Ultrasonic vibration-assisted pelleting of cellulosic biomass for ethanol manufacturing: an investigation on pelleting temperature

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ABSTRACT: Ethanol made from cellulosic biomass is an alternative to petroleum-based liquid transportation fuels. However, large-scale manufacturing of cellulosic ethanol is hindered by the low density of cellulosic biomass. Experiments have shown that ultrasonic vibration-assisted (UV-A) pelleting could compress low-density raw biomass into high-density pellets, and pelleting temperature increased during pelleting process. However, pelleting temperature was not fully investigated. This paper reports an investigation on pelleting temperature in UV-A pelleting of wheat straw. The precision of temperature measurement was first evaluated. Relationships between pelleting temperature and pelleting time were then investigated. Also, the pattern of pelleting temperature distribution was evaluated by ranking the pelleting temperatures at six different locations in a pellet. Finally, effects of three input variables (ultrasonic power, pelleting pressure, and pellet weight) on pelleting temperature were discussed. Results reported in this paper are the foundation of a follow-up paper reporting relationship between pelleting temperature and pellet quality (density, durability, and sugar yield).

Keywords biomass, ethanol, pelleting, temperature, ultrasonic vibration

1 INTRODUCTION

Ethanol produced from cellulosic biomass (herbaceous, woody, and generally inedible portions of plant matter) is an alternative to petroleum-based liquid transportation fuels. Land resources in the U.S. are sufficient to sustain production of enough biomass annually to displace 30% or more of the nation's current petroleum consumption¹. Furthermore, manufacturing and using of cellulosic ethanol can mitigate the accumulation of greenhouse gas in the atmosphere and benefit rural economy^{2,3}.

Major steps for manufacturing of cellulosic ethanol are shown in Figure 1. One major challenge to cost-effective manufacturing of cellulosic ethanol is high transportation and storage costs caused by low density of raw cellulosic biomass (ranging from 24 to 266 kg/m³)⁵. Pelletizing processes can effectively increase density of cellulosic biomass to higher than 600 kg/m³⁶⁻⁹. In turn, costs for transporting and storing of pelleted cellulosic biomass are less than 1/2 and 1/10 of those of raw cellulosic biomass respectively^{11,12}. In addition, pellets with uniform size and shape are easier to handle with existing equipment for grain processing than raw cellulosic biomass⁶.

Several traditional pelletizing methods have been reported in the literature, including ring-die pelletizing^{6, 13-15}, flat-die pelletizing^{13, 14}, screw extrusion^{15, 17}, piston press¹⁸, and roll press¹⁶. For these pelletizing methods, in general, biomass needs to be heated (by high-temperature steam or heated dies) to a high temperature to achieve good pellet quality¹⁶. Faborode¹⁹ reported that biomass should be heated to 100°C to produce high pellet density and durability. Reece²⁰ reported that heating biomass to 60 – 70°C was needed to produce stable pellets. Peng²¹ reported that pellet density correlated with pelletizing temperature. A possible reason for this is that high temperature could melt lignin (a major component in biomass) which would exhibit thermosetting properties and act as the binder material for biomass particles to form pellets²². The glass transition temperature of lignin is 60-140°C depending on moisture content of biomass²¹.

Ultrasonic vibration-assisted (UV-A) pelletizing is a new pelletizing method (in lab-scale) which uses an ultrasonically vibrating tool to compress biomass into pellets (more detailed information about UV-A pelletizing will be provided in Section 2). Unlike most traditional pelletizing methods in which biomass is heated before being compressed, UV-A pelletizing uses unheated biomass as feedstock and produces pellets whose density (>1000 kg/m³) and durability (>90%) are comparable to those produced by traditional pelletizing methods (ring-die pelletizing)^{7-9, 24}. In addition, a previous study reported that cellulosic biomass (switchgrass, corn stover, sorghum stalk) processed by UV-A pelletizing produced 20% higher sugar yield than that not processed by UV-A pelletizing^{7,8}.

