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COOKING OF BEEF BY OVEN ROASTING: A STUDY OF HEAT AND MASS TRANSFER

ABSTRACT

Samples of semimembranosus muscles were oven roasted at 175°C and 225°C from initial temperatures of −20° and +5°C. During heating temperature profiles were determined as a function of heating time. On duplicate samples the corresponding moisture and fat content profiles were determined for a number of heating times. Moisture and temperature profiles were found to be inversely related to each other, with temperature minimum and moisture maximum occurring near the sample center. For fat content no important trend was seen. Heating time was shorter and yield lower at 225°C than at 175°C, and cooking time increased by some 50% when cooking directly from the frozen state. Up to 65–70°C weight loss appears to occur almost entirely by evaporation from a wet surface, the surface temperature being determined by the wet bulb temperature of the oven atmosphere. Also, above 65°C weight loss by liquid drip becomes significant. The results from time/temperature exposure studies on thin slices of meat showed that temperature is more important than time to drip loss, and surprisingly good agreement with experimental profiles was obtained when applying these data to calculate moisture profiles in roasts from known temperature profiles. For temperature calculations both Hottel diagrams and a simple mathematical model were used with promising results. These findings should help clarify the determining factors in oven roasting of meat, and point to means of controlling and optimizing cooking conditions with regard to yield and cooking time.

INTRODUCTION

CONSIDERING the importance of meat in our diet and the fact that frying is the most common method of preparing meat, it is surprising that not more attention has been given to the fundamental aspects of heat and mass transfer during cooking, and how these factors relate with raw material and processing variables and the resulting changes in composition and quality. With the growing importance of industrial and institutional food preparation, such fundamental data will be necessary for the development of optimal cooking procedures and equipment.

The objective of this work was to assess weight loss and the distribution of temperature, moisture and fat in beef samples as a function of initial sample temperature and of heating temperature during oven roasting of beef, and to find out whether the data obtained could be utilized in process calculation studies, and in developing mathematical models for heat and mass transfer during meat frying operations.

Studies of the rate of heat penetration into meat as a function of cooking medium, temperature and sample composition have been reported by Thille et al. (1932), Irmiter et al. (1967), Ferger et al. (1972), and by Funk and Boyle (1972). Their work was limited to temperature rise in the sample center and resulting product quality and yield. This also applies to information on oven cooking reported by Tilgner (1964a, b), and Wollsey and Paul (1969). Carlheim-Gyllensköld (1970) appears to be the only investigator to report detailed studies of temperature progress with time at different depths in heated beef samples, and to attempt systematizing such data as a basis for calculating cooking times in oven roasting and pan frying.

As for differences between cooking frozen meat with or without previous thawing, Causey et al. (1950), Brady et al. (1942), Gac et al. (1966) and Jakobsson and Bengtsson (1973) found frying directly from the frozen state to require longer cooking time but to give better yield, in partial disagreement with findings of Smith et al. (1969) and Lind et al. (1971).

Heat denaturation of the meat and the resulting release of juices are factors that should be of importance to heat and mass transfer during cooking,and which have been considered by several research workers, such as by Hamm and Deatherage (1960), Tilgner (1964a, b) and Laakonen (1970).

EXPERIMENTAL

Raw material and preparation

Beef from the semimembranosus muscle of young cattle was used throught the experiments. The fat content of the meat was 4% or lower, with a variation within muscle of 1–2%. Entire muscles were frozen in a blast freezer at −40°C and sawn into rectangular pieces of 800–900g (15 × 8 × 5.5 cm) for the oven experiments, with the fibers parallel to the flat surface.

The frozen samples were tempered to semisolid state so that thermocouples could be inserted in the desired positions. Before frying, the samples were either thawed to +5°C or refrozen to −20°C, depending on the desired starting temperature. These procedures were necessary to ensure well defined sample geometry and temperature measurements in studies of heat and mass transfer.

Temperature measurement

During the experiments the temperatures at the surface and at prechosen depths were registered by means of Cu-constantan thermocouples (0.25 mm glass fiber insulated wires) and a potentiometric recorder. For measuring surface temperature thermocouples were soldered to a piece of fine brass mesh wire, which was sewn in firm contact with the surface.

The procedure for positioning thermocouples inside the meat was a modification of that described by Carlheim-Gyllensköld (1970). Thin (1 mm) needles of hardened steel were pushed through the meat sample with the aid of a special alignment jig, as shown in Figure 1a. By means of cotton thread and a minute hook at the thermocouple junction, the thermocouples could then be drawn into and fixed in the desired positions. For the experiments, thermocouples were placed at the top and bottom surfaces, in the center, and at distances of 1.5, 9.0 and 18.0 mm from the two surfaces. The samples, with the thermocouples inserted, were X-rayed (Siemens Pleodor, 75 kV, 25 mA) before and after cooking to determine the exact positions of the thermocouple junctions, as shown in Figure 1b. The oven temperature was defined as the wall temperature of the special "inner" oven described in what follows.

