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Journal of Food Engineering 26 (1995) 147–160

0260-8774/95/$9.50

0260-8774(94)00046-8

Heat and Mass Transfer Coefficients During the Refrigeration, Freezing and Storage of Meats, Meat Products and Analogues

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(Received 1 May 1993; revised version received 18 March 1994; accepted 23 August 1994)

ABSTRACT

The existing bibliographical data on heat and mass transfer coefficients during refrigeration, freezing and storage of meat and meat products were reviewed.

Heat transfer coefficients for meat balls and hamburgers were determined experimentally in a prototype belt freezer. Measurements were carried out at different air velocities and directions of air flow. In each case, the coefficients thus obtained were correlated with working conditions.

Mass transfer data for the preceding cases were calculated from the heat transfer coefficients.

NOTATION

C_p	Heat capacity (J/kg K)
d	Diameter (m)
D_a	Diffusion coefficient of water vapour in air (m^2/s)
h	Heat transfer coefficient (W/m^2 K)
k	Thermal conductivity (W/m K)
K	Mass transfer coefficient (kg/m^2 s)
L	Latent heat of sublimation of water (J/kg)
Nu	Nusselt number ($= hd/k_a$)

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Pr Prandtl number ($= C_{p_a}\mu_a/k_a$)
r Radial coordinate (m)
Ra Rayleigh number
Re Reynolds number ($= v_a d\rho_a/\mu_a$)
Sc Schmidt number ($= \mu_a/\rho_a D_a$)
Sh Sherwood number ($= Kd/\rho_a D_a$)
t Time (s)
T Temperature (K)
v Velocity (m/s)
x Axial coordinate (m)

ρ Density (kg/m^3)
μ Viscosity (kg/m s)

Subscripts
a Air
c Cylinder surface
eff Effective value
f Evaluated at film temperature T_f [$T_f = 0{\cdot}5(T_a + T_{sur})$]
j Refers to any circular surface of hamburger (upper or lower)
m Meat
p Plane plate surface
s Sphere surface
sur Surface

INTRODUCTION

Knowledge of air–product heat and mass transfer coefficients is absolutely necessary to design refrigeration, storage and freezing equipment, or to adapt or change the operating conditions of existing units. Coefficients are essential to predict not only process times, but also the weight loss produced by evaporation or sublimation of surface water (Amström, 1970).

Previous research on heat transfer coefficients in foods whose results have been used for food systems include Giambelli (1971), Chavarria and Heldman (1984) and Succar and Hayakawa (1986), who dealt mainly with unwrapped products of regular geometry; Gac and Larbouillat (1962) and Cleland and Earle (1976) who worked with packed products; Vázquez and Calvelo (1980) and Marhic and Singh (1987) who dealt with fluidized bed freezers; and finally Arce and Sweat's (1980) complete review of the existing data about foods, model systems and the most commonly used measuring methods. Kopelman *et al.* (1967), Bonacina and Comini (1972) and Comini (1972) provided detailed information on the conditions to be fulfilled during transient state experiments to obtain the highest possible accuracy. They adopted numerical methods and developed formulae to calculate the errors involved in the calculations.

Information about mass transfer coefficients during refrigeration, freezing and storage is even more scarce. Radford *et al.* (1976) predicted the weight loss from a meat plate and provided values of heat and mass transfer coefficients for certain air velocity ranges. Norwig and Thompson (1984) reviewed dehydration during freezing. Daudin and Swain (1990) analysed the weight loss of meat cylinders suspended in a refrigeration chamber with parallel and axial low velocity air. Kondjoyan and Daudin (1990) presented h and K values for air flow over different shaped foods.

Foods which are more commonly frozen in Argentina were considered in order to make this study useful. They are beef, chicken, pork or fish hamburgers, beef balls, chicken pieces, breaded meat portions, fish fillets and, to a lesser extent, individually quick frozen vegetables, pizzas, prepared foods, etc. Meats and meat products (mainly in the form of hamburgers, meat balls, fillets and breaded portions) cover most of the retail market. This study has focused on these products. In every case it is necessary to consider food shape, size and packaging. As can be easily inferred from Table 1, the existing bibliographical information for these products is scarce and, besides, is often not accurate. Experimental values and regression equations obtained for ideal systems (regular geometries, smooth surfaces, metallic samples of constant thermal properties and isotropic thermal conductivity) must be used in most calculations.

