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Changes in the Surface Heat Transfer Coefficient During Meat Thawing

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INTRODUCTION

The heat transfer coefficient between the surface of the product and the warming medium is the most important factor determining thawing rate of thin materials and a major factor in thawing of thick materials. In equations developed to predict freezing times, but equally applicable to thawing, (e.g. Plank (11)) the heat transfer coefficient enters explicitly. In methods where the differential equations for heat flow are solved by numerical finite difference procedures (Sanders (12), Bonacina et al (2)) or finite element procedures (Miki et al (10), Bonacina et al (1)) the heat transfer coefficient at the surface is required to define the boundary conditions. In his comprehensive review of analytical methods that have been used to estimate freezing and thawing rates in food Hayakawa (5) found that only three types of boundary conditions had been considered:

(a) convective heat exchange between the surrounding medium and the sample surface
(b) convective plus radiative heat exchange
(c) a fixed surface temperature throughout the process

Jason et al (7) have additionally considered the effect on thawing time of very high surface heat transfer coefficients produced by the condensation of steam under vacuum on the surface of frozen fish blocks.

The only reference known to the authors where heat transfer coefficients have been measured and related to a thawing situation is the thesis of Vanichseni (13) who recorded the heat gain on an aluminium block and produced curves of convective and convective plus radiative surface heat transfer coefficients against air velocity for air at 10°C with an unquoted relative humidity. The values obtained, 55 and 30 W/m² °C, at 3 and 1 m/s respectively, are much higher than those published for blast freezing at the same velocities.

In all the cases quoted the surface heat transfer coefficient is not considered to be a function of surface temperature. Our previous experiments (7) showed the rate at which 25 kg unwrapped meat blocks absorbed heat during thawing in moving air (Fig 1). The rate fell steadily for the first six hours, then the slope changed abruptly. The curve shows the rate of heat transfer (Q) during the thawing process, and if the heat transfer coefficient (h) is substantially constant during thawing, as it would be if solely a combination of radiation and conduction components, the total heat flow by integration over the surface area is given by:

$$Q = h \int_s (t_a - t_s)$$

There is no simple way of measuring the average surface temperature of a meat block at a given time and consequently evaluating the integral. However there is no reason why the average surface temperature/time curve should show the abrupt change needed to produce the change of slope shown in Fig 1. Hence, the value of h must have changed suddenly, indicating the involvement of components other than convection and radiation. If in the early part of the thawing process the main component of the overall heat transfer coefficient was provided by condensation, as the dew point was reached this component would suddenly disappear. This paper describes experiments to test this hypothesis and indicate the part played by condensation in the thawing process. The method for determining the value of h is based on that used by Cowell and Namor (4) to investigate heat transfer coefficients in plate freezing.

THEORY

Consider an infinite slab of material of thickness l with one face at x = 0 perfectly insulated, and the face at x = l in contact with stirred fluid at constant temperature t_a. Let the heat transfer coefficient between the fluid and the slab be h.

Cowell and Namor (4) showed that the temperature t at time T in the plane at distance x from the insulated face of the slab is given by:

$$t_a - t = A \exp\left(\frac{-kt\alpha_1^2}{pcl^2}\right) \qquad (1)$$

where α_1 is the first positive root of

$$\alpha \tan\alpha = \frac{hl}{k} \qquad (2)$$

k, p and c are the thermal conductivity, density and specific heat of the slab and A is a factor independent of temperature. Therefore at any depth x, a plot of $\ln(t_a - t)$ against time will become asymptotic to a line of slope

$$m = -\frac{\alpha^2 k}{pcl^2} \tag{3}$$

Expanding $\tan\alpha$ as a series (2) can be written as

$$\alpha\left(\alpha + \frac{\alpha^3}{3} + \frac{2\alpha^5}{15} + \ldots..\right) = \frac{hl}{k} \tag{4}$$

If α is small then only the first term need be retained and

$$h = -mpcl \tag{5}$$

h can be determined by plotting $\ln(t_a - t)$ against time for any point in the block, calculating the gradient m and multiplying this value by the constant pcl. The values of h obtained in this way were then plotted against the surface temperature of the block.

EXPERIMENTAL

Two copper-constantan thermocouples were inserted into the geometric centre and the centre of the largest surface of a 15.5 x 10 x 7cm copper block via holes drilled through the side of the block. The holes were then filled with zinc oxide impregnated silicon grease to ensure good thermal contact between the copper and the thermocouples. The block and thermocouples were then encased in polyurethane foam leaving only one surface exposed.