Table 1 summarizes the input and output variables in UV-A pelletizing that have been investigated. There are few studies that investigated temperature in UV-A pelletizing. Preliminary study shows charring of biomass (due to too high temperature) caused deterioration of pellet density and durability^[25, 40]. Feng et al.³⁹ investigated the effects of input variables of UV-A pelletizing on mold temperature (the mold was used to contain biomass in UV-A pelletizing). However, the results cannot reflect the temperature of biomass in UV-A pelletizing. Tang et al.⁴⁰ measured temperature of biomass in UV-A pelletizing. However, their measurements were taken under one specific pelletizing condition. So far, there is no systematic study in the literature on temperature of biomass in UV-A pelletizing. Since temperature generated in pelletizing process may correlate with pellet quality^[5, 16, 41], more investigation about pelletizing temperature and temperature distribution in UV-A pelletizing should be studied first.

This paper reports results of a study whose objective is to investigate: (1) relationships between pelleting temperature (the temperature of biomass during UV-A pelleting) and pelleting time (the period of time when biomass is treated by UV-A pelleting), (2) effects of three input variables (ultrasonic power, pelleting pressure, and pellet weight) on pelleting temperature, and (3) the distribution of pelleting temperature in a pellet in UV-A pelleting. Results reported in this paper are foundation of a follow-up paper reporting effects of pelting temperature on pellet quality (density, durability, and sugar yield).

2 MATERIAL AND METHODS

2.1 Experimental procedure

The experimental procedure is shown in Figure 2. Raw wheat straw was milled into particles and prepared for UV-A pelleting in three steps: harvesting of raw biomass (wheat straw), milling of raw biomass into particles, and adjusting of biomass moisture content. The prepared wheat straw particles were processed by UV-A pelleting under eight different pelleting conditions (with three input variables and two levels for each input variable). Four replication runs of UV-A pelleting were conducted under each pelleting condition. For each run, pelleting temperature was measured.

2.2 Preparation of wheat straw

The wheat straw used in this investigation was harvested and collected at Deines Farm in Northwest Kansas in late June of 2012. It had been run through a John Deere 9600 combine. The combine separated the grains from the straw and chaff. Wheat straw and chaff exited through the back of the combine. The straw chopper on the combine was disconnected to allow the straw to be baled. The average length of the wheat straw was 17 - 25 cm. After being collected, the wheat straw was transported to the lab in Durland Hall at Kansas State University.

The wheat straw was milled into small particles using a hammer mill (Model 5 from Meadows Mill Inc., North Wickeabord, NC, USA) using a sieve with size of 2 mm. The hammer mill used a 240-volt, 5-horsepower electric motor with a fixed rotation speed (3600 rpm). As shown in Figure 3, 24 hammers were mounted on the rotating shaft and were free to swing. The size of these hammers was $101.6 \times 25.4 \times 4.8$ mm. The wheat straw was fed into the milling chamber from the top of the hammer mill. The rotating hammers impacted the wheat straw to reduce the particle size. Particles would pass through the sieve at the bottom of the milling chamber if they were smaller than 2 mm. The milled wheat straw was kept in sealed plastic bags at room temperature.

Moisture content of biomass represents the amount of moisture (water) contained in a certain amount of biomass. Moisture content of the wheat straw after milling was measured as 5% by following the ASABE Standard S358.2⁴² and adjusted to 10% by following the procedure described in NREL LAP⁴³.

2.3 Experimental set-up for UV-A pelleting

Pelleting was performed on a modified ultrasonic machine (model AP-1000, Sonic-Mill, Albuquerque, NM, USA). Figure 4 is a schematic illustration of the experimental set-up for UV-A pelleting. The ma-

chine was composed of two systems: an ultrasonic-vibration generation system, and a pneumatic loading system.