A concise review of the main research that has provided experimental data and prediction equations for heat and mass transfer coefficients in the air–food system, mainly for meat refrigeration, freezing and storage, is presented in Table 1. Authors, products, experimental conditions and results are briefly mentioned.

The aim of this work was: (1) to review the existing relevant literature on this subject; (2) to determine air–product heat transfer coefficients in belt freezers for hamburgers and meat balls with different air flow directions and rates; (3) to obtain regression equations of the type *Nu* vs (*Re*, *Pr*) and *Sh* vs (*Re*, *Pr*), which facilitate the calculation of heat or mass transfer coefficients for the range of air velocities usually found in industrial freezers.

HEAT TRANSFER COEFFICIENTS

Experimental set-up

The measuring equipment was designed to account for the different shapes and sizes of food frozen in belt tunnels. This is a 2·3 m long prototype tunnel with a 0·50 m × 0·70 m cross-sectional area. The measuring zone was 0·70 m long. The belt could be placed either parallel or at right angles to the air flow in order to study all the situations which are described later. Full details of the prototype were given by Flores and Mascheroni (1988) and Tocci and Mascheroni (1990). Copper–constantan thermocouples were used to measure temperatures. In the case of hamburgers, they were placed at the centre of both circular surfaces and at the geometrical centre of the food. In the case of meat balls, thermocouples were located on the surface and at the centre. They were accurately placed in the samples by means of a hypodermic needle. For the centre, a thermocouple was passed through the needle and its head was attached to the tip of the needle which, when inserted in the sample, exactly reached its centre. Another thermocouple was attached to the surface of the needle in such a way that, when inserted in the sample, the thermocouple lay on its surface. The insertion of the needle into the sample was done with a drill press. In the case of air flow

TABLE 1
Summary of Literature on Transfer Coefficients Between Air and Meat Products or Analogues During Refrigeration, Freezing and Storage

Author(s)	*Product and geometry*	*Experimental conditions*	*Results format*
Giambelli (1971)	Boxes with low height to side-length ratio	Freezing in belt freezer	h and Nu vs position, v_a, length and T
Lind and Skjöldebrand (1984)	Meat loaf and aluminium transducer	Wind tunnel $0 < v_a < 5{\cdot}3$ m/s	h vs v_a
Pham and Willix (1984)	Lamb pieces	Cold storage	Keff and Deff vs weight loss
Chavarria and Heldman (1984)	Ground beef (flat plate)	Freezing with air in belt freezer	Nu vs Re, h vs plate thickness
Flores and Mascheroni (1988)	Beef and model hamburgers	Freezing in belt freezer	Nu vs Re
Scott *et al.* (1992)	Frozen model food slabs	Cold chamber	h vs t
Self and Burfoot (1986)	Meat cylinders	Chilling	h vs v_a and position
Daudin and Swain (1990)	Meat and model cylinders	Refrigerated test chamber	h and K vs v_a and T
Kondjoyan and Daudin (1990)	Elliptic model cylinders	Refrigerated test chamber	h and K vs v_a and shape
Tütüncü *et al.* (1990)	Meat slabs, ground meat cylinders	Refrigerators and freezer	K vs T and type of packaging
Raithby and Eckert (1968)	Smooth spheres	Tunnel for different types of air flow	Nu vs Re
Feldmann (1979)	Suspended ice spheres	Freezing tunnel	Nu vs Re
Arce and Sweat (1980)	Apples, beef carcasses, carrots, eggs, fish, oranges	Review of literature (different conditions)	Nu vs Re or h vs Re
Miles (1982)	Foods		Nu vs Re

perpendicular to the belt, the needle was also used to support the meat ball or the hamburger in the tunnel.

Raithby and Eckert (1968) considered a single sphere and observed the influence of turbulence caused by obstructions (the support in their case). The present tests were intended to simulate, as closely as possible, the real situation in the freezer. Thus, spheres or disks were placed around the studied sample. Therefore, the support only generated a small turbulence additional to that caused by the other samples and the belt. The spheres and disks which surrounded the sample were of the same size but made of expanded polystyrene, since they were only intended to simulate the turbulence in industrial freezers.