Before the start of each experimental run the whole assembly was equilibrated at -30°C in a freezing room. The exposed surface was then covered with a polyurethane slab before moving it into a Zeiss controlled environmental chamber, in which air temperature and dew point could be set to ±0.1°C between -40° and +50°C and -30° to +50°C respectively. The covering slab was then removed and the two thermocouples, together with the temperature and dew point of the chamber, were monitored at two minute intervals using a Solatron computer-controlled logging system.

In the experiments the air temperature in the chamber and the air speed over the surface of the block were controlled at 30° ± 0.1°C and 3.2 ± 0.2 m/s respectively. Dew points 1°, 14° or 28°C were set in the chamber and the experiments carried out initially with the exposed block surface horizontal, and then with the surface vertical, giving six treatment combinations. For each of three replicate runs at each of the six treatment combinations, plots of $\ln(t_a - t)$ against time and surface temperature (t_s) against time were transformed to give a plot of h against t_s.

RESULTS

The average $\ln(t_a - t)$/time and t_s/time plots for the horizontal and vertically orientated block under the three dew points are shown in Figs 2a and 2b respectively and h/t_s in Fig 3. Errors caused by differences in loading times, ambient temperature and temperature measurement are estimated to have produced a maximum error of ± 4 W/m²°C in any value of h. Figure 3 shows the relationship between h and surface temperature for horizontal and vertical surfaces at each dew point. The curves are similar in that h either remains constant or rises initially, followed by an inflexion and a subsequent rapid fall. However, there is a marked difference in the values of h attained at each dew point. Over the range of surface temperatures between -20° and +28°C the values of h measured at a dew point of 28°C are 2 to 3.5 times those obtained at a dew point of 1°C.

DISCUSSION

Figure 3 shows clearly that even with a very low dew point of 1°C, corresponding to dry air in a commercial situation, the surface heat transfer coefficient is not a constant when measured over the range of surface temperatures encountered in a normal thawing cycle. Above 15°C h is constant and its value of 35 W/m²°C agrees with predicted theory for a predominantly convective heat transfer coefficient, and is very close to that reported by both Hodgson (6) and Cleland (3) for chilling and freezing in air at a similar velocity.

At a dew point of 28°C, which would be considered to be saturated air in practical thawing systems, h varies from 70 to a peak value of 115 W/m²°C over the surface temperature range -20° to +26°C. The value obtained by Vanichseni (13) (55 W/m²°C) lies within the range of heat transfer coefficient values measured during these investigations and thus corresponds to a high humidity but not a saturated air stream.

The curves of h against surface temperature can be divided into specific sections, which are related to the dew point of the air and the orientation of the block. At surface temperatures below 0°C water sublimes to ice on the surface of the block enhancing the heat transfer coefficient as a result of the phase change. At 0°C this ice layer melts, and a temporary heat requirement causes the inflexion in the curve. From 0°C to the dew point, water vapour condenses as liquid on the surface, further enhancing the heat transfer coefficient by the heat of condensation. Above the dew point conditions are reversed; the layer of condensate evaporates and the heat transfer coefficient falls because of the evaporative requirement. When evaporation is complete h becomes a constant value dependent on convection and radiation. The duration of the evaporative section is clearly affected by the orientation of the surface since a much larger amount of condensate will remain on a horizontal than an inclined surface.

It is beyond the scope of this initial investigation to go more deeply into the shape of the curves obtained. In thawing of meat the shape of the curves will be affected by the surface characteristics of the joint and the environmental conditions which will govern the thickness of the ice and liquid condensate layers that are deposited before the dew point is reached. Since sublimation and condensation occur on the surface on these layers it is important that in future experiments the temperature of this surface is either measured or calculated. Experiments are now being undertaken using a meat surface to study these effects.

A modified version of the predictive programme described by James and Bailey (8) has been used to provide surface and centre temperature/time curves for both constant and modified heat transfer coefficients (Figure 4). It can be seen that even with thick (15cm) blocks the result of neglecting the effect of the condensation component of the surface heat transfer coefficient can lead to an over-estimate of 20% in the required thawing time.

