CONTACT HEAT TRANSFER COEFFICIENT DURING DOUBLE-SIDED COOKING OF HAMBURGER PATTIES

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ABSTRACT

Contact heat transfer coefficient values during double-sided contact cooking of hamburger patties were calculated from grill plate temperatures, patty surface temperatures, and heat flux values. The patties were cooked for 130 s using different top and bottom grill plate temperatures (177C, 191C, or 204C) and gap thicknesses between plates (10.0 mm, 10.5 mm, or 11.0 mm). Heat transfer coefficient values obtained were in the range of 250 to 650 W/m²C, depending on the cooking conditions. After reaching a maximum value, the coefficient decreased and reached an asymptotic value at the end of the cooking cycle. The maximum heat transfer coefficient values depended on top or bottom grill plates and gap thicknesses between plates. Average heat transfer coefficient values during 80 to 130 s of cooking depended on top or bottom grill plates and set grill temperatures.

INTRODUCTION

Beef hamburgers are popular among consumers. A popular cooking method used in many fast food restaurants is double-sided contact cooking. Because of many outbreaks of food borne disease caused by *Escherichia coli* O157:H7 have occurred in undercooked beef patties (Buchanan and Doyle 1997), the USDA and FDA recommend that ground beef products be cooked to certain minimum temperatures to ensure their microbiological safety (71C for home preparation and 68C with 15 s holding time for foodservice industries). However, to measure the internal temperature may be difficult, especially at the foodservice

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establishments. Mathematical models have been applied as a tool for predicting the internal temperature of beef patties (Dagerskog 1979a; Ikediala *et al.* 1996; Pan 1998; Zorrilla and Singh 2000). The contact heat transfer coefficient is an essential parameter for these models.

The contact heat transfer coefficient or its reciprocal value, called thermal contact resistance, appears between two solids that are not perfectly in contact. There are many difficulties in measuring the contact heat transfer coefficient in food due to its nonhomogeneous composition or to biochemical changes that may take place during a process. Particularly, during hamburger cooking processes, considerable lowering in water-holding capacity and meat shrinkage occur because of protein denaturation (Davídek *et al.* 1990; Lawrie 1998; Beilken *et al.* 1990). Water and fat may be partially squeezed out because of meat shrinkage and external pressure. These phenomena make it difficult to measure the contact heat transfer coefficient during contact cooking of hamburgers (Houšová and Topinka 1985). Most of the research papers address contact between metals under steady state conditions (Madhusudana 1996), but little information is available on contact heat transfer coefficient values for food.

Houšová and Topinka (1985) have shown experimentally that the contact heat transfer coefficient depends on product type, contact plate temperature, contact pressure, and stage in heat treatment. The contact heat transfer coefficient values measured were in the range of 200 to 1200 W/m^{2}C. Dagerskog and Sörenfors (1978) found contact heat transfer coefficient values for cooking of minced meat patty in the range of 260 ± 50 W/m^{2}C during contact cooking and 90 ± 20 W/m^{2}C during cooking in a convection oven. Dagerskog (1979a) obtained contact heat transfer coefficient values in the range of 425 ± 33 W/m^{2}C during double-sided contact frying of meat patties. In contact cooking of hamburger patties, some authors used constant contact heat transfer coefficient values of 300 W/m^{2}C (Dagerskog 1979b), 250 W/m^{2}C (Ikediala *et al.* 1996), and 900 W/m^{2}C (Zorrilla and Singh 2000) for the mathematical models.

Some factors that may affect the contact heat transfer during frying hamburger patties are as follows. (1) Product composition that may affect the cooking loss behavior during cooking (Houšová and Topinka 1985; Dagerskog and Bengtsson 1974; Dagerskog and Sörenfors 1978), and consequently the composition of layer between the hamburger patty and grill plate. (2) Contact plate temperatures that may have an effect on the thermal and physical properties of the contact region (Houšová and Topinka 1985). (3) Contact pressure that may influence the contact between the hamburger patty and grill plate. A higher contact pressure may cause a higher contact area and consequently a higher contact heat transfer (Houšová and Topinka 1985; Dagerskog and Bengtsson 1974; Dagerskog 1979a; Dagerskog and Sörenfors 1978). (4) Surface roughness of both surfaces that may affect the contact area.