Cooking equipment and procedure

A rectangular "oven" (24 × 25 × 32 cm) made of 2 mm aluminium plate with black inner surfaces, was placed inside a forced convection oven with an accurate temperature regulator to maintain the walls of the insert oven at the desired temperature with a variation over the entire inner wall surface in the order of ±1°C. This would have been very difficult to achieve in a directly heated oven.

The meat sample was placed on a tray of coarse metal netting, positioned at the center of the insert oven. In studies of the rate of weight loss, the tray was suspended from a Mettler balance standing on

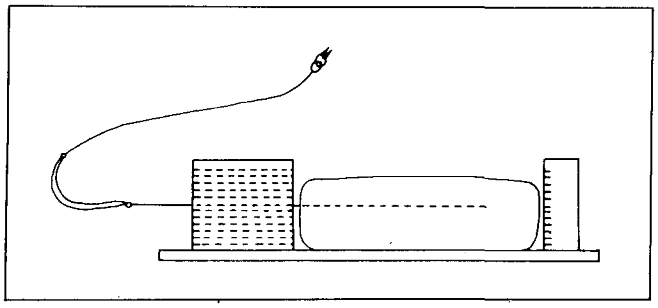

Fig. 1a–Jig for positioning thermocouples inside the meat samples.

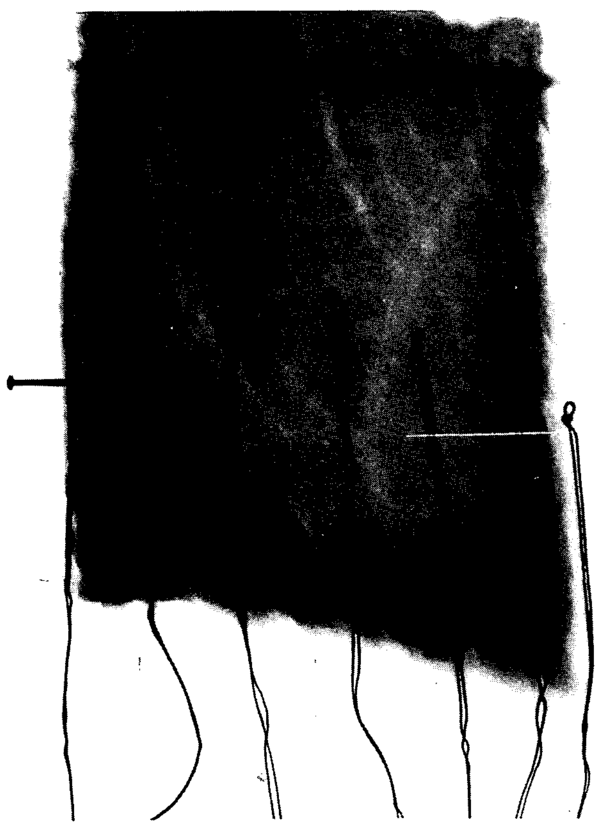

Fig. 1b–X-rayed beef sample with inserted thermocouples.

Table 1–Results from oven roasting experiments to +40°C (rare) and +70°C center temperature (well done)

Oven temp (°C)	Initial center temp (°C)	Final center temp (°C)	Frying time (min)	Weight loss (%)	Max surface temp (°C)	Max % steam in oven by vol
175	+5	+40	39	12	–	–
		+70	80	24	85	50.6
225	+5	+40	32	16	–	–
		+70	60	30	92	65.0
175	–20	+40	88	15	–	–
		+70	120	29	83	44.0

top of the convection oven, so that change in weight could be continuously recorded. In supplementary experiments, the oven was equipped also with a dry bulb-wet bulb thermocouple device for measuring relative humidity (RH).

In an experiment designed to estimate the weight loss due to evaporation and to drip separately, meat samples were packed into tightly fitting heat insulated boxes without a lid (one flat surface exposed). Evaporative loss was studied in heating runs with the exposed surface uppermost, and combined drip and evaporative loss in runs with the box inverted. Temperature was measured at prechoosen points in the meat during these experiments. Evaporative loss and combined loss were plotted against time, and drip loss estimated as the difference between them.

Water and fat gradients in the samples at given time intervals were determined by the following procedure, designed to minimize the time for migration between the end of frying and sampling. A 3-cm thick central transverse slice was immediately cut (perpendicular to its flat surface) from each oven-roasted sample and frozen by liquid nitrogen pulsed immersion. It was partially thawed, and subdivided into eleven fine slices, cut in parallel to the original flat surface, for determination of water and fat gradients. In preliminary tests we checked that no mass transfer occurred under the freezing conditions used. The slices were immediately refrozen and freeze dried to assess their water content. Fat content was determined by Soxhlet extraction of the freeze-dried samples in petroleum ether. Water and fat content were expressed in g per 100g fat-free dry substance (FFDS) as a fair representation of their quantitative distribution. Each experiment was made at least twice. Experimental techniques were developed in a large number of preliminary experiments.

Experimental plan

The main experiment comprised frying at two oven temperatures, 175°C and 225°C, from initial temperatures of –20°C and +5°C to end center temperatures of 40°C and 70°C, and the determination of the resulting yield and gradients for temperature and for moisture and fat content.

