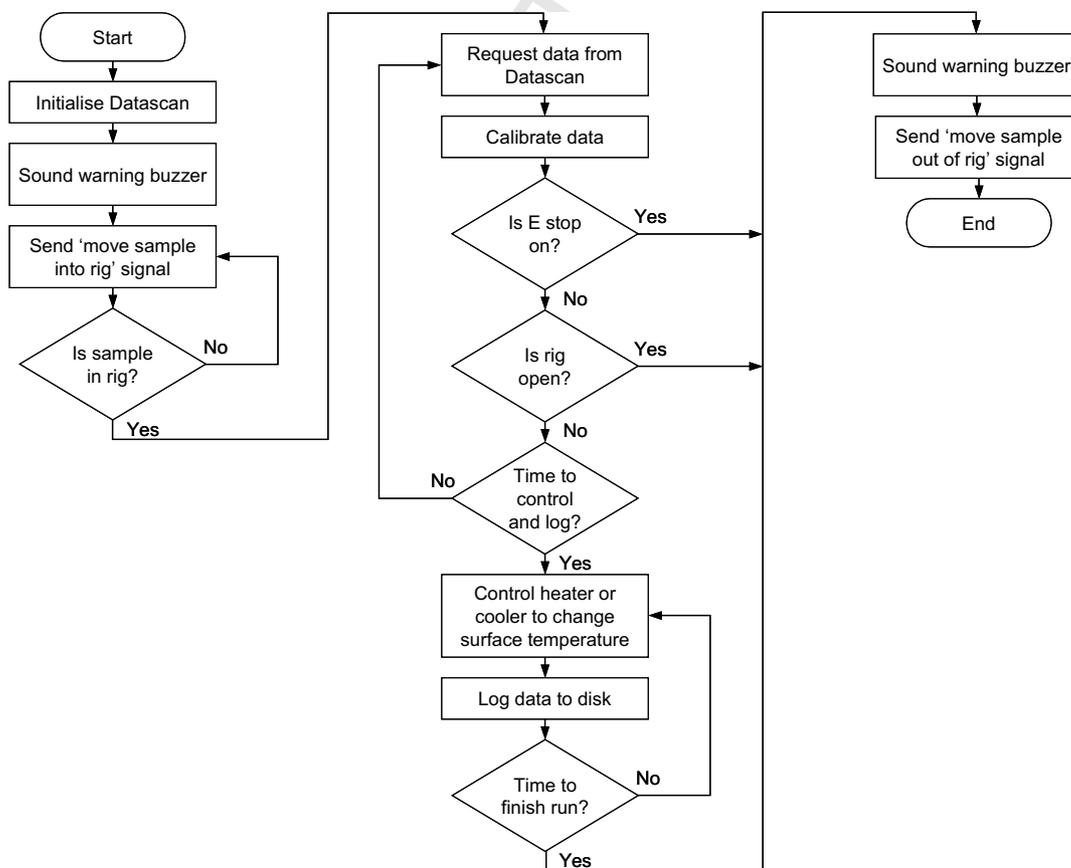


Fig. 6. Simplified flow diagram of control procedure.

430 resistance thermometer (Fluke 2180A), calibrated to na-
431 tional standards.

432 4.10.2. Calibration of IR thermometer in a dry 433 environment

434 Experiments were carried out to evaluate an accurate
435 way of calibrating the IR thermometer in a dry environ-
436 ment. These experiments showed that a uniform temper-
437 ature could be achieved over the surface of a high
438 conductivity sample if it was placed in the sample holder
439 and heated slowly (from 20 to 100 °C in 900 s). A ther-
440 mocouple was positioned just below the surface of the
441 high conductivity sample and it was demonstrated that
442 this gave an accurate measurement of surface tempera-
443 ture at these heating rates. This method of achieving a
444 slowly changing, accurately measured surface tempera-
445 ture enabled accurate calibration of the IR sensor. The
446 IR thermometer was calibrated in this way using a sam-
447 ple manufactured from aluminium and its top surface
448 painted matt black. The sample used a type-K thermo-
449 couple (calibrated as with the process thermocouples,
450 above) placed in the centre, just below the top surface
451 to measure surface temperatures during the heating.
452 Rotation of the sample was unnecessary, as it had been
453 established that the surface would be of uniform temper-
454 ature during this calibration process. To avoid twisting
455 and breakage of the thermocouple the rotation was
456 therefore stopped by turning off the motor. The IR ther-
457 mometer was calibrated against the thermocouple in the
458 aluminium sample during the treatment. The emissivity
459 of the matt black surface was assumed to be 1.0 and the
460 settings of the IR thermometer set appropriately.