Procedure

Two types of food were tested: (1) commercial beef hamburgers, 1 cm thick, 10 cm diameter and 83 g weight; (2) meat balls of pure minced beef with no additives, 3·8 cm diameter. Balls were prepared in a mould specially chosen to obtain uniform sizes and weight.

Air at room temperature was circulated by means of a 1400 rpm blower, with speed control. Air velocity was measured with a TSI 1650 hot-wire anemometer, its resolution being 0·1 m/s. The samples were previously stabilised at the initial temperature of the experiment (−60°C). Then they were placed in the tunnel and the test run until they reached a surface temperature of −20°C. This final temperature was chosen because at this temperature the samples were still completely frozen and constant properties could be used in the calculations.

Method of calculation

Heat conduction in the samples was axial and radial for hamburgers, but it was only radial for meat balls. Thus, the following heat balances were solved:

$$\rho_m C_{p_m} \frac{\partial T}{\partial t} = k_m \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial T}{r \partial r} + \frac{\partial^2 T}{\partial r^2} \right] \quad \text{for hamburgers}$$

$$\rho_m C_{p_m} \frac{\partial T}{\partial t} = k_m \left[\frac{2 \partial T}{r \partial r} + \frac{\partial^2 T}{\partial r^2} \right] \quad \text{for meat balls}$$

The boundary conditions for hamburgers were:

$$k_m \frac{\partial T}{\partial r} = h_c (T_a - T_c) \quad \text{for the lateral surface of the cylinder}$$

$$k_m \frac{\partial T}{\partial x} = h_{pj} (T_a - T_j) \quad \text{for both circular faces}$$

$$\left. \frac{\partial T}{\partial r_r} \right|_{r=0} = 0 \quad \text{by symmetry, at the centre}$$

and for the meat balls were

$$\left.\frac{\partial T}{\partial \pi}\right|_{\pi=0} = 0 \quad \text{by symmetry, at the centre}$$

$$k_m \frac{\partial T}{\partial r} = h_s(T_a - T_s) \quad \text{for the surface}$$

We have assumed constant properties (k_m, ρ_m, C_{p_m}). This is valid with very little error provided -20°C is not exceeded as a gradual ice melting takes place at higher temperatures with related change in thermal properties. As the variation of h with position could not be taken into account for meat balls, a global h was obtained. In the case of hamburgers, a global h could be determined for each circular surface.

In each experiment the measured thermal histories were compared with theoretical curves calculated numerically for different Biot numbers. The value of Bi corresponding to the best fit curve for the experimental data was selected. From the Bi obtained by this comparison, the corresponding h was calculated.

In the case of axial asymmetry in the thermal history of hamburgers (when heat transfer coefficients on both circular surfaces were different), the procedure for finding Biot numbers consisted of a search of two Biots, one for each surface. Using the exact solution, simulation was performed for different pairs of Biot numbers. Curves of best fit for the thermal histories of both surfaces were selected.

For h_c, Morgan's correlation (1975) was used. It is as follows:

$$Nu = 0{\cdot}148 Re^{0{\cdot}633} \quad \text{for } 5000 \leq Re \leq 50\,000$$

$$Nu = 0{\cdot}0208 Re^{0{\cdot}814} \quad \text{for } 50\,000 \leq Re \leq 230\,000$$

RESULTS

A range of v_a between 1 and 7·5 m/s was covered in the experiments, taking several replicates (at least three) for each velocity. Once the coefficients for different air velocities were obtained, correlations were performed in order to get simple prediction formulae. Statistical software (Systat, Inc.) for non-linear regression was used.

Generally, a correlation of the form $Nu = Af_1(Re)f_2(Pr)$ is associated with forced convection (Perry & Chilton, 1973; Arce & Sweat, 1980). However our experimental data covered a very narrow range of Prandtl numbers and no accurate statistics of the dependence of Nu on Pr could be obtained. Perry and Chilton (1973) and Arce and Sweat (1980) state that for bodies immersed in flowing fluids, $f_1(Re) = Re^b$ and $f_2(Pr) = Pr^{1/3}$. Thus, regressions of the type $Nu = ARe^bPr^{1/3}$ were obtained. The values of A and b can be found in Table 2. In all the calculations thermal properties were evaluated at a film temperature T_f [$T_f = 0{\cdot}5(T_a + T_{sur})$].