Supplementary experiments were done to assess the relationship between temperature and evaporative and drip losses, the influence of relative humidity and wet bulb temperature during oven cooking, and water retention in very thin slices of beef as a function of temperature and time.

RESULTS

Overall cooking time and yield

Mean values for cooking time to +40°C (rare) and to +70°C center temperature (well done) and the resulting total weight loss (drip plus evaporation) are given in Table 1. The differences between duplicate runs were very slight, for which reason individual results are not reported.

Like Tilgner (1964a, b) and Wollsey and Paul (1969), we found both heating time and yield to decrease with increased oven temperature. In agreement with Brady et al. (1942), Gac et al. (1966) as well as other workers, cooking time was considerably prolonged (by about 50%) when beef was oven fried directly from the frozen state. With the particular sample dimensions and heating conditions used, also weight loss increased. These results were in partial disagreement with those reported in the literature in this respect (Smith et al., 1969; Lind et al., 1971), probably because of differences in experimental conditions and sample dimension. When final center temperature was +70°C (well done) weight loss was twice as large as when the temperature was +40°C (rare).

Evaporation and drip loss

The weight loss curves, including the combined effect of evaporation and drip loss, for the actual frying experiments in Table 1, are shown in Figure 2. The curves obtained were nearly straight lines up to the point where surface temperature passed about 70°C (indicated by arrows). The slope of the weight loss curves is steeper for the higher oven temperature.

In a model experiment (in insulated boxes with one surface exposed) the relationship between weight loss by evaporation and by drip was studied as a function of time-temperature, as shown in Figure 3. The curves for evaporative loss and total weight loss (evaporation and drip combined) were fairly linear and nearly superimposed until surface temperature reached 65–70°C, indicating that only evaporative losses occurred up to that point. From then on, drip loss appeared to rise quite rapidly. This was in good agreement with Tilgner's statement (1964a, b) that protein denaturation occurs mainly between 57–75°C in meat, and that juice leakage commences between 60–70°C. In some of our experiments it was also confirmed by visual observation.

The almost linear shape of the evaporation curve in Figure 3 suggests that evaporation occurs from a wet surface (first order dehydration) for the entire cooking time at this oven temperature (160°C), and that surface temperature therefore remains slightly below the wet bulb temperature (T_W) in the oven atmosphere. The wet bulb temperature increased during the experiment because of the accumulation of steam from evaporated meat juice.

Profiles for temperature, and for water and fat content

For the combinations of oven temperature and initial sample temperature given in Table 1, profiles for temperature and for moisture and fat content were determined at 10-min intervals (for separate samples) during oven frying of 55 mm thick rectangular beef samples. The results are shown in Figure 4.

Both temperature and moisture profiles were steeper during the early stages of frying. The profiles also became steeper when using a higher oven temperature or when frying samples directly from the frozen state (without previous thawing). Maximum surface temperature was higher when frying at 225°C than at 175°C, while the maximum surface temperature differed but little when frying from initial sample temperatures of −20°C or of +5°C.

Temperature and moisture profiles varied inversely with each other, a high temperature corresponding to a low moisture content, while the fat profiles seemed to be affected more by raw material variation than by heating. It is noteworthy that the fat content, calculated on the basis of fat free dry substance, is higher after the sample has been heated.

Simulation of temperature profiles

From the temperature profiles, the ratio between heat transfer coefficient (α) and thermal conductivity (λ) can be calculated from the measured intercept with the x-axis of the tangent to the temperature profile at the meat surface (according to Holman, 1968). As seen from Figure 4, the slope of the tangent decreases in the course of frying. Assuming λ to remain constant, the overall heat transfer coefficient will gradually diminish (from about 15 to 3 $J/m^2,s,°C$ in these experiments).

A modified computer program based on finite-difference technique for the solution of the 3-dimensional transient heat equation (according to von Rosenberg, 1969) was used to simulate the temperature profiles in Figure 4, utilizing the above data for α and a constant λ of 0.40 $J/m,s,°C$ based on literature data (Hill et al., 1967; Woodams and Nowrey, 1968) and personal measurements. As seen from Figure 5, the calculated profiles showed good agreement with experimental data, except that the temperature rise was slightly too rapid above 60°C. It should be observed that the experimental profiles were not quite symmetrical.

If the relative humidity (or wet bulb temperature) is known as a function of time and temperature, it is not necessary to know the heat transfer coefficient to calculate temperature profiles. Bimbinet et al. (1971) has shown that during the first period of drying (wet surface) heat transfer behaves as though the solid were heated in a bath at the wet bulb temperature (T_W) with a constant fluid-solid heat transfer coefficient.

Simulation of moisture profiles

In a separate series of experiments, beef was cut into 2 mm slices, which were vacuum sealed in plastic pouches and dipped into water baths of given temperatures for a series of exposure times. The weight loss was determined after the sample had been drained for 1 min on absorbing paper at room temperature. Curves for retained water content as a function of temperature and heating time are given in Figure 6. Moisture loss becomes noteworthy from an exposure temperature of about 60–65°C and appears to be more dependent on temperature than on time. This is in fair agreement with similar data reported by Körmendy et al. (1963) for salted ground pork.