461 4.10.3. Calibration of IR thermometer in a wet 462 environment

463 IR thermometers can accurately measure the product
464 surface temperatures through air. Water in the environ-
465 ment between the product surface and IR thermometer,
466 both in the form of droplets in the treatment stream and
467 condensed on the surface (as happens during a steam
468 treatment), lead to inaccurate temperature readings.

469 Experiments were carried out to evaluate an accurate
470 way of calibrating the IR thermometer in a wet environ-
471 ment. There was not a consistent correlation between
472 the surface temperatures measured by the thermocouple
473 in the high conductivity sample and the IR thermome-
474 ter, making calibration impossible.

475 It was found that condensation on the sample surface
476 was dependent on initial surface temperature but there
477 was also a highly variable element introduced by forma-
478 tion of water droplets on the surface (Ulloa, Rouaud,
479 Foster, Kondjyan, & Havet, in preparation).

5. Performance 480

5.1. Surface temperature treatment 481

5.1.1. Dry heating/cooling 482

483 The apparatus heated the surface of a sample from 5
484 to 100 °C in a duration that was settable by the user.
485 There was also an option to hold the surface tempera-
486 ture at up to 100 °C for a duration that was settable
487 by the user.

488 There was no minimum heating duration that could
489 be entered into the GUI. If a duration was entered
490 which was too small for the heating equipment to raise
491 the temperature of the surface to the required tempera-
492 ture in the required time, the heater would heat the
493 product surface at the maximum rate until the end of
494 the heating duration. In these cases, it could be seen
495 from the output file that the ‘control temperature’ lagged
496 behind the ‘desired control temperature’.

497 Heating tests were carried out in the apparatus using
498 a sample made from a test substance (hydroxyethylm-
499 ethylcellulose, Gutschmidt, 1960; Riedel, 1960), com-
500 monly known as Tylose, a food simulant with similar
501 thermal properties to lean beef. When set to ‘maximum
502 heating’, the apparatus was able to heat the surface of a
503 Tylose sample from 9 to 100 °C in 25 s (Fig. 7), a heating
504 rate of 3.6 K s⁻¹. This ‘maximum heating’ setting heated
505 the sample as quickly as possible to a target tempera-
506 ture, instead of in a straight-line ramp. The temperature
507 of the air exiting the hot air nozzle rose to a maximum of
508 250 °C at the end of heating.

509 When set to ‘maximum cooling’ (again, cooling as
510 rapidly as possible and so not a straight line ramp),
511 the apparatus was capable of cooling the surface of a
512 Tylose sample from 100 to 40 °C in 51 s (1.2 K s⁻¹)

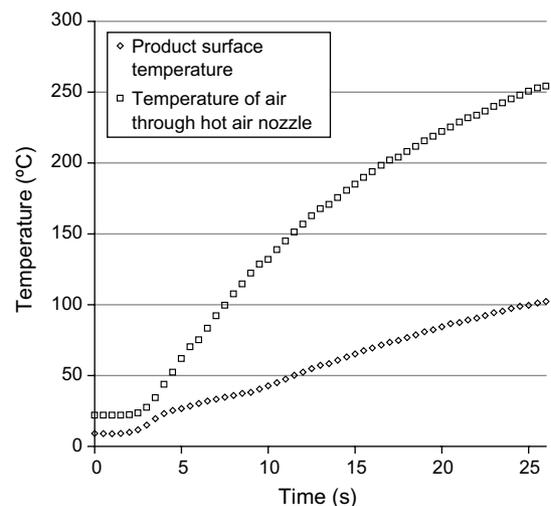


Fig. 7. Temperatures measured on the surface of Tylose and the air exiting the process nozzle for a maximum heating (uncontrolled) treatment.

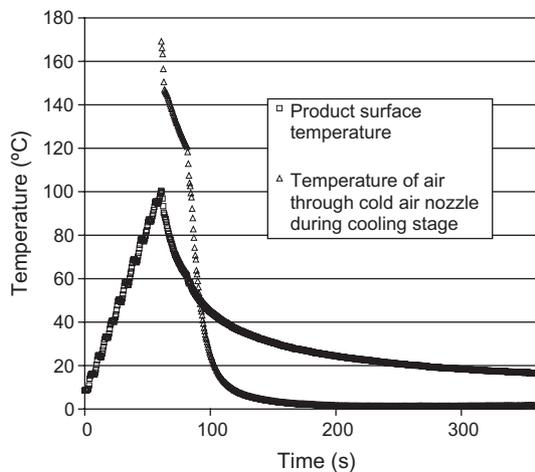


Fig. 8. Temperatures measured on the surface of Tylose and the air exiting the process nozzle for a maximum cooling (uncontrolled) treatment.