Several arrangements of belt, food and direction of airflow were tested:

(a) air flow parallel to the belt;
(b) downward air flow through the belt with air impinging first on the sample and then on the belt [downward transverse (DT) flow];
(c) upward air flow through the belt with air impinging first on the belt and then on the sample [upward transverse (UT) flow].

Detailed experimental data are presented elsewhere (Flores & Mascheroni, 1988; Tocci & Mascheroni, 1990). The respective regression curves are represented in Figs 1 and 2 for hamburgers and meat balls, respectively.

Discussion of heat transfer coefficient results

From the data for hamburgers (Fig. 1 and Table 2), it is clear that the values reached by the heat transfer coefficient for transverse air flow, were higher and more uniform for DT flow than for UT flow. They were also higher than those for horizontal air flow at low air velocities ($v_a < 3$ m/s). This can be explained by the differences in flow patterns caused by the belt and by the attack angle of the air on the sample (Amström, 1970).

In the meat balls under investigation, the h values found in transverse flow were appreciably lower for DT than for UT flow. At the same time h values for parallel flow ranged between those of DT flow (for low v_a) and those of UT flow (for high v_a). This indicated that the influence of the belt on the turbulence of the system differed according to air flow direction. In the horizontal flow, the turbulence was produced by the belt and the other balls also present on the belt. In the UT flow, it was caused by the belt. In both cases the turbulence produced an increase in the values of h compared to the case of a single sphere (Tocci & Mascheroni, 1990).

It can also be said that the case of meat balls, which had a partial contact with the belt, was different from that of hamburgers, which had the whole circular

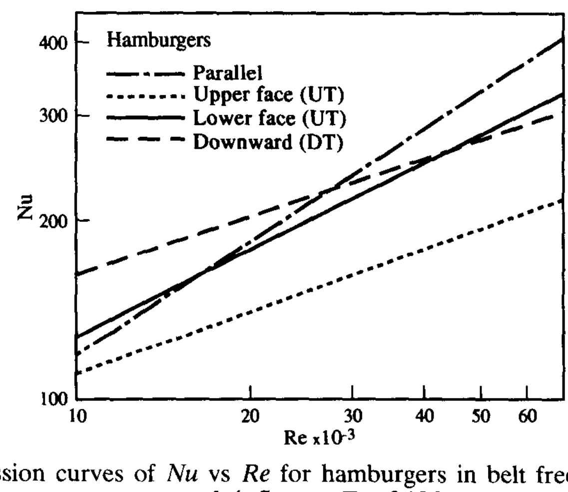

Fig. 1. Regression curves of Nu vs Re for hamburgers in belt freezers for different types of air flow, at $T_a = 248$ K.

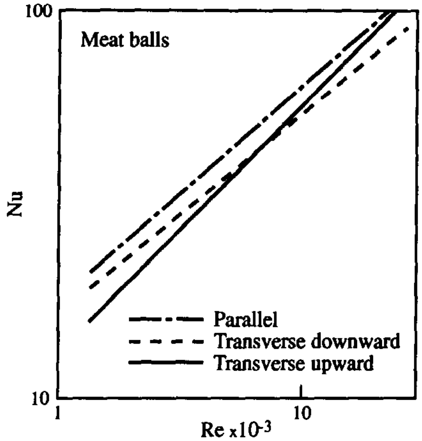

Fig. 2. Regression curves of *Nu* vs *Re* for meat balls in belt freezers for different types of air flow, at $T_a = 248$ K.

face in contact with the belt. In this case, horizontal and DT air flows which impinged on the sample first, had *h* values of the same order (with different *Nu* vs *Re* slopes) and equal for both faces. This was not so for the remaining case (upward flow) in which the hamburger face in contact with the belt (i.e. the face on which air strikes) had a coefficient 40–50% higher than the other face and of the same order of those measured for the other two air flow types.

MASS TRANSFER COEFFICIENTS

As was stated in the Introduction, most authors have made systematic experimental determinations of weight variations of products only for refrigeration at low air velocities (Daudin & Swain, 1990; Radford *et al.*, 1976) or in storage (Fulton *et al.*, 1987). In addition, Sukhwal and Aguirre-Puente (1983), Lambrinos and Aguirre-Puente (1983) and Sakly *et al.* (1988) studied weight loss of frozen meat, potato and test material for different relative humidities and temperatures of air in the low velocity range (up to 2·5 m/s). Thus, there is a lack of systematic information on mass transfer coefficients obtained experimentally under freezing conditions.