The ultrasonic-vibration generation system was consisted of three major parts: a power supply, a converter, and a pelleting tool. The power supply converted 60-Hz electrical power into 20-kHz electrical power. The converter converted high-frequency electrical energy into mechanical motion. The pelleting tool was made from titanium. It was connected to the converter and used to compress biomass. The tip of the tool was a solid cylinder (17.4 mm in diameter) with a flat end.

The pneumatic loading system was consisted of three major parts: an air compressor (1.2 kw, 125 liter, Sears, Roebuck and Co., Hoffman Estates, IL, USA), a pressure regulator, and a pneumatic cylinder (104.4 mm in diameter). Air pressure in the air compressor was set at 0.8 MPa (120 psi). The pressure regulator controlled the air pressure in the pneumatic cylinder. The pneumatic cylinder was driven by the compressed air and pushed the pelleting tool against biomass in a mold. The mold, as illustrated in Figure 5, was consisted of two pieces. When the two pieces were assembled together, they formed two slots (the width of the slots was 2 mm) and a cylinder cavity (the diameter of the cavity was 18.6 mm). Before pelleting, the mold was clamped by a fixture on to the machine.

The temperature measurement system was consisted of three major parts: thermocouples, a thermometer, and a computer with data acquisition software package. Four thermocouples of metal wire-type (K-type, Model SC-GG-K-30-36, OMEGA Engineering, Inc, Stamford, CT, USA) were inserted in pellets through the slots of the mold. The thermometer (Fluke, HH147U, OMEGA Engineering, Inc., Stamford, CT, USA) had four channels and each channel was connected with one thermocouple. The measured data were recorded by the data acquisition software package (Temp Monitor_S2, OMEGA Engineering, Inc., Stamford, CT, USA) with a frequency of one measurement per second. The recorded temperature data were saved in an Excel file.

2.4 Input variables in UV-A pelleting and their values

Three input variables were selected in UV-A pelleting: ultrasonic power, pelleting pressure, and pellet weight. Ultrasonic power was the power provided by the power supply. It controlled the amplitude of tool vibration in UV-A pelleting. A larger ultrasonic power would result in a larger vibration amplitude. Ultrasonic power was expressed as a percentage of the maximum ultrasonic power for the power supply. It could be adjusted from 0 (no ultrasonic power) to 100% (the maximum ultrasonic power). Pelleting pressure was the pressure in the pneumatic cylinder. A higher pelleting pressure means that a higher air pressure in the pneumatic cylinder applied on the tool. The air pressure in the pneumatic cylinder can be adjusted from 0 to 0.34 MPa (50 psi) by the regulator. Pellet weight was the weight of the wheat straw particles used to make a pellet.

Table 2 lists the values of the three input variables. Ultrasonic power was from 20% to 60%. 20% ultrasonic power was the lowest value applicable for making good-quality pellets, and 60% was the highest value which would not generate charring of biomass (a phenomenon of biomass burning due to extremely high pelleting temperature, more information about charring of biomass in UV-A pelleting can be found elsewhere ²⁵). Pelleting pressure was from 0.14 to 0.34 MPa (20 to 50 psi). Any pressure below 0.14 MPa was too low to make pellets and 0.34 MPa was the highest value available for the machine.

Pellet weight was from 1.4 to 2.6 g. On the one hand, if pellet weight was less than 1.4 g, it was difficult to put three thermocouples in biomass. On the other hand, it was difficult to put more than 2.6 g of biomass in the mold. Table 3 lists the eight pelleting condition (a 2³ full factorial design) with three input variables and two levels for each variable. Levels of the three input variables are: 60% (+) and 20% (-) for ultrasonic power, 0.34 MPa (+) and 0.14 MPa (-) for pelleting pressure, and 2.6 g (+) and 1.4 g (-) for pellet weight.