513 and to 16.4 °C in 5 min (0.3 K s^{-1}) (Fig. 8). These data
514 were for a sample that had been heated from 5 to
515 100 °C in 60 s (in a controlled, straight line ramp, with-
516 out holding at 100 °C).

517 The rate of cooling was significantly lower than the
518 rate of heating. The reason for the slow cooling is shown
519 by the temperature history of the air exiting the cold
520 nozzle. The cold air was 170 °C at the start of cooling
521 and took a further 31 s to fall below the surface temper-
522 ature of the sample (51 °C). The main reason for this
523 was that the temperature of the cooling nozzle rose sig-
524 nificantly during the heating treatment as it was heated
525 by the hot air from the heating nozzle. This in turn
526 heated the cold air as it was blown into the chamber.
527 The air from the cold air nozzle reached a minimum
528 of 1 °C during the cooling treatment.

529 Fig. 9 shows the temperature history of a sample of
530 Tylose, with a heating treatment of 5–60 °C in 30 s, fol-
531 lowed by holding at 60 °C for 30 s and then a cooling

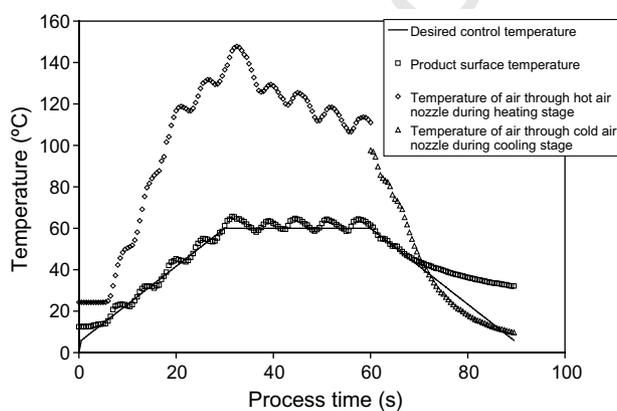


Fig. 9. Temperature history for a Tylose sample with a 5–60 °C in 30 s heating treatment followed by a 30 s holding period and a 60–5 °C in 30 s cooling treatment.

532 treatment of 60–5 °C in 30 s. The temperatures of the
533 air at the exit of both the heating and cooling nozzles
534 are also shown during their respective treatments. The
535 temperature of the sample can be seen to fluctuate above
536 and below the desired control temperature as the heater
537 switches on and off. The average absolute errors were
538 1.7 °C during the heating ramp and 2.4 °C during the
539 holding period. The surface temperature was, on aver-
540 age, higher than the desired control temperature because
541 the rate of heating was much higher than the rate of
542 cooling, meaning that one 0.5 s control increment of
543 heating increased the temperature more than one incre-
544 ment of cooling reduced it. For the first 5 s after holding,
545 the cooling valves cycled on and off to keep the surface
546 at the desired temperature. After this point the actual
547 cooling rate was less than the desired rate and so the
548 cooling was always on.

5.2. Steam 549

550 It is not possible to show the temperature history of
551 the surface during a wet heat experiment, as the IR ther-
552 mometer did not provide a meaningful surface tempera-
553 ture. This is explained in Section 4.10.3.

5.3. Humidity measurements 554

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

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

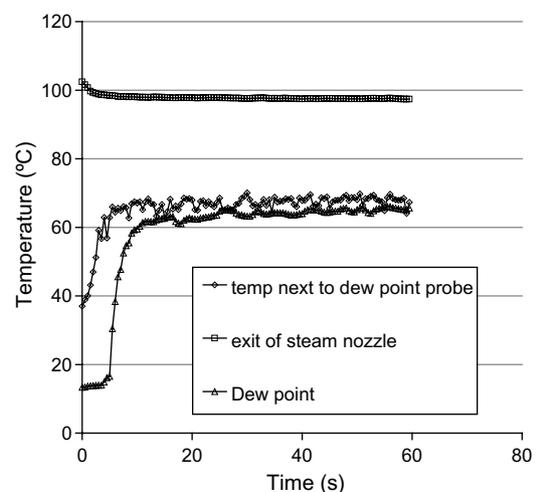


Fig. 10. Temperature history during a wet heat treatment on a Tylose sample.

564 the position of the dew point probe, giving a relative
565 humidity (RH) of nearly 100%. As the product sample
566 was closer to the wet heating stream than the dew point
567 sensor, it was assumed that the RH over the sample was
568 100%.