Concluding that temperature is of prime importance for the release of juice, moisture profiles were calculated from the

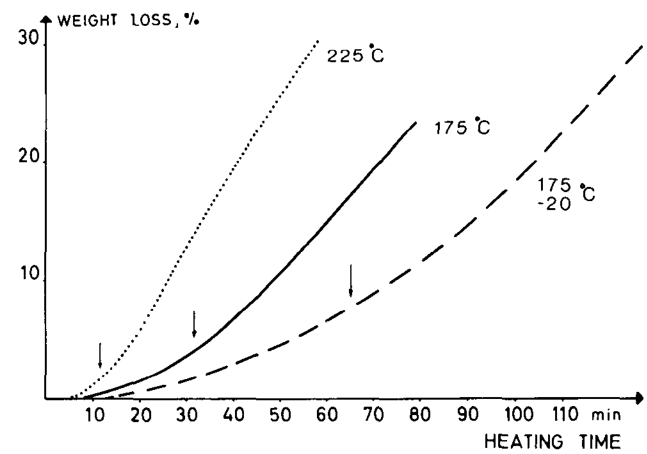

Fig. 2—Weight loss curves for end center temperature of 70°C. Arrows indicate time to reach 70°C surface temperature.

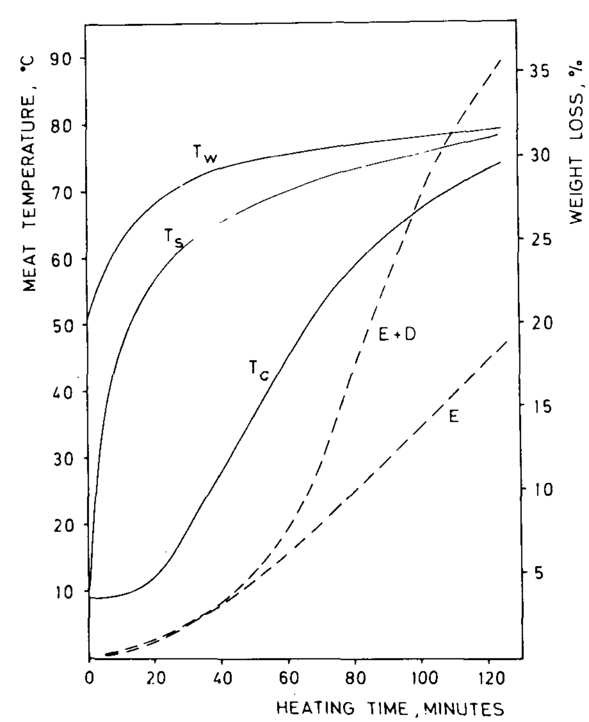

Fig. 3—Relations between weight loss by evaporation (E) and by drip (D) as a function of center (Tc), surface (Ts) and wet bulb temperature (Tw).

temperature profile in Figure 4, and the corresponding data for water content as a function of temperature from Figure 6. As seen from Figure 7, the agreement between experimental and calculated moisture profile was fairly good initially (after cooking to +40°C center temperature) in spite of the very approximate nature of this estimate, in which no corrections were made for evaporation etc. For cooking to a center temperature of +70°C, however, the calculated moisture retention was somewhat less than found experimentally. This suggests that some water was retained or blocked inside the intact meat sample, or that the losses of fat-free dry substance were larger than in the experiments with the thin (2 mm) slices.

Using temperature data for approximate process calculations

When the experimentally determined time-temperature relations during oven broiling were plotted in a Hottel diagram, according to McAdam (1954), a stright line was formed when frying from the thawed state (Fig. 8a), and a broken line when frying from the frozen state (Fig. 8b).

In the Hottel diagram, which is commonly used in heat transfer calculations for building materials etc., a dimensionless temperature expression $(t_a - t_m)/(t_a - t_b)$ (where t_a denotes surrounding air temperature and t_m and t_b the actual central and initial temperatures respectively) is plotted against $(\lambda/\rho \cdot c_p)(\tau/\ell^2)$ (where $\lambda/(\rho \cdot c_p)$ is the thermal diffusivity, τ is the time and ℓ^2 the square of the product thickness).

These diagrams can then be used to calculate approximately the time required to reach a desired center temperature for any combination of initial sample temperature, oven temperature and product thickness. It is, however, important to retain nearly the same relations between height, length and width of the product as in the underlying experiment, unless some kind of shape factor is introduced (Carlheim-Gyllenskõld, 1970). The linear relationship obtained means that the time to reach a given center temperature will vary inversely with the thermal