CONCLUSIONS

The effect of condensation and subsequent evaporation on the overall surface heat transfer coefficient during thawing is considerable. If meat is to be thawed unwrapped or with a tight polyethylene wrapping the surface heat transfer coefficient and the surface temperature must be known before any accurate prediction of thawing time can be carried out.

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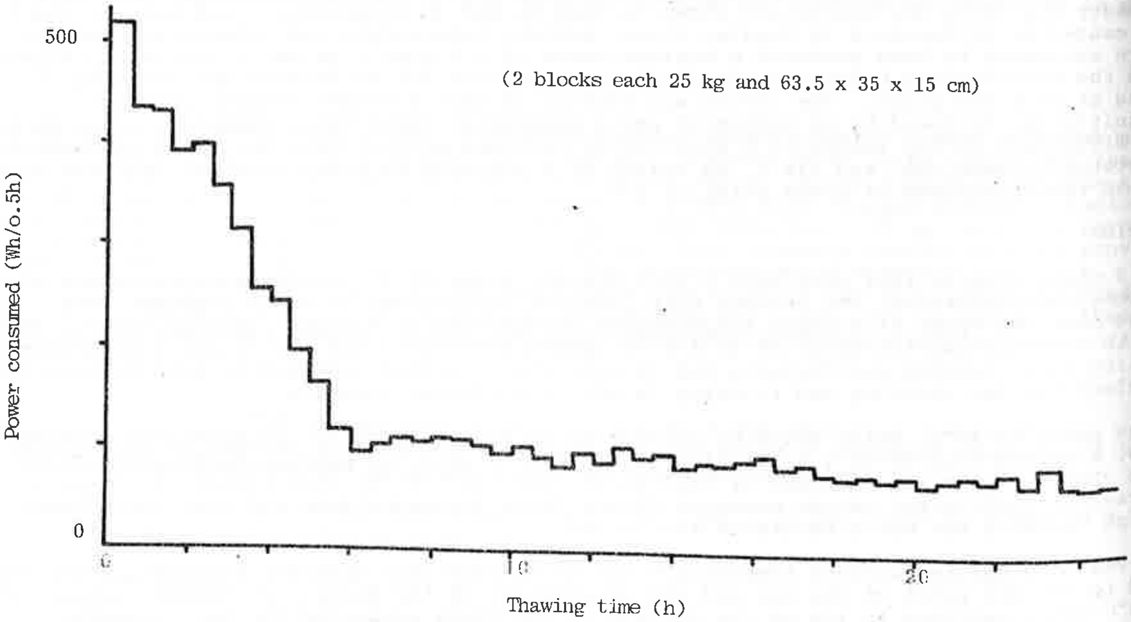

Figure 1. Power absorbed by polyethylene wrapped meat blocks during a 24h thawing cycle in air at 30°C, 3 m/s.