569 5.4. Uniformity of heating

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

574 5.5. Thermocouple method

575 The aluminium sample used in these experiments was
576 similar to that used in Section 4.10, except that it had a
577 second thermocouple placed 16 mm from the centre, just
578 under the surface. This thermocouple was used to mea-
579 sure either leading or trailing edge temperatures,
580 depending on the orientation of the sample to the hot
581 air nozzle. To avoid breakage of the thermocouples dur-
582 ing these experiments the sample rotation was disabled
583 as in Section 4.10.

584 The advantage of this method was that a history of
585 the temperature uniformity was measured during the en-
586 tire heating process. However, this method was not very
587 comparable to the process that the food samples under-
588 went, as the aluminium sample would have had very dif-
589 ferent thermophysical properties to the foods that were
590 processed in the apparatus and the rotation of the sam-
591 ple was disabled, which would have caused larger tem-
592 perature differences on the surface than if it had been
593 rotating.

594 5.6. Thermal imaging method

595 A thermal imaging camera (ThermaCam E4, FLIR
596 Systems AB, Sweden) was used to determine the temper-
597 atures on the surface of a Teflon sample, after a rapid,
598 high temperature dry heating treatment (20–100 °C in
599 60 s). The camera had been calibrated using radiation
600 sources that are traceable to National Standards. The
601 emissivity of the camera was set to 0.95. It was not pos-
602 sible to take the image to measure temperatures whilst
603 the sample was in the chamber and therefore the sample
604 was removed from the apparatus directly after heating
605 and the thermal image taken as soon as possible. The
606 duration between end of heating and taking the image
607 was 9 s. The same heating treatment was applied to Ty-
608 lose samples with and without sample rotation.

609 The advantage of this method was that real surface
610 temperatures were measured at all positions on the sur-
611 face of a sample that had similar properties on a food
612 product. The only disadvantage was that it was not pos-

sible to measure temperature data using the camera dur- 613
ing the heating process or immediately afterwards. 614

575 5.7. Dry air treatment 615

616 Fig. 11 shows the temperature history during a rapid 616
hot air treatment followed by a holding period using the 617
thermocouple method. The heater was unable to main- 618
tain the specified heating gradient and therefore gave 619
maximum heating until the holding period. The differ- 620
ence between the leading and trailing edge temperatures 621
reached a maximum of 10 °C, 25 s after the treatment 622
started. 623

624 Fig. 12 shows the thermal image 9 s after a rapid hot 624
air treatment with no sample rotation. It can be seen 625
that there is a temperature gradient from top to bottom, 626
representing the leading and trailing edge of the sample. 627
The maximum and minimum surface temperatures of 628

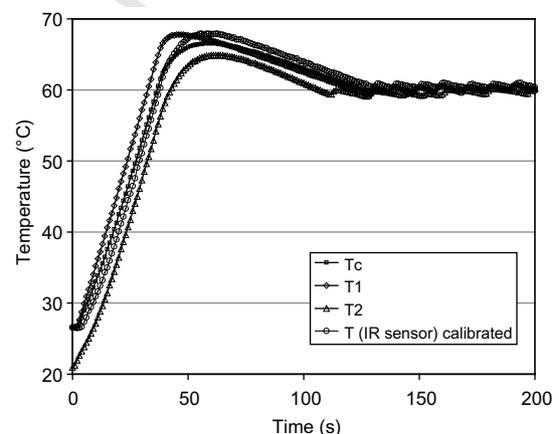


Fig. 11. Temperature history during a fast hot air treatment. Centre thermocouple (Tc), leading edge thermocouple (T1), IR sensor temperature (T(IR sensor)) and trailing edge thermocouple (T2) are plotted.

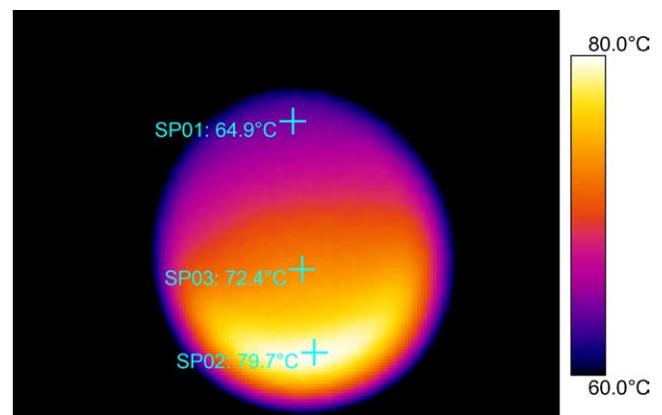


Fig. 12. Temperature uniformity taken by a thermal imaging camera, 9 s after heating to 100 °C in 60 s. Sample rotation was disabled.