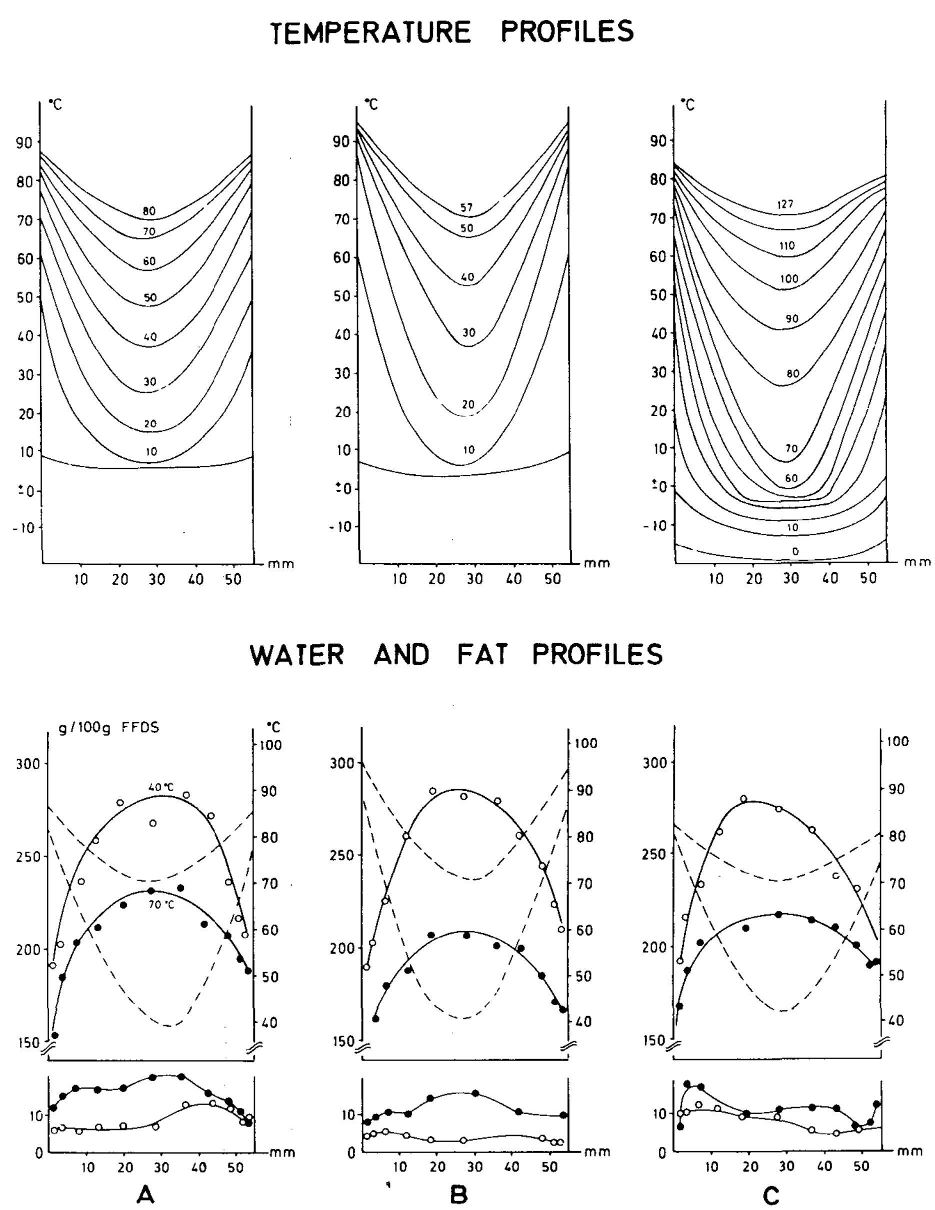

Fig. 4—Temperature, water and fat profiles for oven temperatures 175°C (A) and 225°C (B) from start temperature +5°C and for oven temperature 175°C (C) from start temperature −20°C. The water and fat profiles for end center temperatures of 40°C and 70°C are indicated by open and filled circles respectively. The corresponding temperature profiles are indicated by dashed lines in the same diagram.

diffusivity and directly with the square of the product thickness.

DISCUSSION & CONCLUSIONS

IN THE COOKING experiments with thawed beef to a given final center temperature, increasing the oven temperature from 175° to 225°C resulted in steeper temperature gradients, shorter cooking time and lower yields under the experimental conditions used (Table 1).

During cooking in an oven with free convection, the meat surface remains wet during most of the heating cycle, which means that the primary stage of dehydration prevails, and that weight loss by evaporation is directly proportional to the heating time. The wet surface temperature will then remain close to the wet bulb temperature of the oven air space. The relationships between dry bulb and wet bulb temperatures, relative humidity and percentage of moisture by volume in the airspace is given in Table 2, as calculated from psychrometric formulas (Bindon, 1965). For a given wet surface temperature, the driving force of heat transfer to the interior will remain the same irrespective of oven temperature. In the experiments performed at 175° and 225°C oven temperatures, the wet surface temperature was higher at 225°C than at 175°C, which in turn resulted in steeper temperature gradients, shorter total heating time and larger weight loss at 225°C oven temperature.