The objectives of this study were to obtain contact heat transfer coefficient values under various cooking conditions to determine the changes in heat transfer coefficient during the cooking process and the influence of factors for each cooking condition on heat transfer coefficient.

MATERIALS AND METHODS

Frozen beef patties packed in insulated boxes with dry ice were shipped from a commercial company (Golden State Foods, City of Industry, CA) via overnight mail. Prior to use, the patties were stored in a walk-in freezer at -30C. All experiments were done within 1 week of receiving the patties. The hamburger patties were 11.68 ± 0.44 mm in thickness, 11.83 ± 0.15 cm in diameter, and 15.23 ± 1.08 g in weight. The patties contained 22.06% fat, 16.29% protein, and 61.01% wet basis moisture. A commercial clamshell grill (Taylor Company, Rockton, IL; Model 32) was used for all cooking experiments. The grill has two separated top heating plates covered with Teflon release sheets and one common bottom heating plate. The set grill temperature and gap thickness (the distance between the top and bottom plates during cooking) were controlled by a control panel.

Heat Flux and Temperature Measurements

The heat flux was measured by using a heat flux sensor HFS-23 (Omega Engineering, Stamford, CT). It was assumed that the heat flux sensor does not affect heat transfer to the patty. The heating plates contained K-type thermocouples installed in tiny holes drilled into the plates by the grill manufacturers and located approximately at 6 mm below the grill surface. For all cooking trials, a hamburger patty was placed near the region where one of the thermocouples was located. The temperature recorded by that thermocouple was corrected for conduction (5 to 6C) to obtain the surface temperature of the grill plate. The average temperature difference used for this correction was measured experimentally using a disk-type thermometer (Model 31308KF, type K thermometer, Atkins Technical, Inc., Gainesville, FL) and the temperature recorded by the thermocouples installed in the grill. Perfect contact between grill surface and the disk-type thermometer was assumed. The patty surface temperature was measured by a thermocouple (T-type, Omega Engineering, Stamford, CT), 0.25 mm in diameter, placed between the surface of the hamburger patty and the heat flux sensor. A data acquisition system composed of DataShuttle DS-16-8-TC (Iotech, Inc., Cleveland, OH) and a laptop computer was used for recording the temperatures of the grill plates, surface temperature of the hamburger patty, and temperature and heat flux from the heat flux sensor.

Contact Heat Transfer Coefficient Calculation

The thermal conductance or contact heat transfer coefficient was calculated using Newton's law of cooling:

$$h=\frac{q}{T_{s1}-T_{s2}} \tag{1}$$

where h is contact heat transfer coefficient during cooking a hamburger patty, W/m^{2}C; q is heat flux transferring from the grill plate to a hamburger patty, W/m^2; T_{s1} is grill plate temperature (top or bottom plate), °C; and T_{s2} is patty surface temperature (in contact with the selected grill plate), °C.

Experimental Design

A split-split plot design was applied to 6 replicate experiments. This type of design has been explained by Snedecor and Cochran (1976). The set grill temperature (177C; 191C; 204C) was considered as a main plot. The grill plate (top plate; bottom plate) was considered as a subplot. The gap thickness between the top and the bottom grill plates (10.0 mm; 10.5 mm; 11.0 mm) was considered as a sub-subplot.

Statistical Analysis

Factors considered for affecting contact heat transfer coefficient and its relative variables (grill plate temperature, patty surface temperature, and heat flux) during the cooking process were set grill temperature, grill plate, and gap thickness. The results were based on ANOVA analysis with 95% confidence intervals. TableCurve^{TM}2D (v.4.0, AISN Software, Inc., San Rafael, CA) was used to determine one of the characteristic parameters from the contact heat transfer coefficient profiles. SuperANOVA (v.1.1, Abacus Concepts, Inc., Berkeley, CA), and Minitab (release 12.2, Minitab Inc., State College, PA) were used to obtain statistical analysis.