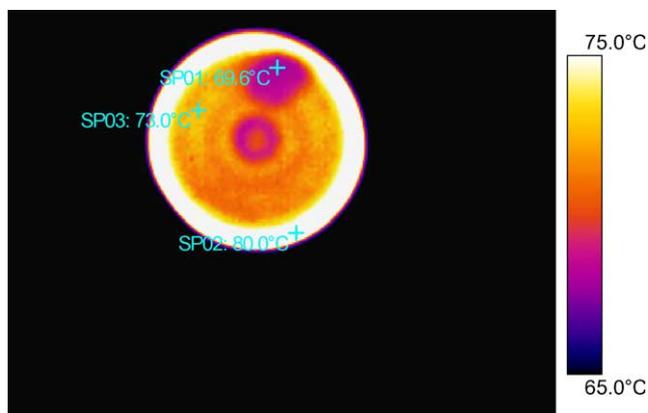


Fig. 13. Temperature uniformity taken by a thermal imaging camera, 9 s after heating to 100 °C in 60 s.

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

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

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

644 5.7.1. Wet treatment

645 Fig. 14 shows the temperature history during a 60 s
646 steam treatment using the thermocouple method. The
647 temperature exiting the steam nozzle reached 100 °C
648 after 2 s. There was a difference between leading and

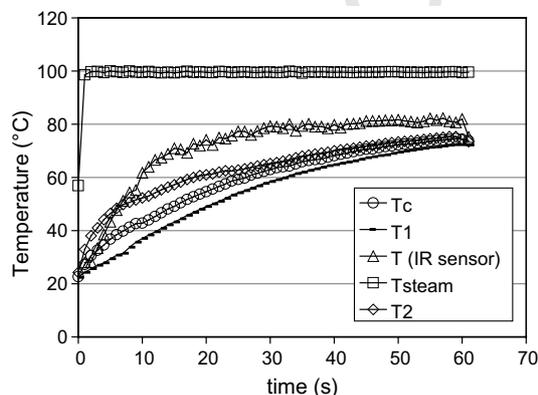


Fig. 14. Temperature history during a 60 s steam treatment. Steam temperature (T_{steam}) centre thermocouple (T_c), trailing edge thermocouple (T_1), IR sensor temperature (T (IR sensor)) and leading edge thermocouple (T_2) are plotted.

trailing edge temperatures that reached a maximum of 649
18 °C, 7 s after the treatment started. 650

6. Discussion and conclusion 651

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

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

665 Surface temperatures were controlled using tempera-
666 tures measured by a calibrated IR thermometer during
667 the dry experiments. It was not possible to obtain reli-
668 able measurements from the IR thermometer during
669 wet heating treatments and so these treatments were
670 controlled on duration only.

671 The apparatus was shown to heat a Tylose (meat sim-
672 ulant) sample from 9 to 100 °C at a rate of up to
673 3.6 K s^{-1} and cool it to 40 °C at a rate of up to
674 1.2 K s^{-1} then to 16.6 °C at a rate of up to 0.3 K s^{-1} .
675 Temperature control to a defined ramp was achieved
676 at an average accuracy of 1.7 °C and 2.4 °C on the sam-
677 ple surface, during heating and holding periods,
678 respectively.

679 It was not possible to measure temperature uniform-
680 ity during a real treatment on real food. A maximum
681 surface temperature difference of 10 °C and 18 °C were
682 recorded (with thermocouples) for air and steam respec-
683 tively, just under the surface of an aluminium sample
684 without sample rotation. Thermal imaging allowed tem-
685 peratures across the surface of a Tylose sample to be
686 measured 9 s after a rapid heating treatment. These
687 showed a large temperature difference of 14.8 °C be-
688 tween the leading and trailing edge without sample rota-
689 tion, but a much smaller temperature difference of
690 3.4 °C with sample rotation.

691 Delivering the treatment streams across (parallel to)
692 the surface of the sample allowed the space above the
693 sample to be used for surface temperature measurement
694 using an IR thermometer and viewing with a light sensi-
695 tive camera. However, delivering the treatment streams
696 across the surface was not ideal, as it led to uneven sur-
697 face temperatures. Temperature uniformity was greatly
698 increased by sample rotation although this did not
699 allow measurement of sample temperatures with
700 thermocouples.

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

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

713 7. Uncited references

714 Soto and Borquez (2001)

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