Our observations also suggest means to reduce weight loss by evaporation and drip. Since drip becomes significant only at temperatures above about 65°C (see Fig. 3) it can be minimized by using heating conditions where this temperature is not exceeded. One possibility to do this is by using a very low thermal driving force and correspondingly prolonged heating time, such as reported by Laakkonen et al. (1970). Other possibilities would be to use suitably programmed oven temperatures or to combine oven heating with microwave heating, as suggested by Bengtsson and Ohlsson (1974). Evaporative loss could easily be reduced by raising the RH, and lowering the oven temperature to maintain the same thermal driving force. As seen from Table 2, an increase in RH from 2.7 to 7.2% at 175°C oven temperature (which corresponds to a volumetric increase in water vapor from 23.3 to 63.0%) will raise the wet bulb temperature and the maximum wet surface temperature from 70 to 90°C. This will give the same thermal driving force and the same heating rate as at an oven temperature of 225°C at an RH of 2.4%. Evidently an optimum combination of oven temperature, RH, heating time, yield and surface crust formation is indicated.

Cooking directly from the frozen state at 175°C oven temperature resulted in steeper temperature gradients, lower wet surface temperature, about 50% longer heating time and a larger weight loss (for the particular sample size used) than from the thawed state. This is not necessarily incompatible with previ-

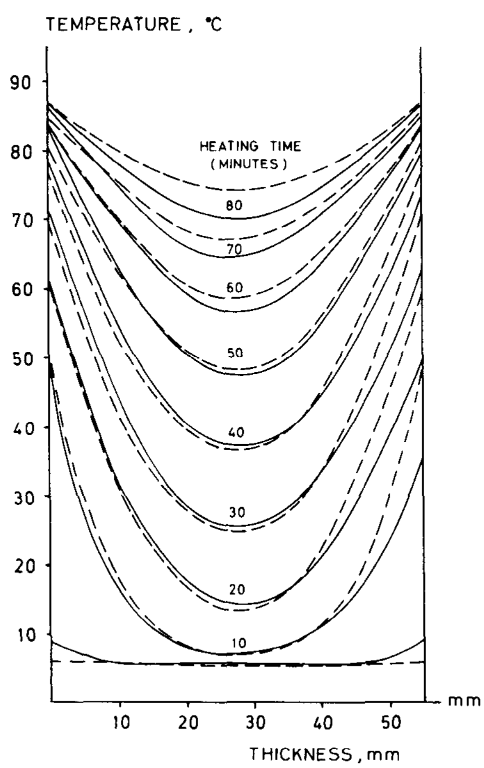

Fig. 5—Comparison between experimental (solid lines) and calculated (dashed lines) temperature profiles at 175°C oven temperature.

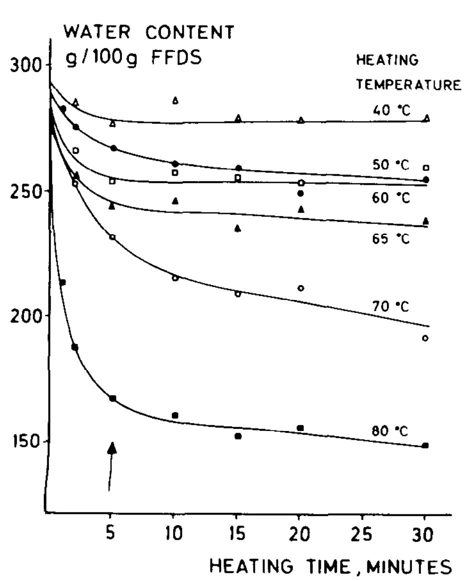

Fig. 6a—Water retention in 2 mm meat slices as a function of temperature and heating time.

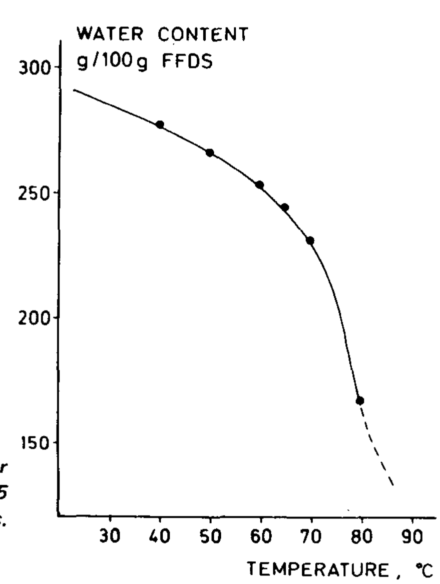

Fig. 6b—Relations between water content and temperature after 5 min heating of 2 mm meat slices.

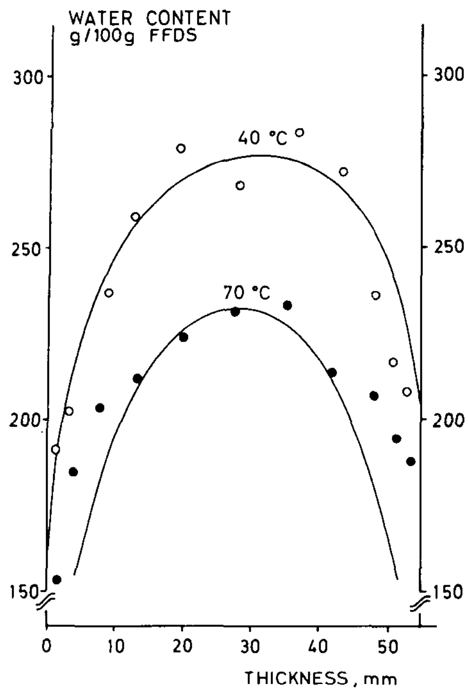

Fig. 7–Calculated water profiles (solid lines) for end center temperatures of 40°C and 70°C oven temperature in comparison with experimental values (points) as Fig. 4 (A).

