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Cooling process and heat transfer parameters of cylindrical products cooled both in water and in air

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Abstract—This study presents an investigation of transient heat transfer from cylindrical products to both the water and air flows and obtains the methods for determining the cooling process parameters (cooling coefficient, lag factor, half cooling time and seven-eighths cooling time) and heat transfer parameters (thermal conductivity, thermal diffusivity, specific heat, and heat transfer coefficient). The various batches of the cylindrical products were cooled in the water flow at constant flow velocity and the same batches of the cylindrical products were also cooled in air at different flow velocities. During cooling experiments, the center temperatures of the individual products were measured and the temperature data were used to determine the cooling process and heat transfer parameters. The results of the present study showed that the half cooling times and seven-eighths cooling times increased at constant flow velocity with increasing batch weight in water cooling and decreased with increasing the flow velocity in air cooling and that the heat transfer coefficients decreased by 47.7% at constant batch weight (5 kg) with an increase in the batch weight in water cooling and increased by 46.2% with an increase in the flow velocity in air cooling.

INTRODUCTION

FRESH fruits and vegetables are cooled to their storage temperatures shortly after harvesting, in order to reduce the rate of quality degradation and to extend their shelf life. In this respect, several cooling methods, namely water cooling, air cooling, hydraircooling, and vacuum cooling are used in practice. In order to design an efficient and effective cooling system for the products, engineers and researchers must make an exact analysis of transient heat transfer during food-cooling and have knowledge of the many variables, namely product size, shape and thermal properties, cooling conditions and configuration of the product during cooling, which affect cooling rate. Interactions between some of these variables must be obtained and the heat transfer must be analyzed to determine the optimum processing conditions which can give a minimum cooling cost for certain specified conditions. Determination of the cooling process parameters, namely cooling coefficient, lag factor, half cooling time and seven-eighths cooling time and heat transfer parameters, namely thermal conductivity, thermal diffusivity, specific heat, and heat transfer coefficient are important for a proper design and operation of such systems. But the most important parameter within the heat transfer parameters is the heat transfer coefficient which is defined as the thermal transmission in unit time to or from unit area of a surface in contact with its surroundings for unit difference between the temperature of the surface and the environmental fluid temperature.

Limited investigations have been reported in order to analyze the cooling data and to estimate process parameters of the food products during cooling [1–3]. These investigations included the theoretical approaches. Within these investigations, Pflug and Blaisdell [2] suggested several theoretical methods for analyzing cooling data. Additionally, Dincer *et al.* [4] carried out a detailed experimental study and determined the process parameters using an efficient technique. Some experimental and theoretical studies have been made for determining the heat transfer coefficients during food-cooling [5–9]. In the present study, a new approach is presented to determine the heat transfer coefficients for the cylindrical products during cooling in water and in air. No similar study appears in the literature.

The main purpose of the present study is to investigate transient heat transfer which takes place during both water and air cooling of the individual cylindrical products and to determine the cooling process parameters and the heat transfer parameters.

EXPERIMENTAL

Experimental investigation was carried out in two cases, namely case 1 : cooling with water and case 2 : cooling with air.

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NOMENCLATURE

a	thermal diffusivity [$m^2 s^{-1}$]
a_w	thermal diffusivity of water at the initial product temperature, [$0.148 \times 10^{-6} m^2 s^{-1}$]
Bi	Biot number
C	cooling coefficient [s^{-1}]
D	diameter [m]
Fo	Fourier number
h	heat transfer coefficient [$W m^{-2} K^{-1}$]
J_1	lag factor
J_0	zeroth order Bessel function of first kind
k	thermal conductivity [$W m^{-1} K^{-1}$]
L	length [m]
M	root of Bessel characteristic equation
r	radial coordinate
R	radius [m]
R^2	regression coefficient
S	seven-eighths cooling time [s]
t	time [s]
T	temperature [°C or K]
U	flow velocity [$m s^{-1}$]
w	crate load (batch weight) [kg]
W	water content, in decimal unit
Z	half cooling time [s].

Greek symbols

Γ	dimensionless radial distance
θ	dimensionless temperature
ϕ	temperature difference [°C or K].

Subscripts

a	medium condition
e	final
i	initial
w	water
n	refers to nth number of characteristic value
1	refers to 1st number of characteristic value.

Case 1 : *cooling with water*

In the hydrocooling experiments, cucumbers were used as cylindrical products. Test samples consisted of batches of 5, 10, 15, and 20 kg of product.

The experimental facility, shown in Fig. 1, consisted of a conventional refrigeration unit (Tecumseh CK-99301-2 model reciprocating compressor of 9280 W capacity, a condenser cooled by dual 370 W fans, a Flica TMC 4.5 model expansion valve, and a water-cooled evaporator) and a cold water pool (inner dimensions $1.996 \times 0.776 \times 0.4$ m). The cold-water pool consisted of a lidded tank, insulated with glass wool, through which cooled water was pumped. The pool-water level was held at 2/3 full. The flow velocity of water in the tank was measured to be 50 mm s^{-1} using a digital flowmeter (Hoentzsch GmbH, Germany). The water temperature was measured with three thermocouples at the inlet, just behind the crate and outlet. Batches of 5, 10, 15, and 20 kg from each food commodity were placed in slatted polyethylene crates (polyethylene boxes, open at the top and with grids in the surfaces) with the dimensions of 0.25 m^2 area and 0.2 m deep and thermocouples were embedded at the centers of 12 products randomly selected in a crate containing each batch for each experiment. Each crate containing products (cucumbers: $D = 0.038 \pm 0.001$ m and $L = 0.160 \pm 0.005$ m) was dipped into the cold water flow and therefore, each experiment was made. This procedure was repeated for each batch. In all experiments, the same crates were used. All fifteen DCK8 Cu/Cu–Ni thermocouples were calibrated at 1°C and had wires 50 mm long and 1.2 mm in diameter to minimize conduction errors. Measurements, accurate to ± 0.1°C, were continuously recorded by a calibrated CMC 821 multi-channel microprocessor device (Ellab Instruments, Denmark) at 30 s intervals until all of the center temperatures of the products reached the storage temperatures, i.e. 4°C for cucumbers. Temperature data measured at the centers of 12 individual products in each batch were averaged for data analysis. The water contents of the products were determined by using

