MEASUREMENT OF THE HEAT TRANSFER COEFFICIENT IN A THAWING TUNNEL

V. GEKAS[1], I.S. CHRONAKIS[2,5], C. ESCADA[3] and I. SJÖHOLM[4]

[1]*Department of Environmental Engineering*
TUC, 73100, Hania, Greece

[2]*Department of Physical Chemistry 1*
[4]*Department of Food Engineering*
Center for Chemistry and Chemical Engineering
Lund University
POB 124, S-221 00, Lund, Sweden

[3]*Escola Superior de Biotecnologia*
Universidad Católica Portuguesa
Rua Antonio Bernandini de Almeida
4200 Porto, Portugal

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ABSTRACT

In a convective (air) thawing tunnel designed in the department of Food Engineering at Lund, and previously applied for the thawing of meat, we have measured the heat transfer coefficient using an ice model with a geometry which could be approximated to an infinite slab. The heat transfer coefficient was deduced from the agreement between experimental and simulated (using a commercial numerical program) data. The results could be summarized by the following equation: $Nu = 1.27 Re^{0.553}$. *Thus, the dependency of the heat transfer coefficient on the Reynolds number agrees well with correlations found in the literature for similar kinds (freezing, thawing) of application. In particular the found Nusselt relationship was in a very good agreement with the Heldman correlation for freezing of foodstuffs in the turbulent regime.*

INTRODUCTION

Preservation by freezing of the quality of fruits (such as berries, kiwi, etc.) and vegetables is attractive for both the industry and also for the catering business. Whereas a lot is known on freezing, thawing has not been studied equally well, so that it is observed, especially in the second case (catering), that

[5] Author to whom the correspondence should be sent. Tel. +46-46222 8154, Fax +46-46222 4413, email: Ioannis.Chronakis@fkem1.lu.se

the good quality of a frozen product is often unnecessarily destroyed upon thawing or in other cases unnecessary prolonged and badly controlled thawing even results in higher costs besides the quality losses. Thawing to and by unnecessarily high temperatures for example could give structure changes causing drip losses (juice losses) in the jam industry. In industry and especially in the catering branch humid air is used as the thawing medium (convective thawing).

Heat transfer coefficient data in the literature are provided in the form of Nusselt correlations which are semiempirical in their nature, containing constants which depend strongly on the design of a particular equipment and also on the geometry of the product, its way of placement in the equipment and so on. Therefore, it is not possible to know *apriori* whether a literature correlation is applicable in a given equipment and given geometry or position conditions. Then it is necessary to estimate the heat transfer coefficient from own experimental and theoretical data valid in the system under study.

In our case the system is a thawing tunnel, initially used for the thawing of meat products (Lind and Hulthen 1986). In a first approximation the heat transfer coefficient is independent from the kind of the product to be processed, its geometry only excluded, and this was the case for example in a recent study concerning convective drying of potato, apple and carrot (Ratti and Crapiste 1995). This approximation is a very reasonable assumption in most of the cases and especially for the kind of process engineering purposes like the one in the present study. In some more sophisticated cases the heat transfer coefficient might be dependent on the kind of the product, for example roughness effects (Gekas 1992) or mass transfer effects resulting from the particular kind of a food (Lind 1988).

Based on the above we have chosen an ice model for the frozen foods or vegetables, this being an intermediate between an aluminum specimen and a real food specimen. The approach followed was to obtain experimental temperature-time data for various air velocities (Re numbers) and then simulate the thawing process with the value of heat transfer coefficient giving the best agreement (minimization of the error sum of squares) between the experimental and simulated temperature-time points.

MATERIALS AND METHODS

Thawing Tunnel

The thawing tunnel used has been described elsewhere (Lind and Hulthen 1986; Lind 1991a;b) and it is shown in Fig. 1. Some data are briefly given below: The product chamber, being a 330 mm side cube, was incorporated in a tunnel through which the air flows. Air temperature (between -5 up to +25C), air flow rate (0-6 m/s) and to some extend air humidity (75% ± 5%), could be easily controlled. The product could be either placed on a wire mesh shelf or hung below an electronic balance placed on top of the chamber (see Fig. 1), so that the product could be continuously weighed. Of the two modes the former was chosen (wire mesh shelf).