2.5 Temperature measurement

Recording of temperature data started when ultrasonic power was turned on and lasted for 180 seconds (which was the longest pelleting duration used in one run of UV-A pelleting in previous studies). For each pelleting condition, pelleting temperature was measured at six locations in a pellet based on an assumption that temperature distribution is symmetric in a pellet. As shown in Figure 6, top center (TC), middle center (MC), and bottom center (BC) were located at the center axis of a pellet. Top side (TS), middle side (MS), and bottom side (BS) were at the side (2 mm away from the mold) of a pellet. It was ensured that thermocouples were not in contact with the mold or the pelleting tool because direct contact could adversely affect the accuracy of measurements. However, pelleting temperature was measured at four locations for each replication run because only four thermocouples could be used at same time.

In each run, 0.2 gram of wheat straw particles was first loaded in the mold. Then, two thermocouples were placed at BC and BS. When pellet weight was 1.4 gram, 0.5 gram of wheat straw particles was put between MC (MS) and BC (BS), and another 0.5 gram between MC (MS) and TC (TS). When pellet weight was 2.6 gram, 1.1 gram of wheat straw particles was put between MC (MS) and BC (BS), and another 1.1 gram between MC (MS) and TC (TS). Finally, 0.2 gram of wheat straw particles was loaded above TC and TS.

3 Results and discussion

3.1 Precision of the measurements

Under each pelleting condition, similar temperature-time curves were obtained for four replication runs. This indicates that high precision (or good repeatability) in temperature measurements was obtained. To illustrate the precision of the measurements, the temperature-time curves under two pelleting conditions are shown in Figures 7 and 8. The condition (pressure = 0.14 MPa, ultrasonic power = 20%, and pellet weight = 1.4 g) for Figure 7 had the best precision, and the condition (pressure = 0.34 MPa, ultrasonic power = 60%, and pellet weight = 1.4 g) for Figure 8 had the worst precision among measurements under all the test conditions.

In Figure 7, the same shape of temperature-time curves at all locations was obtained for all four runs. It can be seen that there was a rapid increase in temperature at five locations (Tmc, Tms, Tts, Tbc, and Ttc) during the first 60 seconds and a gradual increase afterwards. In contrast, for all four replication runs, Tbs showed a consistently gradual increase over the entire pelleting duration. In addition, the overall rate of temperature increase at the six locations has the same order (Tmc > Tms > Tts > Tbc > Tts > Tbs). The average and standard deviation of the measurement data at the end of pelleting time are shown in Table 4. The standard deviations at all locations were smaller than 3°C.

In Figure 8, the same shape of temperature-time curves at all locations was obtained for all four runs. The temperatures at four locations (T_{mc}, T_{ms}, T_{bc}, and T_{bs}) underwent an initial increase followed by a decrease. In contrast, the temperatures at the other two locations (T_{tc} and T_{ts}) underwent a consistent increase. However, these four runs did not share the same order of the temperatures at different locations at the end of pelleting duration. The order in the fourth run (T_{mc} > T_{ts} > T_{ms} > T_{bc} > T_{tc} > T_{bs}) was slightly different from those in the other three runs (T_{mc} > T_{ts} > T_{tc} > T_{ms} > T_{bc} > T_{bs}). The average and standard deviation of the measurement data at the end of pelleting duration are shown in Table 5. The standard deviations were larger than those in Table 4 but smaller than 10°C.

The precision of the temperature measurements for other conditions was between those for the two conditions described above. Overall, a good precision in temperature measurement was achieved using the experimental setup. Under each pelleting condition, the temperature-time curves obtained from different runs had the same shape. Therefore, one measurement from each pelleting condition was conducted and used in the following discussions.