RESULTS AND DISCUSSION

During cooking of hamburger patties, temperatures of the grill plate, patty surface, and heat flux were recorded. Figure 1 shows typical temperature profiles in a 130-s cooking cycle for one of the replicates. The grill plate temperature started close to the set grill temperature, but dropped from the initial value after a frozen hamburger patty was placed on the grill. It reached an asymptotic value near the end of the cooking cycle. The patty surface temperature started from the initial low temperature and increased rapidly during the first 40 s of cooking. After that, it gradually increased. During the first 40 s of the cooking cycle, the heat from the grill plates was largely used to thaw the frozen hamburger patty. The patty surface temperature increased rapidly until reaching 100C (the boiling point of water). As heat penetrates the frozen patty, two moving boundaries can be distinguished: the thawing and the evaporation boundaries (Singh 2000). After the water was mostly evaporated in the surface layers, the temperature of the patty surface increased to around 110C. The patty surface temperature profiles were similar for all cooking conditions.

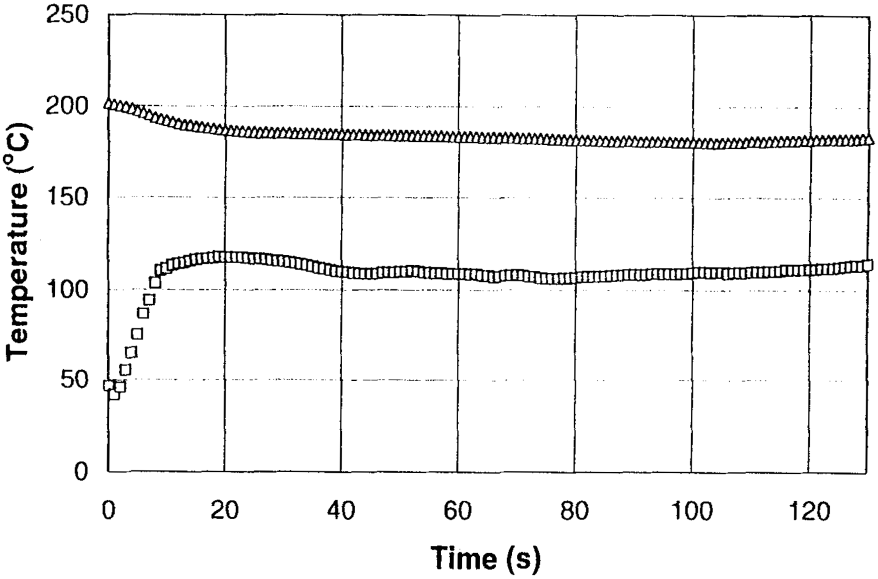

FIG. 1. TEMPERATURE PROFILES FOR 204C SET GRILL TEMPERATURE AND 11.0 MM GAP THICKNESS: (□) PATTY SURFACE TEMPERATURE; (Δ) BOTTOM PLATE TEMPERATURE

The heat flux started increasing until reaching a maximum value, after which it decreased and reached an asymptotic value at the end of the cooking cycle (Fig. 2). The contact heat transfer coefficient, which was obtained by using Newton's law of cooling, had a similar behavior to that of the heat flux, increasing during the cooking time until reaching a maximum value (Fig. 3). Then, it decreased and reached an asymptotic value at the end of cooking cycle.