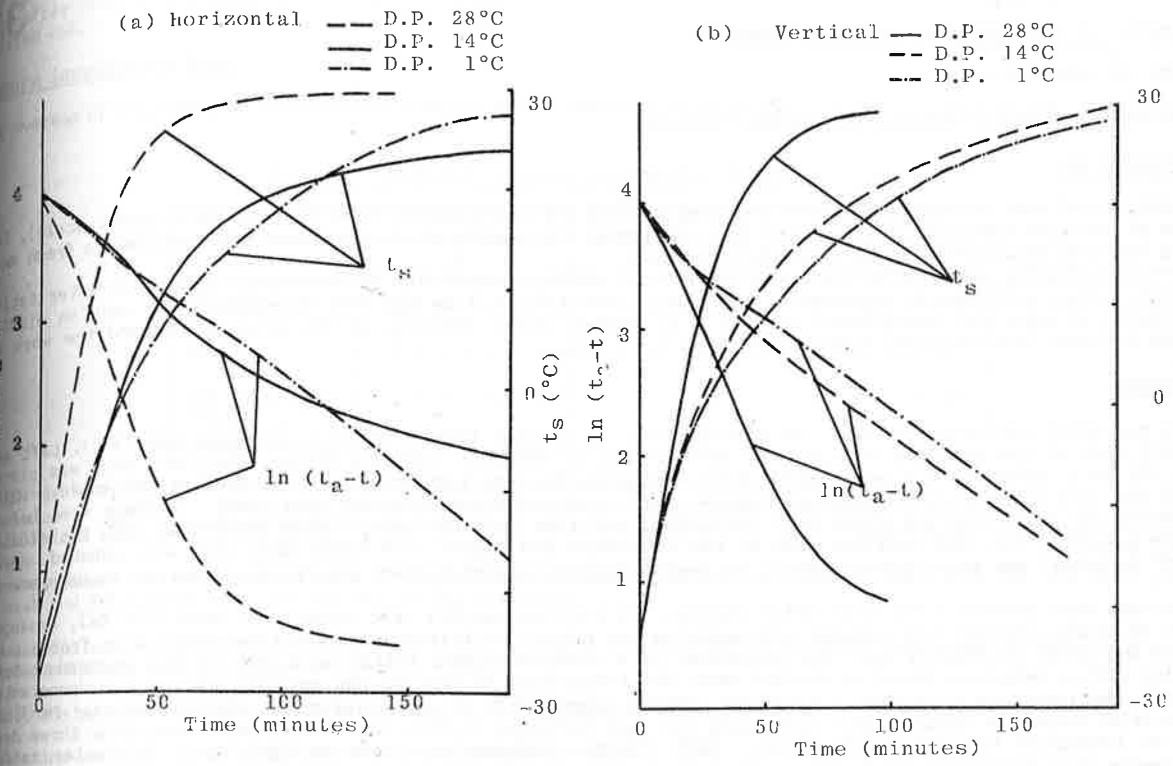

Figure 2. Variation of ln (t_a-t) and t_s with time in heating a copper block from -30°C in air at +30°C for different dewpoints (D.P.)

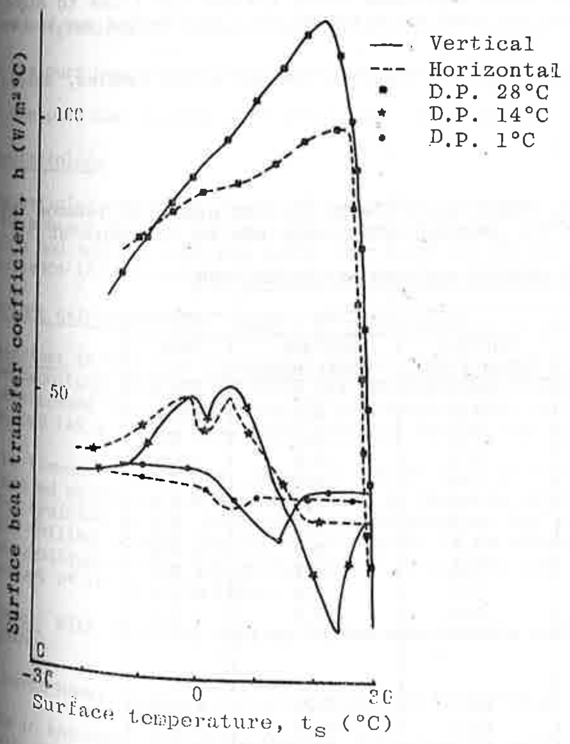

Figure 3. Relationship between h and t_s in heating vertical and horizontal surfaces of a copper block from -30°C in air at +30°C for different dewpoints.

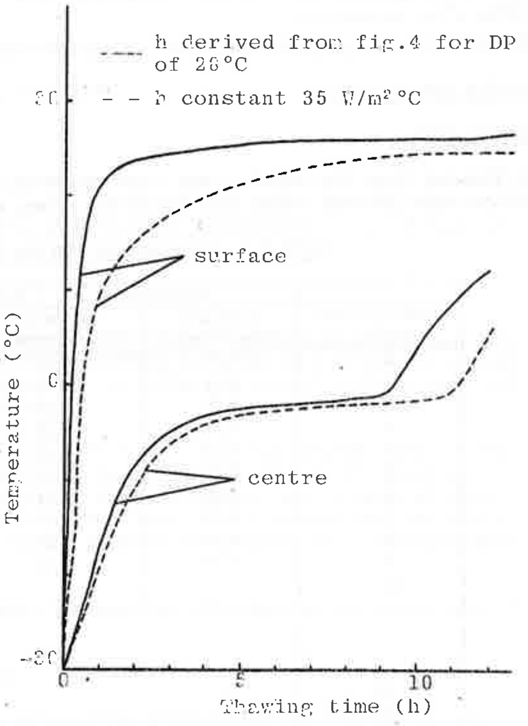

Figure 4. Predicted thawing curves at the centre and surface of 15 cm thick meat blocks in air at 30°C.