3.2 Relationships between pelleting temperature and pelleting time

The relationships between pelleting temperature and pelleting time are presented as temperature-time curves shown in Figures 9–14 for each location under eight pelleting conditions. These curves can be classified into three basic groups based on two attributes of their shapes (increasing rate of temperature and existence of decline in pelleting temperature): (a) pelleting temperature increases rapidly during the first 60 seconds, then increases slowly, and becomes constant eventually; (b) pelleting temperature increases consistently slowly for almost the entire duration, and becomes constant eventually; and (c) pelleting temperature increases rapidly during the first 60 seconds, then decreases slightly, and remains constant eventually. For each combination of measurement location and pelleting condition, the increase speed of temperature and highest temperature point in each location during the pelleting time (180 seconds) are different in this study.

The majority of the curves in Figures 9–14 belong to group (a), including conditions 1–8 in Figures 9 and 10, conditions 1-3, 6, and 8 in Figures 11 and 12; conditions 1, 3, and 8 in Figure 13; and conditions 1 and 3 in Figure 14. Group (b) includes conditions 5 and 7 in Figures 11–13, and conditions 5, 7, and 8 in Figure 14. Group (c) includes condition 4 in Figures 11 and 12, and conditions 2, 4, and 6 in Figures 13 and 14.

Tang et al.⁴⁰ reported the temperature-time curves for four positions (TC, MC, BC, and BS) under one pelleting condition (pelleting pressure = 0.28 MPa, ultrasonic power = 40%, and pellet weight = 2 g). The shape of three curves reported (MC, BC, and BS) was consistent with that obtained in this study. However, the shape of their TC curve (belonging to group (c)) was different from that of TC curve obtained in this study (belonging to group (a)). It is noted that the thermocouple at TC contacted the pelleting tool in their study but not (there was 0.2 g of biomass between the thermocouple and the pelleting tool) in this study. This could lead to two possible explanations for the inconsistent curve shape at TC. First, T_{tc} in these two studies refers to the temperature at different locations—at very top of pellet in Tang et al.'s study and at a certain distance (the height of 0.2-gram biomass) away from the very top of pellet. Second, the direct contact between the thermocouple and the metal pelleting tool could probably affect the temperature measurement, resulting in changed curve-shape.

From Figures 9–14 it can be seen that, for each location and each pelleting condition, the temperature at the end of pelleting duration was higher than the initial temperature, indicating that UV-A pelleting increased biomass temperature as time increased. Also, pelleting temperature became constant sooner or later regardless of the position and pelleting condition, indicating that a thermal balance (the heat generated equaled the heat dissipated) in a pellet was achieved during UV-A pelleting. Furthermore, the highest pelleting temperature occurred during the first 180 seconds in UV-A pelleting. These findings are consistent with the results reported by Tang et al.⁴⁰.

Under some pelleting conditions, a slight decline in pelleting temperature in the middle stage of pelleting duration was observed at some locations. Such decline was not observed for any condition at TC and TS. It was observed under condition 4 at MC and MS, and under conditions 2, 4, and 6 at BC and BS. The decline in pelleting temperature occurred more frequently at the bottom of a pellet. This is possibly due to the fact that the heat dissipation at the bottom of a pellet was faster than that at the middle or top of a pellet (because the contact surface between the bottom of a pellet and the mold was much larger than that between the middle or top of a pellet and the mold). It was also observed that the decline in pelleting temperature occurred only when the higher ultrasonic power (60%) was used. Under condition 4, the decline in pelleting temperature was found at four locations (MC, MS, BC, and BS); under conditions 2 and 6, the decline in pelleting temperature was found only at BC and BS.

3.3 Rank of pelleting temperature at different locations

Pelleting temperatures at different locations were ranked to describe a basic pattern of biomass temperature distribution in UV-A pelleting. Given that the highest pelleting temperature generated was of high interest in UV-A pelleting (the highest pelleting temperature was closely related to pellet charring²⁵), the temperatures at different locations were ranked based on the highest pelleting temperature obtained during the entire pelleting time.