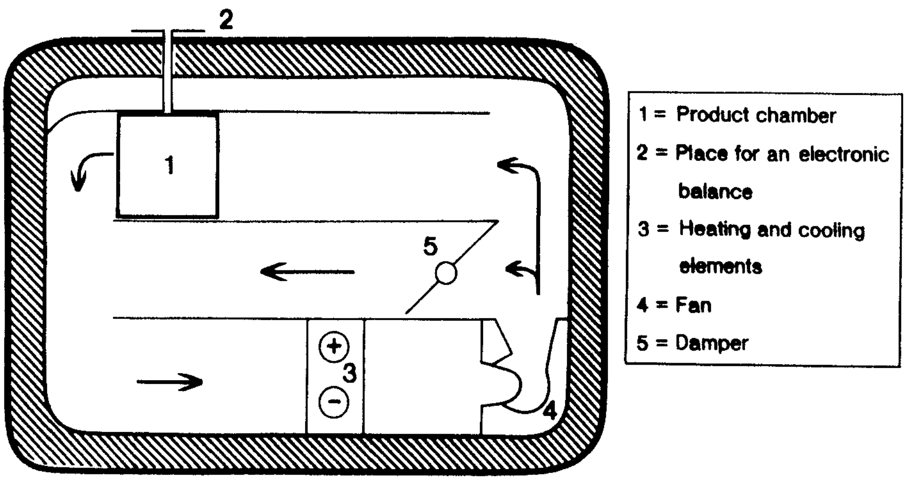

FIG. 1. A SCHEMATIC DIAGRAM OF THE THAWING TUNNEL

Physical Model

A piece of ice was put in a box made of aluminum foil with dimensions 180 × 140 × 52 mm^3. The upper surface of 180 × 140 mm^2 was the only one exposed to the air flow, all others having been isolated with fiber glass. The geometry and the partial isolation done were ensuring treatment of the specimen as an infinite slab with Newton's law of cooling as the top surface boundary condition and with the no-heat flux condition as the bottom surface boundary condition. Copper-constantan thermocouples were used for the temperature registration in the air, in the bottom and the top surface of the specimen. To overcome the problem of a precise measurement of the top surface temperature, the thermocouples were immersed a little distance within the ice (approx. one mm) and it was that point that has also been considered in the numerical simulations. The thermocouples were connected to a computer for the automatic reading of the evolution of temperature at different positions in the specimen and also air temperature with time. For future use with the real products, it can be said that there is the possibility of reporting air humidity as well through both wet and dry air temperature.

Thawing

Prior to thawing, the specimens were frozen to -20C and the conditions in the tunnel were adjusted. Thawing experiments were carried at constant air temperatures of 10, 12.2, 15 and 19C. At each temperature the air velocities were 1.6, 3.4, 4.1, 4.6, 5.1 and 6.2 m/s. The thawing of the ice piece was proceeding until reaching a temperature of -2C at the bottom (a thawing time of approximately three hours). This was a good practical choice, concerning both experimental duration and need, in a first place, to know what happens during warming at subzero temperatures without implication of the phase change.

Simulation

The numerical simulation was done with a commercial computer program developed by Dr. A.C. Cleland (FINDIFF) for heat transfer processes including freezing/thawing (Hallström *et al.* 1988; Gekas 1992; Cleland 1996). The FINDIFF program asks to feed the data of the thermal properties of the product, alternatively provides the user to consult/use a library for the thermal properties at various temperatures. The basis of the numerical simulations of the Fourier equation or other forms of the generalized transport equation is described in several teaching books and it is assumed here as known (Hallström *et al.* 1988; Gekas 1992). For the heat transfer the second Fourier's law and the boundary conditions are discretized using a finite difference approach thereby converting the differential equations to algebraic ones.

The heat transfer coefficient appears in the top surface boundary condition and its knowledge it is not *apriori* known, as said in the Introduction. Therefore, an iterative method is used, by which an arbitrary, although a reasonable one to avoid a lengthy simulation procedure, value of the heat transfer coefficient is fed to the program and then this value is in subsequent runs adjusted so that the simulated temperature-time curve agrees with the experimental one to a desired accuracy. The accuracy was obtained by the minimization of the error sum of squares values.

RESULTS AND DISCUSSION

The results were obtained in the form of temperature-thawing time diagrams containing the experimental points as well the simulated curve for each set of air temperature-air velocity conditions for the heat transfer coefficient giving the relatively best fitting. In Fig. 2, there is shown an example of these diagrams. In general bottom temperature was better fitted than top temperature, due most probably to the measurement difficulties concerning the latter.