To partially fill in this information gap, this work also dealt with the calculation of mass transfer coefficients based on the heat transfer coefficients found experimentally for hamburgers and meat balls. This procedure has proved to be useful since experimental determinations are very complex and require very accurate methods. This is due to the fact that good data is difficult to obtain because of the small size of the samples and the low value of the weight difference to be determined.

TABLE 2

Coefficients of the Regression Equations of the Type $Nu = ARe^{b} Pr^{1/3}$ Obtained from Experimental Data of Heat Transfer Coefficients in Belt Freezers

Air flow	*Product*	*Surface*	*A*	*b*	*Re range*	*Approximate Nu range*
Parallel to the belt	Hamburger	Both	8·770	0·328	10 000–70 000	160–300
	Meat ball	Global	0·175	0·642	2 500–25 000	25–105
Upward, transverse to the belt	Hamburger	Upper	4·666	0·355	10 000–70 000	110–220
		Lower	1·461	0·496	10 000–70 000	125–330
	Meat ball	Global	0·535	0·515	2 500–25 000	25–90
Downward, transverse to the belt	Hamburger	Both	0·363	0·640	10 000–70 000	120–410
	Meat ball	Global	0·448	0·552	2 500–25 000	30–110

Many attempts to develop correlations that predict mass transfer coefficients from heat transfer coefficients have been carried out. The best and most commonly used results were obtained by Ranz and Marshall and are presented in the literature (Sherwood *et al.*, 1975). They provided graphs or equations relating both transfers by replacing *Sh* by *Nu* and *Sc* by *Pr*.

Pham and Willix (1984) specify that coefficients h and K are correlated according to

$$\frac{h}{K} = C_{\mathrm{p}}\left(\frac{Sc}{Pr}\right)^{a}$$

the exponent a has been determined by several authors. The value most usually chosen is that of Kusuda (1965) who suggested that $a = 2/3$. We have used this relation in our calculation.

Replacing our function

$$Nu = \frac{hd}{k_{\mathrm{a}}} = A Re^{b} Pr^{1/3}$$

in the relation provided by Pham and Willix (1984), and substituting *Sh*, the following expression was obtained:

$$Sh = \left[\frac{Sc}{Pr}\right]_{\mathrm{af}}^{1/3} Nu_{\mathrm{f}} = \left[\frac{k_{\mathrm{a}}}{\rho_{\mathrm{a}} Cp_{\mathrm{a}} D_{\mathrm{a}}}\right]_{\mathrm{f}}^{1/3} A Re^{b} Pr^{1/3}$$

The values of k_{a}, ρ_{a}, $C_{\mathrm{p_a}}$, μ_{a} and D_{a} were calculated as a function of temperature using the following equations taken from Perry and Chilton (1973), Weast (1975) and Bolz and Tuve (1980):

$$k_{\mathrm{a}} = \frac{2{\cdot}646 \times 10^{-3} T_{\mathrm{a}}^{1{\cdot}5}}{T_{\mathrm{a}} + 245{\cdot}4 \times 10^{(-12/T_{\mathrm{a}})}}$$

$$C_{\mathrm{p_a}} = \left[1025{\cdot}75 + 0{\cdot}07724 T_{\mathrm{a}} + 1{\cdot}488 \times 10^{-5} T_{\mathrm{a}}^{2} - \frac{5{\cdot}7135 \times 10^{6}}{T_{\mathrm{a}}^{2}}\right]$$

$$D_{\mathrm{a}} = 1{\cdot}4047 \times 10^{-9} T_{\mathrm{a}}^{1{\cdot}75}$$

$$\rho_{\mathrm{a}} = \frac{349{\cdot}43}{T_{\mathrm{a}}}$$

$$\mu_{\mathrm{a}} = \frac{1{\cdot}458 \times 10^{-6} T^{1{\cdot}5}}{T + 110{\cdot}4}$$

As an example of the values obtained for air flow parallel to the belt, Fig. 3 shows the variation of *Sh* with *Re* for meat balls at different air temperatures. The same information is given for hamburgers (Fig. 4). In both cases it is clear that air temperature had little influence on the predicted coefficients. Figures 5