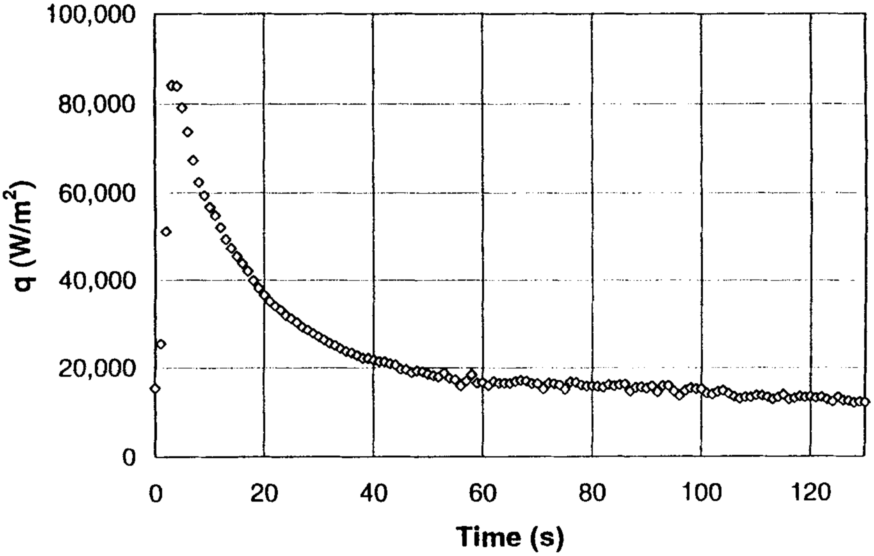

FIG. 2. HEAT FLUX PROFILE INVOLVING THE BOTTOM PLATE FOR 204C SET GRILL TEMPERATURE AT 11.0 MM GAP THICKNESS

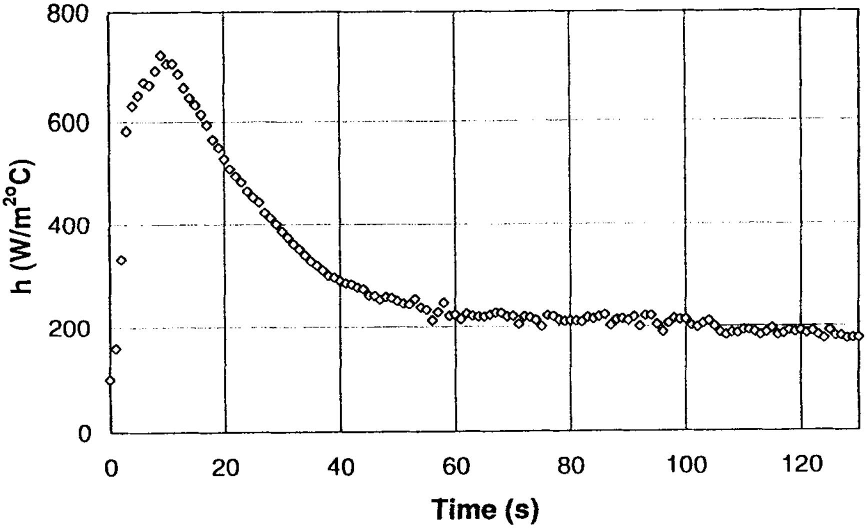

FIG. 3. HEAT TRANSFER COEFFICIENT VALUES INVOLVING THE BOTTOM PLATE FOR 204C GRILL TEMPERATURE AT 11.0 MM GAP THICKNESS

Considering the typical profiles obtained for patty surface temperature, heat flux, and contact heat transfer coefficient, the following parameters were used in the statistical analysis to study the effect of the set grill temperature, grill plate, and gap thickness: t_{100C} which is the time to reach 100C at the surface of a patty, q_{peak} which is the maximum heat flux value, q_{tail} which is the average heat flux during 80- to 130-s cooking cycle, E_{80} which is the energy used for cooking a hamburger patty during the first 80 s of cooking cycle and calculated as the area under the heat flux curve, h_{peak} which is the maximum heat transfer coefficient value, and h_{tail} which is the average heat transfer coefficient during 80- to 130-s cooking cycle.

Effects of Set Grill Temperature

The grill plate temperature in this study was a function of the set grill temperature (177C, 191C, and 204C; Fig. 4). It is hypothesized that the set grill temperature may influence an increase in grill plate temperature during the cooking process. The grill plate temperature affected heat flux (including the energy used for this cooking period) and contact heat transfer coefficient during the cooking process. For heat flux, the increase in q_{peak} values was determined when the set grill temperature increased (Fig. 5). However, the difference of q_{peak} values was not significant when the grill temperature was higher than 191C. The E_{80} values also changed in the same manner (Table 1). A high value for h_{tail} was found when the set grill temperature was low (177C; see Fig. 6). This phenomenon depended only on the temperature difference between the grill plate temperature and patty surface temperature, because the heat flux seemed to be constant during this cooking period. At high temperatures, more dehydration near the patty surface occurs, increasing the cohesive forces of the protein matrix. Therefore, the adhesion to the grill surface may decrease, decreasing the contact area and the contact heat transfer coefficient. This phenomenon needs further investigation. No significant effect on t_{100C}, q_{tail}, and h_{peak}, was observed.