Under each pelleting condition, ANOVA was performed to compare pelleting temperature at each location using Tukey's method⁴⁴ at significance level of 0.05. The temperatures were then ranked based on the comparison results. Table 6 shows the ranked temperatures at different locations. Under each condition, MC was the highest or one of the highest among the six temperatures, and BS was the lowest or one of the lowest. This indicates that the highest temperature always occurred in the pellet's core, primarily because the increasing rate of T_{mc} was much higher than those of temperatures at other locations. This result can explain the finding in our previous study²⁵ that charring in UV-A pelleting always started in a pellet's core.

In general, the temperatures at the other four locations (T_{tc} , T_{ts} , T_{ms} , and T_{bc}) were between T_{mc} and T_{bs} . When the lower pelleting pressure (0.14 MPa) was used (under conditions 1, 2, and 6), T_{ms} was significantly higher than T_{bc} , T_{tc} , and T_{ts} . When the higher pelleting pressure (0.34 MPa) was used (under conditions 3, 4, and 8), there was no significant difference between T_{ms} , T_{bc} , T_{tc} , and T_{ts} . This indicates that a higher pelleting pressure could make pelleting temperature more evenly distributed in a pellet. When the lower ultrasonic power (20%) and larger pellet weight (2.6 g) was used (under conditions and 7), there was no significant difference between T_{tc} , T_{ts} , T_{mc} , and T_{ms} ; but they were significantly higher than T_{bc} and T_{bs} .

3.4 Effects of input variables on pelleting temperature

Ultrasonic power significantly affects on pelleting temperature. Increasing rate of pelleting temperature during the first 60 seconds was greatly affected by ultrasonic power. It can be seen from Figure 9-14. For each location, the increasing rate when the higher ultrasonic power (60%) was used (at condition 1, 3, 5, and 7) was much higher than that when the lower ultrasonic power (20%) was used (at condition 2, 4, 6, 8).

For Figure 9-14, there was no obvious effect of pelleting pressure on the increasing rate at each location (after comparing condition 1 vs. condition 3, condition 2 vs. condition 4, condition 5 vs. condition 7, and condition 6 vs. condition 8). Furthermore, effects of pellet weight on the increasing rate depended on the ultrasonic power used. When the lower ultrasonic power (20%) was used, effect of pellet weight did not obviously affect the increase rate of temperature (after comparing condition 1 vs. condition 5, and condition 3 vs. condition 7). When the higher ultrasonic power (60%) was used, the increasing rate of temperature for smaller pellet weight (1.4 g) was higher than that for larger pellet weight (2.6 g) for most locations (TC, MC, MS, BC, and BS). An opposite trend was obtained for TS. Under the same pelleting condition, the increasing rate was different at different locations. For example, under condition 4 (ultrasonic power = 60%, pelleting pressure = 0.34 MPa, and pellet weight = 1.4 g), the increasing rate at MC was the highest, followed by MS, BC, TC, TS, and BS.

4 Conclusions

This paper reports an investigation on biomass temperature in ultrasonic vibration-assisted (UV-A) pelleting of cellulosic biomass. The following conclusions can be drawn:

(1) A good precision in temperature measurement could be achieved using the experimental setup used in this study.

(2) The obtained temperature-time curves could be classified into three groups based on their shapes. The curve shape depended on both measurement location and pelleting condition. For each combination of measurement location and pelleting condition, the speed of temperature increase and highest temperature point in each location during the pelleting time (180 seconds) are different in this study.

(3) In UV-A pelleting, the highest pelleting temperature always occurred at the middle center (the core) of a pellet. The lowest pelleting temperature always occurred at the bottom side of a pellet. The distribution of pelleting temperature (presented by the rank of pelleting temperatures at the six locations) was affected by pelleting condition. When a high level of pelleting pressure was used, pelleting temperature was more evenly distributed in a pellet, meaning that there was no significant difference in pelleting temperature between the four locations (TC, TS, MS, and BC).

(4) Pelleting temperature in UV-A pelleting was significantly affected by ultrasonic power. At certain condition, pellet weight also affected the speed of temperature increase under certain pelleting conditions.