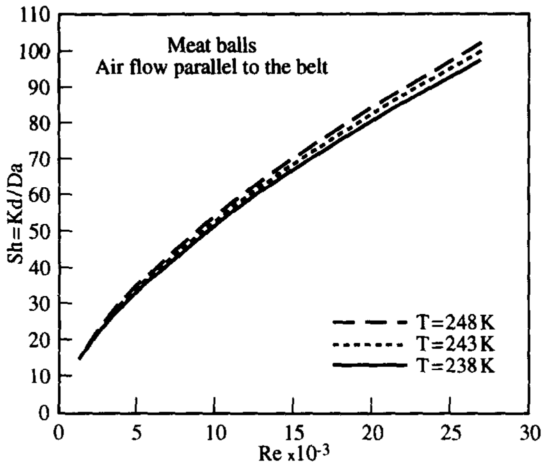

Fig. 3. Predicted variation of *Sh* with *Re* for meat balls at different air temperatures and for air flow parallel to the belt.

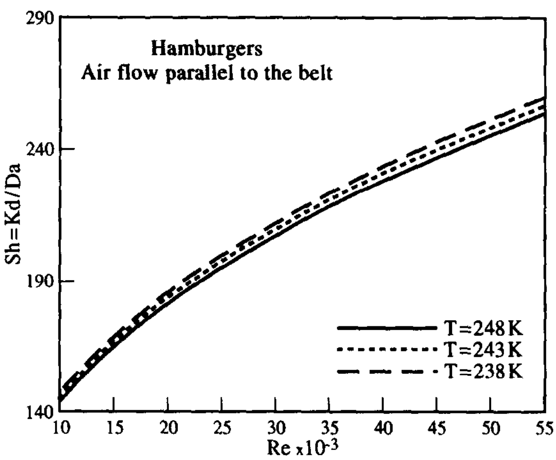

Fig. 4. Predicted variation of *Sh* with *Re* for hamburgers at different air temperatures and for air flow parallel to the belt.

and 6 show, for meat balls and hamburgers, respectively, the variation of *Sh* for a given temperature and different types of air flow.

It is noticeable that, in all cases, an increase of air velocity increased both *h* and *K* in a similar way. Related to this fact, the rate of weight loss during freezing also increased but, as the freezing time was shorter, both factors partially balanced. Therefore the effect of air velocity on the weight loss is small (Tocci & Mascheroni, 1994). Finally, the same type of conversion made in

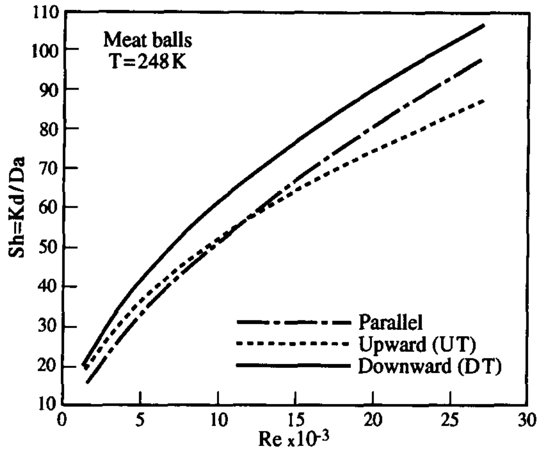

Fig. 5. Predicted variation of Sh with Re for meat balls at $T_a = 248$ K and for different types of air flow.

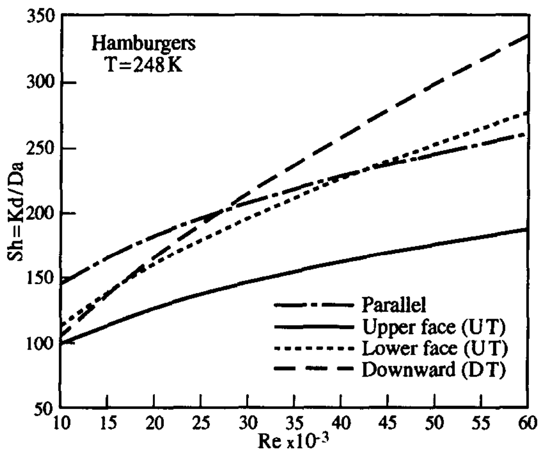

Fig. 6. Predicted variation of Sh with Re for hamburgers at $T_a = 248$ K and for different types of air flow.

previous paragraphs can be applied to reliable h results for other products or types of equipment to obtain the related K values.

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