Effects of Grill Plate

Top and bottom plates were considered in this study and were found to affect every parameter. A higher value for every parameter was observed with the bottom plate than with the top plate. The main reason for this was because the Teflon release sheet used to cover the top plate offered some resistance to heat transmitted to the hamburger patty during cooking (Fig. 7 for q_{peak}; Fig. 8 for h_{peak} and h_{tail}). Melted fat and water evaporation may also have some additional effect on the high h values observed when bottom plate was considered.

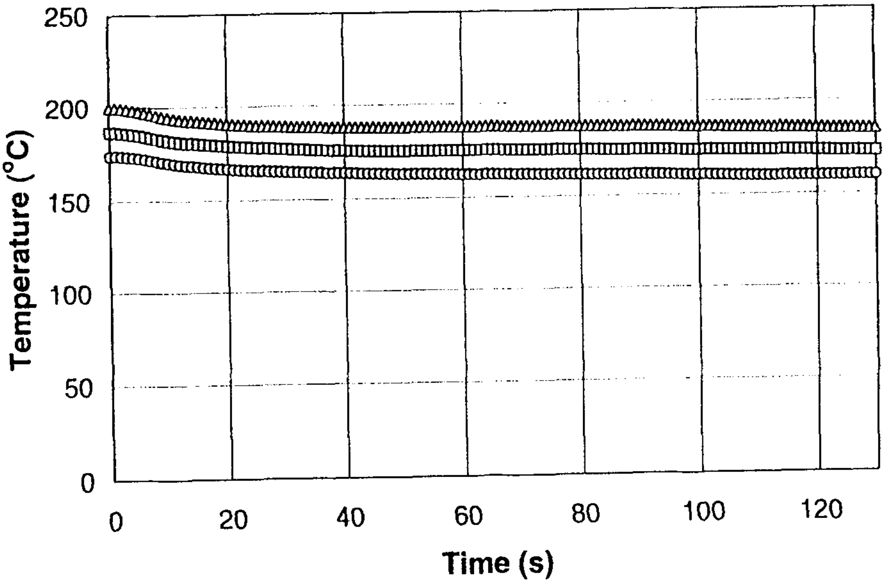

FIG. 4. AVERAGE TEMPERATURES OF TOP PLATE AT DIFFERENT SET GRILL TEMPERATURES: (○) 177C; (□) 191C; (Δ) 204C

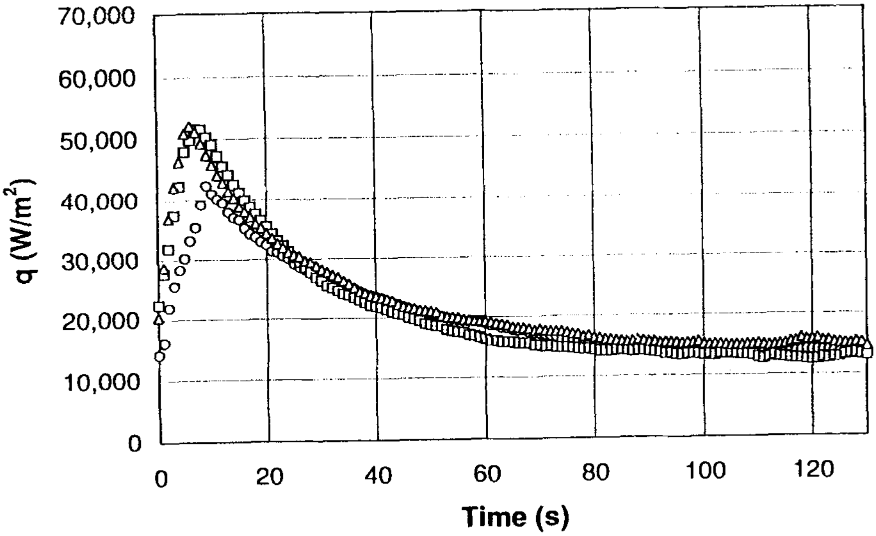

FIG. 5. AVERAGE HEAT FLUX VALUES INVOLVING THE TOP PLATE FOR 11.0 MM OF GAP THICKNESS AT DIFFERENT SET GRILL TEMPERATURES: (○) 177C; (□) 191C; (Δ) 204C