Table 2–High temperature psychrometric chart[a]

Dry bulb temperature		Wet bulb temperature (Tw) 60	65	70	75	80	85	90	100
150	RH	2.8	4.0	5.3	7.0	8.9	11.1	13.8	20.5
	V%	13.3	18.7	25.1	32.7	41.7	52.4	64.8	96.4
175	RH	1.4	2.0	2.7	3.5	4.5	5.8	7.2	10.8
	V%	11.6	16.9	23.3	30.9	39.9	50.6	63.0	94.5
200	RH	0.6	1.0	1.4	1.9	2.5	3.2	4.0	6.0
	V%	9.8	15.1	21.5	29.1	38.1	48.7	61.2	92.7
225	RH	0.3	0.5	0.8	1.1	1.5	1.9	2.4	3.6
	V%	7.9	13.4	19.7	27.3	36.2	46.8	59.4	90.9

[a] RH = [Pv/Pvs(T)] 100, V% = (Pv/P) 100 where P = moist air pressure; Pv = vapor pressure; Pvs(T) = the saturated vapor pressure with respect to water of moist air at pressure P and temperature T; Tw = wet bulb temperature; and T = ambient temperature

ously reported results of pan frying (Bengtsson and Jakobsson, 1974), where the samples were only 9 mm thick. It is quite possible that an inherent advantage in water binding when heating directly from the frozen state may have been more than offset by evaporative losses during the 40 min prolongation of heating time in oven cooking of 55 mm thick beef samples.

Comparing experimental temperature profiles to computer simulated ones, a certain discrepancy was found at temperatures above 60°C. This may be due to meat swelling during heating. Another possibility is that the thermal conductivity in the outer parts decreases owing to their lower water content. The calculations were based on a change in heat transfer coefficient with time, which was actually calculated from the experimental temperature profiles, assuming a constant thermal conductivity throughout. A decrease in effective λ would also mean a decrease in α and thus in the driving force during the later stages of cooking compared to the calculated profiles in Figure 5.

Juice release during heating proved to be more a function of temperature than of time in the experiments with very thin meat slices. Attempts to calculate the moisture profile for a given heating time directly from the observed temperature profile and the known relationship between time, temperature and juice release were successful for heating up to a center temperature of 40°C. For cooking to 70°C central temperature the calculated water profiles were steeper than the experimental ones, probably due to losses of fat-free dry substance.

Plotting experimental data in Hottel-diagrams resulted in a

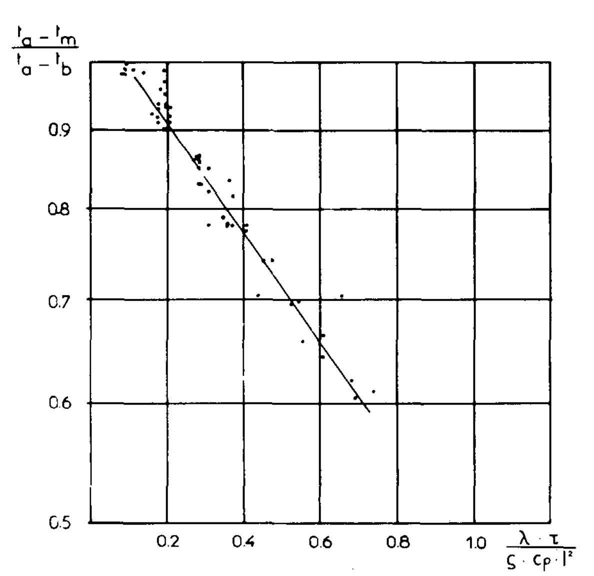

Fig. 8a–Hottel diagram when frying from thawed state.

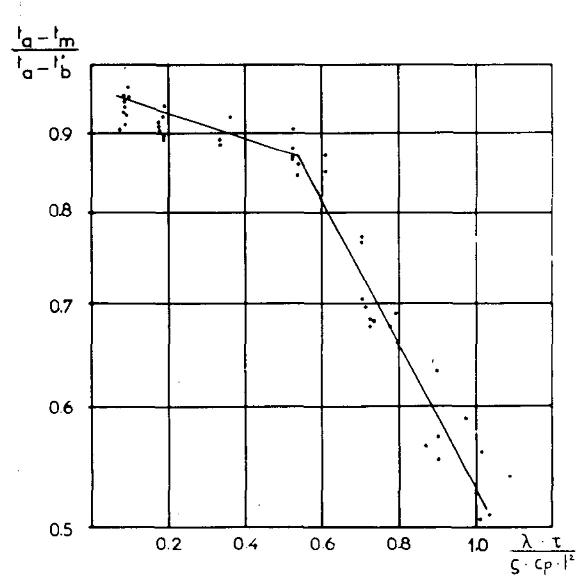

Fig. 8b–Hottel diagram when frying from frozen state.

linear relationship, from which calculations of cooking time or overall thermal diffusivity can be made. This is rather surprising in view of the complex nature of the biological material during heating in comparison to materials like brickwalls etc. for which Hottel diagrams have normally been used. Our observation are in principle in very good agreement with those of Carlheim-Gyllensköld (1970).