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Notes

The authors declare no competing financial interest.

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Figure 1 Major steps for manufacturing of cellulosic ethanol (after [3, 4]).

Figure 2 Experimental procedure

Figure 3 Illustration of hammer milling

Figure 4 Illustration of experimental set-up for UV-A pelleting

Figure 5 Illustration of the mold used for temperature measurement

Figure 6 Illustration of the six locations in a pellet where temperatures were measured

Figure 7 Temperature-time curves under the best-precision condition

Figure 8 Temperature-time curves under the worst-precision condition

Figure 9 Temperature-time curves at top center

Figure 10 Temperature-time curves at top side

Figure 11 Temperature-time curves at middle center

Figure 12 Temperature-time curves at middle side

Figure 13 Temperature-time curves at bottom center

Figure 14 Temperature-time curves at bottom side

Table 1. Investigated input and output variables in UV-A pelleting

Output variable	Input variable						Reference
	Biomass type	Moisture content	Particle size	Pellet weight	Pressure	Ultrasonic power	
Charring	√	√	√			√	(25)
Density	√	√	√	√	√	√	(7,26-32)
Durability		√	√	√	√	√	(7,27,29-31,33)
Power consumption	√	√	√		√	√	(34-36)
Stability		√	√		√	√	(9,27,29-32)
Sugar yield		√	√		√	√	(9,30,31,37,38)
Temperature		√	√		√	√	(39,40)

Table 2 Input variables and their values

Variable	Unit	Value
Pressure	MPa	0.14; 0.34
Ultrasonic Power	%	20; 60
Weight	g	1.4; 2.6

Table 3 Values of input variables for each pelleting condition

Condition #	Ultrasonic power (%)	Pelleting pressure (MPa)	Pellet weight (g)
1	20	0.14	1.4
2	60	0.14	1.4
3	20	0.34	1.4
4	60	0.34	1.4
5	20	0.14	2.6
6	60	0.14	2.6
7	20	0.34	2.6
8	60	0.34	2.6

Table 4 Temperature measurements (°C) under the best-precision condition

Run #	Bottom side	Bottom center	Middle side	Middle center	Top side	Top center
1	33.8	50.7	63.4	75.1	53.0	48.8
2	32.8	54.6	64.5	73.0	56.8	47.1
3	36.4	50.2	61.0	73.8	52.3	49.2
4	33.3	55.3	59.7	73.1	53.4	53.7
Mean	34.1	52.7	62.2	73.8	53.9	49.7
Standard deviation	1.6	2.6	2.2	1.0	2.0	2.8

Table 5 Temperature measurements (°C) under the worst-precision condition

Run #	Bottom side	Bottom center	Middle side	Middle center	Top side	Top center
1	65.9	87.8	101.8	127.5	113.5	113.4
2	68.0	91.8	103.0	126.9	106.2	106.7
3	66.3	86.3	106.5	133.4	116.9	111.4
4	55.8	88.2	104.6	128.0	107.0	95.3
Mean	64.0	88.5	104.0	129.0	110.9	106.7
Standard deviation	5.5	2.3	2.0	3.0	5.2	8.1

Table 6 Rank of temperatures at different locations

Condition	Rank of temperature*
1	MC > MS > (BC,TC,TS) > BS
2	MC > MS > (BC,TC,TS) > BS
3	MC > (MS,BC,TC,TS) > BS
4	MC > (MS,BC,TC,TS) > BS
5	(TC,TS, MC, MS) > (BC,BS)
6	MC > MS > (BC,TC,TS) > BS
7	(TC,TS, MC, MS) > (BC,BS)
8	MC > (MS,BC,TC,TS) > BS

* The symbol ">" means "significantly higher than (at the significance level of 0.05)", and the temperatures encapsulated in one pair of parentheses are not significantly different from each other.