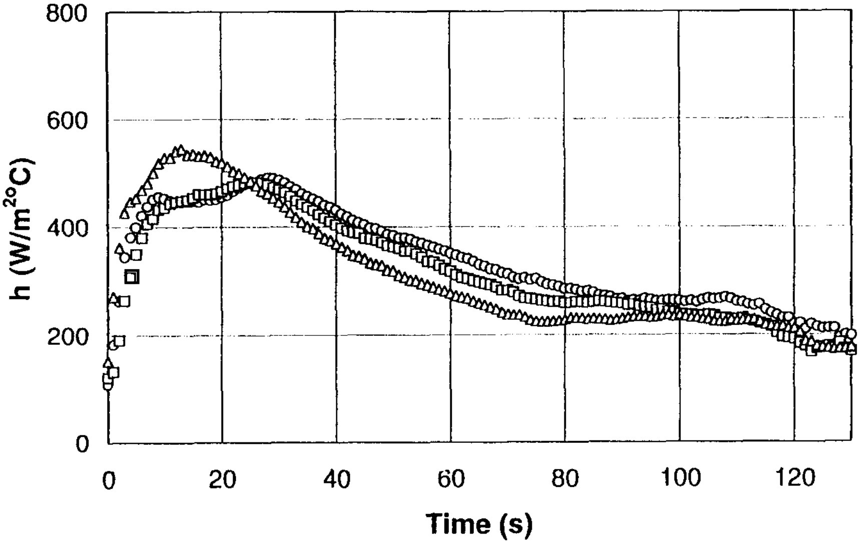

FIG. 6. AVERAGE CONTACT HEAT TRANSFER COEFFICIENT VALUES INVOLVING THE TOP PLATE FOR 10.0 MM OF GAP THICKNESS AT DIFFERENT SET GRILL TEMPERATURES: (○) 177C; (□) 191C; (Δ) 204C

In the case of patty surface temperature, the difference appeared when the temperature reached 100C (t_{100C}; see Fig. 9). This was due to the way the time was recorded. After a patty was placed on the grill surface, the bottom plate heated the bottom surface of a hamburger patty for 4 or 5 s before the top plate closed and touched the top surface of the patty. The recording of time began then. No significant effect on q_{tail} and E_{80}, was observed.

Effects of Gap Thickness

Three gap thicknesses, 10.0 mm, 10.5 mm, and 11.0 mm, were considered in this study. They affected both the heat flux value as energy used for cooking a hamburger patty during the first 80 s of cooking (E_{80}) and the h_{peak} value. The smaller gap thickness resulted in higher values in both parameters compared with the larger gap thickness. For E_{80}, the 10-mm gap thickness resulted a higher E_{80} value compared with the 11-mm gap thickness (Table 2). For h_{peak}, the 10.5-mm gap thickness resulted in a higher h_{peak} value compared with the 11-mm gap thickness (Fig. 10). These may due to the contact pressure between the grill plates and a hamburger patty during cooking. The high compression of the small gap thickness enhanced a better contact between them. No significant effect on t_{100C}, q_{peak}, q_{tail}, and h_{tail}, was observed.

TABLE 1.

MEAN E_{80} VALUES FOR DIFFERENT SET GRILL TEMPERATURES

T (°C)	C	M (kJ/m^2)	STD (kJ/m^2)	SEM (kJ/m^2)
177	36	2,079	181	30
191	36	2,157	148	25
204	36	2,281	284	47

T = set grill temperature; C = the total number of tests used for calculating the mean value; M = the mean value; STD = Standard deviation of the mean value; SEM =Standard error of the mean value.

The heat transfer coefficient values were close to those obtained by other authors in contact cooking studies (Dagerskog and Sörenfors 1978; Dagerskog 1979a; Houšová and Topinka 1985). In this work, the new information obtained on the effect of processing conditions on contact heat transfer coefficient is useful to improve specifications for current equipment and design new equipment. Furthermore, the results are useful for a better understanding of the contact cooking process and for reliable values of variable h for mathematical simulations.