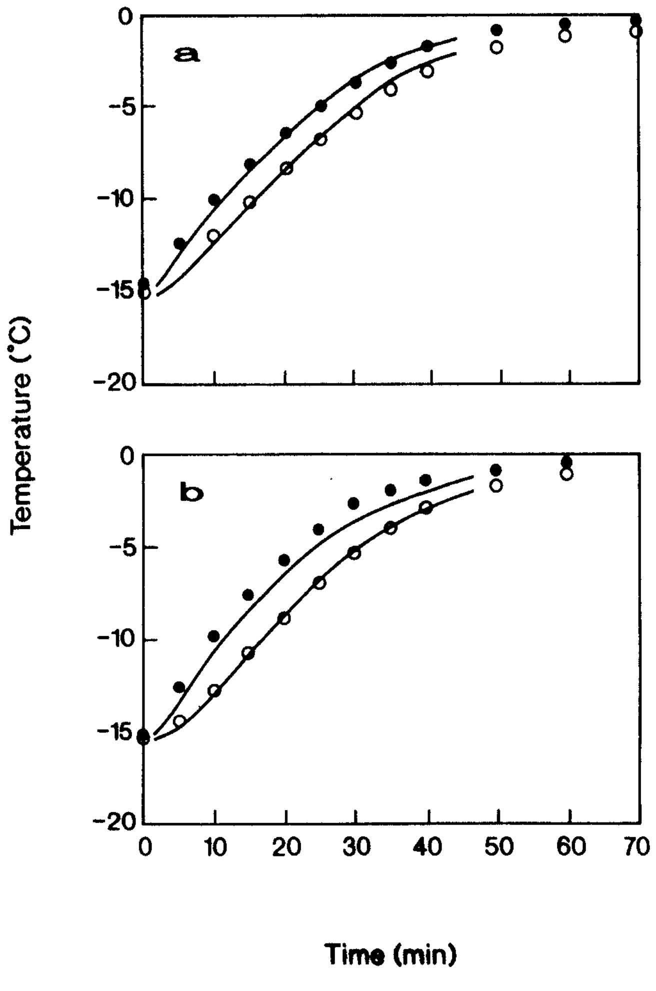

FIG. 2. AN EXAMPLE OF TEMPERATURE-TIME EVOLUTION DURING THAWING OF AN ICE SPECIMEN

Air flow velocity 4.1 m/s for two air temperatures (a) 10C and (b) 12.2C. Best fitting value for the simulated data (continuous lines) h=52 W/m^{2}K. Open circles refer to bottom-, filled circles to the top-surface of the specimen.

The results in terms of the heat transfer coefficient (h) at various air flow velocities (u) are shown in Table 1. In a regression analysis, in the turbulent region, it was easy to show a dependency of the h on the 0.553 power of the flow velocity, reflecting a similar dependency of the Nu number from the Reynolds number (Fig. 3). The Nu-Re dependency found is not too far from the one reported by Heldman in an application of freezing of minced meat: $Nu = 0.579\ Re^{0.582}$. In general the type of Nu correlations in the literature are of the form $Nu = c_1\ Re^{c2}\ Pr^{c3}$.

TABLE 1.
HEAT TRANSFER COEFFICIENT ESTIMATED AT VARIOUS AIR FLOW RATES

Air Flow Rate (u, m/s)	Heat Transfer Coefficient (h, W/m²K)
Laminar regime	
1.6	37
Turbulent regime	
3.4	47
4.1	52
4.6	57
5.1	60
6.2	65

All estimated h values are accurate to the last digit (57 means for example 57.0 ± 0.5)