It is evident from the present work that oven temperature, relative humidity, sample dimensions and initial sample temperature play an important role in the resulting temperature development and yield during oven cooking of beef. Better knowledge of physical data such as thermal conductivity and specific heat in relation to composition and experimental conditions are required, but sufficient knowledge is now available to permit approximate calculations of heating times and resulting temperature and moisture profiles, as well as deductions as to what conditions are optimal for oven cooking.

REFERENCES

Bengtsson, N.E. and Ohlsson, T. 1974. Microwave heating in the food industry. Proceedings of the IEEE 62(7): 44.

Bengtsson, N.E. and Jakobsson, B. 1974. Cooking of meat patties for freezing—A comparison of conventional methods and their combination with microwave heating. Microwave energy applications Newsletter 7(6): 3.

Bimbinet, J.J., Loncin, M. and Brusset, H. 1971. Heat and mass transfer during air drying of solids. Canadian J. Chem. Engr. 49: 860.

Bindon, H.H. 1965. "A Critical Review of Tables and Charts used in Psychrometry. Humidity and Moisture." Ed. Wexlar, A., Vol 1—4:1. Reinhold Publishing Corp., New York.

Brady, D.E., Frei, P. and Hickman, G.W. 1942. Effect of freezing rate on quality of broiled steaks. Food Research 7: 388.

Carlheim-Gyllensköld, H. 1970. The penetration of salt and of heat into foodstuffs while being cooked. Acta polytechnica Scandinavica Ch 93, Stockholm 1970.

Causey, K., Hausrath, M.E., Ramstad, P.E. and Fenton, F. 1950. Effect of thawing and cooking methods on palatability and nutritive value of frozen ground meat. 2. Beef. Food Research 15: 249.

Ferger, D.C., Harrison, D.L. and Anderson, L.L. 1972. Lamb and beef roasts cooked from the frozen state by dry and moist heat. J. Food Sci. 37: 000.

Funk, K. and Boyle, M.A. 1972. Beef cooking rates and losses. J. Am. Diet. Assoc. 61: 4.

Gac, A., Lafon, J. and Lebel, J. 1966. Essais de conservation de longue durée des viandes congelées. Revue generale du froid 57: 789.

Hamm, R. and Deatherage, F.E. 1960. Changes in hydration, solubility and charges of muscle proteins during heating of meat. Food Research 25(5): 587.

Hill, E.J., Leetman, J.D. and Sunderland, J.E. 1967. Thermal conductivity of various meats. Food Technol. 21: 1143.

Holman, J.P. 1968. "Heat Transfer." McGraw-Hill, New York.

Irmiter, T.F., Aldrich, P.J. and Funk, K. 1967. Rate of temperature rise, physical and chemical properties of ground beef cylinders fabricated from selected muscles of the round. 1. Effect of fat content. Food Technol. 21: 779.

Jakobsson, B. and Bengtsson, N.E. 1973. Freezing of raw beef: Influence of aging, freezing, rate and cooking method on quality and yield. J. Food Sci. 38: 560.

Körmendy, L., Fenyes, T., Szeredi, I., Zukál, E. and Gantner, G. 1963. Some fundamental relationships of cooking losses, temperature and time. 9th European Meeting of Meat Research Workers, Budapest 1967, Paper 47.

Laakkonen, E., Wellington, G.H. and Sherbon, J.W. 1970. Low-temperature, long-time heating of bovin muscle. 1. Changes in tenderness, water-binding capacity, pH and amount of water-soluble components. J. Food Sci. 35: 175.

Lind, M.L., Harrison, D.L. and Kropf, D.H. 1971. Freezing and thawing rates of lamb chops: Effects on palatability and related characteristics. J. Food Sci. 36: 629.

McAdam, W.H. 1954. "Heat Transmission," 3rd ed. McGraw-Hill Book Company, New York.

Smith, G.C., Carpenter, Z.L. and King, G.T. 1969. Consideration for beef tenderness evaluations. J. Food Sci. 34: 612.

Thille, M., Williamson, L.F. and Morgan, A.F. 1932. The effect of fat on shrinkage and speed in the roasting of beef. J. Home Econ. 24: 720.

Tilgner, D.J. 1964a. Graveränderungen und Garzustand von Fleisch. Fleischwirtschaft 44(11): 1115.

Tilgner, D.J. 1964b. Die technologische Systematik der Wärmebehandlung von Fleisch. Fleischwirtschaft 44: 955.

von Rosenberg, D.V. 1969. "Methods for the Numerical Solution of Partial Differential Equations." American Elsevier Publishing Co., Inc., New York.

Woodams, E.E. and Nowrey, J.E. 1968. Literature values of thermal conductivities of foods. Food Technol. 22: 494.

Woolsey, A.P. and Paul, P.C. 1969. External fat cover influence on raw and cooked beef. 1. Fat and moisture content. J. Food Sci. 34: 554.

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