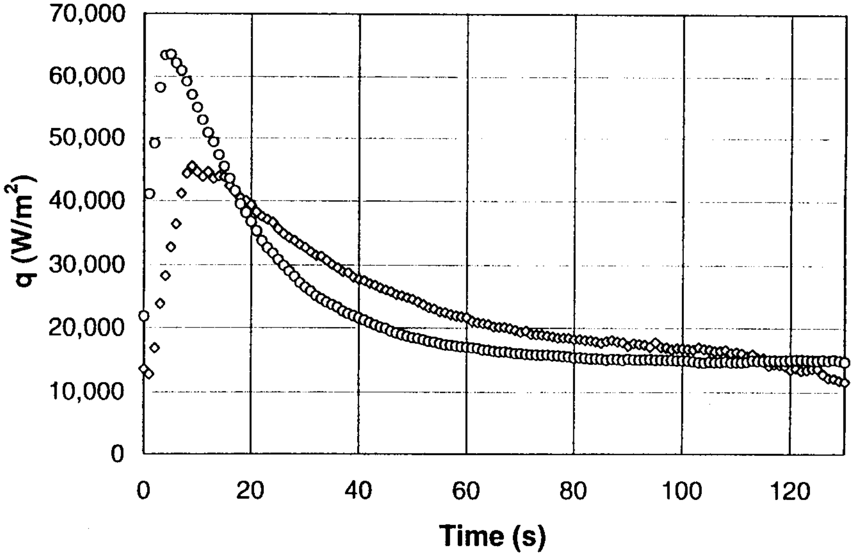

FIG. 7. AVERAGE HEAT FLUX VALUES INVOLVING TOP AND BOTTOM PLATES FOR 204C SET GRILL TEMPERATURE AND 10.5 MM GAP THICKNESS: (◇) TOP PLATE; (○) BOTTOM PLATE

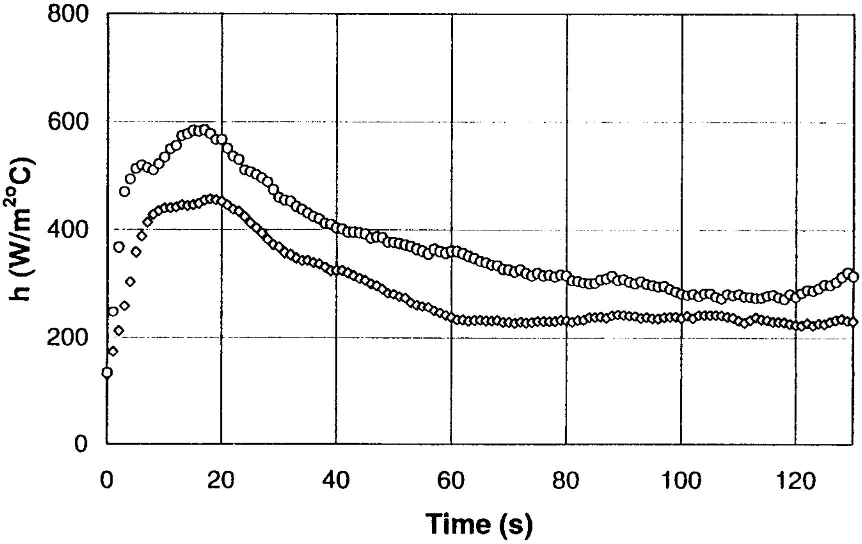

FIG. 8. AVERAGE HEAT TRANSFER COEFFICIENT VALUES INVOLVING TOP AND BOTTOM PLATES FOR 191C SET GRILL TEMPERATURE AT 11.0 MM GAP THICKNESS: (◇) TOP PLATE; (○) BOTTOM PLATE