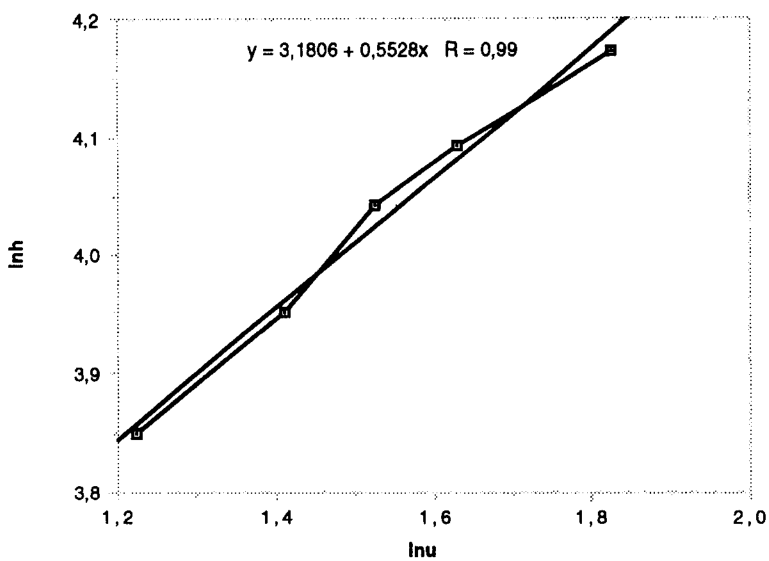

FIG. 3. REGRESSION ANALYSIS OF THE RELATIONSHIP HEAT TRANSFER COEFFICIENT (h) - AIR FLOW RATE (u), IN THE TURBULENT REGION (u is in m/s and h in W/m²K)

The type of correlations, like Heldman's or the one found in the present work in which the Pr number is not explicitly present in the equation ($Nu = c_1' Re^{c2}$), may suggest that this number containing the physical properties of the cooling or heating medium (air) is included in the constant c_1'. In other cases as well, for example in dehydration, where the water is mainly responsible for the thermal properties of the product, the same type of correlations were found (as for example, Ratti and Crapiste 1995, recently, for drying).

To estimate the constant c_1' in our case, we take into account the following (Fig. 3):

$$\ln h = 3.18 + 0.553 \ln u \qquad (1)$$

$$\ln Nu = \ln c_1' + 0.553 \ln Re \qquad (2)$$

But, by definition: $Nu = hd/\lambda$ and $Re = du/\nu$, where d is the characteristic length of the tunnel taken as d=0.330 m, and λ, ν thermal conductivity and kinematic viscosity of the air in the 10-20C region, values in SI units from literature Tables (CRC Handbook of Chemistry and Physics). Then c_1' could be estimated through Eq. (1) and (2) to 1.27 giving $Nu = 1.27\ Re^{0.553}$. In the present approach we have not considered mass transfer effects and this choice is justified by the fact that this effect should be negligible since we have avoided a final product temperature beyond phase change. In the real situations to be studied in the next we intend, if necessary, to account for such effects.

CONCLUSIONS

It was possible to estimate the heat transfer coefficient in a thawing tunnel using convective air flow, with an air temperature in the interval 10-20C. An ice piece model for the food was used, heated ion the tunnel from -20 to -2C. The correlation found was $Nu = 1.27\ Re^{0.553}$.

NOMENCLATURE

c_1 constant in the h-u correlation (SI-units)
c_1' constant in the Nu-Re correlation (-)
c_2 exponent of the Re number in the Nusselt correlations (-)
c_3 exponent of the Prandtl number in the Nusselt correlations (-)
d characteristic length (m)
h heat transfer coefficient (W/m^2K)
u air velocity (m/s)

Nu Nusselt number (-)
Pr Prandtl number (-)
Re Reynolds number (-)
λ heat conductivity (W/mK)
ν kinematic viscosity (m^2/s)

REFERENCES

CLELAND, A.C. 1996. *Food Refrigeration Processes-Analysis, Design and Simulation*. Chapman and Hall, London.

GEKAS, V. 1992. *Transport Phenomena of Foods and Biological Materials,* (P. Singh and D. Heldman, eds.) CRC Press, Boca Raton, FL.

HALLSTRÖM, B., SKJÖLDEBRANDT, C. and TRÄGÅRDH, C. 1988. *Heat Transfer and Food Products*, Elsevier, London.

HELDMAN, D.R. 1975. *Food Process Engineering*, Van Nostrand Reinhold/ AVI, New York.

HELDMAN, D.R. 1980. Prediction of food product freezing rates. In *Food Process Engineering*, Vol. 1, (P. Linko, Y. Mälkki, J. Ulkku and J. Larinkari, eds.) Applied Science Publishers, London.

LIND, I. 1988. Surface heat transfer by forced air convection. J. Food Eng. *7*, 19–39.

LIND, I. 1991a. The measurement and prediction of thermal properties of food during freezing and thawing. A review. J. Food Eng. *13*(4), 285–319.

LIND, I. 1991b. Mathematical modelling of the thawing process. J. Food Eng. *14*(1), 1–23.

LIND, I. and HULTHEN, B. 1986. Thawing of food in catering. J. Foodservice Systems *4*, 81–96.

RATTI, C. and CRAPISTE, G.H. 1995. Determination of heat transfer coefficients during drying of foodstuffs. J. Food Process Engineering *18*, 41–53.