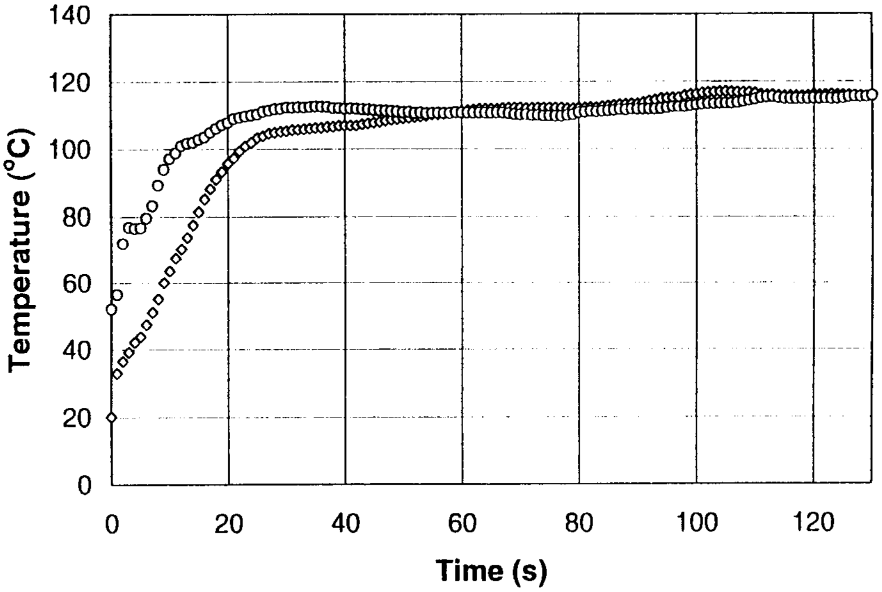

FIG. 9. THE AVERAGE PATTY SURFACE TEMPERATURE INVOLVING TOP AND BOTTOM PLATES FOR 204C SET GRILL TEMPERATURE AND 10.0 MM GAP THICKNESS: (◇) TOP PLATE; (o) BOTTOM PLATE

TABLE 2.
MEAN E_{80} VALUES FOR DIFFERENT GAP THICKNESSES

G (mm)	C	M (kJ/m^2)	STD (kJ/m^2)	SEM (kJ/m^2)
10.0	36	2,226	210	35
10.5	36	2,160	193	32
11.0	36	2,131	265	44

G = gap thickness; C = the total number of tests used for calculating the mean value; M = the mean value; STD = standard deviation of the mean value; SEM = standard error of the mean value.

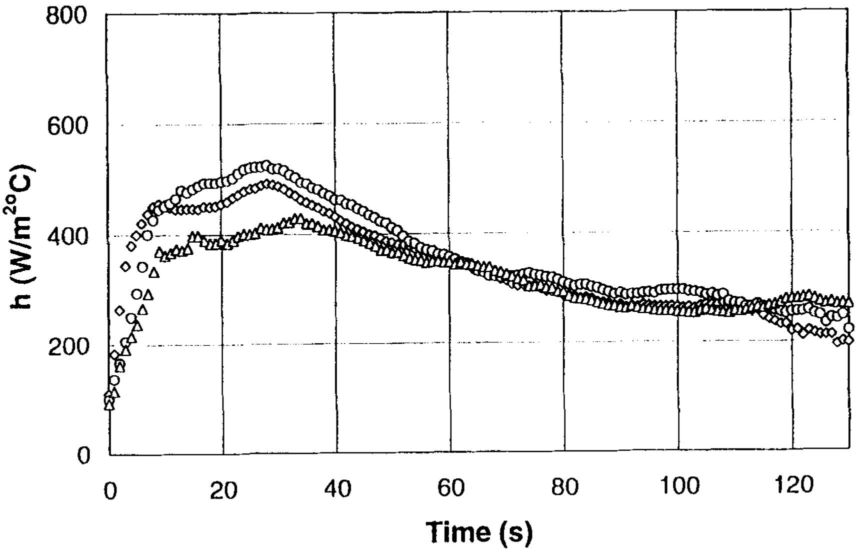

FIG. 10. AVERAGE HEAT TRANSFER COEFFICIENT VALUES INVOLVING THE TOP PLATE FOR 177C SET GRILL TEMPERATURE AT DIFFERENT GAP THICKNESSES: (◇) 10.0 MM; (○) 10.5 MM; (△) 11.0 MM

CONCLUSIONS

Contact heat transfer coefficient values varied from 250 to 650 W/m^{2}C, depending on the cooking conditions. These values also changed during the cooking process. An increase in the grill plate temperature caused an increase in the maximum heat flux value. The Teflon release sheet offered finite resistance to heat transfer to the hamburger patties during cooking. The small gap thickness enhanced a better contact between a patty and the grill surfaces. The high heat transfer coefficient values after reaching maximum value were found with the low set grill temperature (177C) and may result from the boiling phenomenon occurring between the patty surface and the grill surfaces.

ACKNOWLEDGMENTS

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