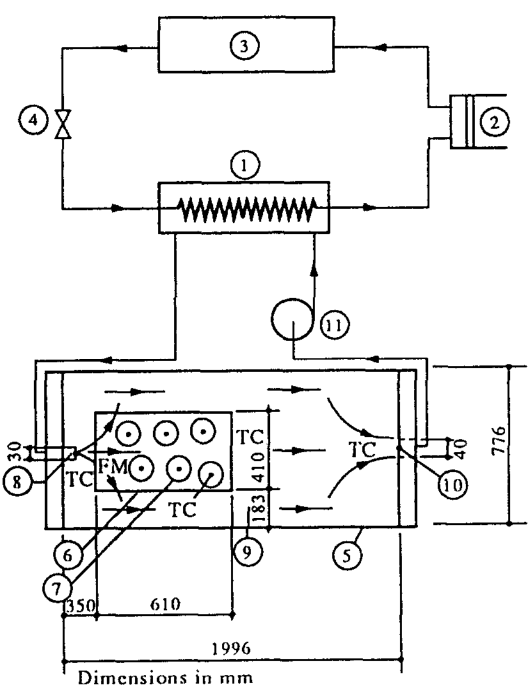

FIG. 1. A schematic drawing of the hydrocooling system: 1, evaporator; 2, compressor; 3, condenser; 4, expansion valve; 5, cold water pool; 6, crate; 7, product; 8, water inlet; 9, water flow; 10, water outlet; 11, circulation pump; TC, thermocouple; FM, flowmeter.

a dry-matter method in the laboratory. A detailed description of the experimental apparatus and procedure, including schematic diagrams of the arrangements of the products, the position of the crate, and the direction of flow is given in Dincer [4, 9, 10].

Case 2: cooling with air

Due to technological importance of accurately analyzing heat transfer and determining the cooling process parameters, a large body of experimental data is necessary. In addition to hydrocooling experiments, a forced-air experimental investigation was conducted to determine temperature distributions of the individual cylindrical products.

Apparatus. The forced-air cooling system was designed and built in a Pilot Plant of the Refrigeration Technology Department and was used in the experimental investigation. The complete experimental system consists of two major parts, namely a cooling chamber (test section) and a combined refrigerating unit. A schematic diagram of the experimental apparatus is given in Fig. 2.

Cooling processes were obtained in the test chamber with the outer dimensions of $1 \times 1 \times 2$ m. The chamber was manufactured from 0.04 m square profiles whose surface was plated with stainless steel sheets of 0.0005 m in thickness. Glass wool was filled between the inside and outside sheets to prevent heat losses. A radial fan, having a power of 1500 W and running at 2830 r.p.m., provided air-flow velocities at 1, 1.25, 1.5, 1.75 and 2.0 m s^{-1} in the cooling chamber. Various air velocities were obtained by the fan motor having a variable speed controller unit. Air was circulated through a channel of 0.28 m diameter made from PVC. A bellow was installed to absorb the fan vibrations. The temperatures of the products in the crate and that of the air at various points were measured by an Ellab CMC 821 multi-channel microprocessor device (Ellab Instruments, Copenhagen), which is capable of measuring with an accuracy of ± 0.1°C. To minimize the conduction losses in these experimental investigations, the shortest temperature probes (DCK 8 copper–constantan thermocouples, having 0.05 m long and 0.0012 m in diameter) were used. The temperatures were read, displayed and printed at every 30 s. The change of the relative humidity inside the test chamber was measured by a Squirrel Meter/Data Logger (Grant Instruments Ltd., Cambridge), having capacitive vaisala probes. The flow velocity of air over the products inside the test chamber was measured with a digital flowmeter (Hoentzsch GmbH, Germany). The initial and final water contents of the products were measured by drying the sample in a vacuum oven at 100°C for 24 h. In these experiments, the same crates which were used in the water-cooling were used. Initial product-temperatures were measured to be 22 ± 0.5°C.

Procedure. The experimental studies were conducted to determine the temperature distributions of the cylindrical products exposed to the forced-air cooling at various air flow velocities. For each test, a batch of 5 kg from approximately cylindrical products was selected and placed into a polyethylene crate. The twelve temperature probes were embedded at the center positions of the twelve samples selected randomly in each batch. The other remaining probes were provided to measure temperatures at the bottom, in the middle, and on top of the chamber, and inlet and outlet temperatures of the cooling-air. The relative humidity probes were located inside the chamber. After reaching the desired temperature and relative humidity level in the chamber, the crate containing

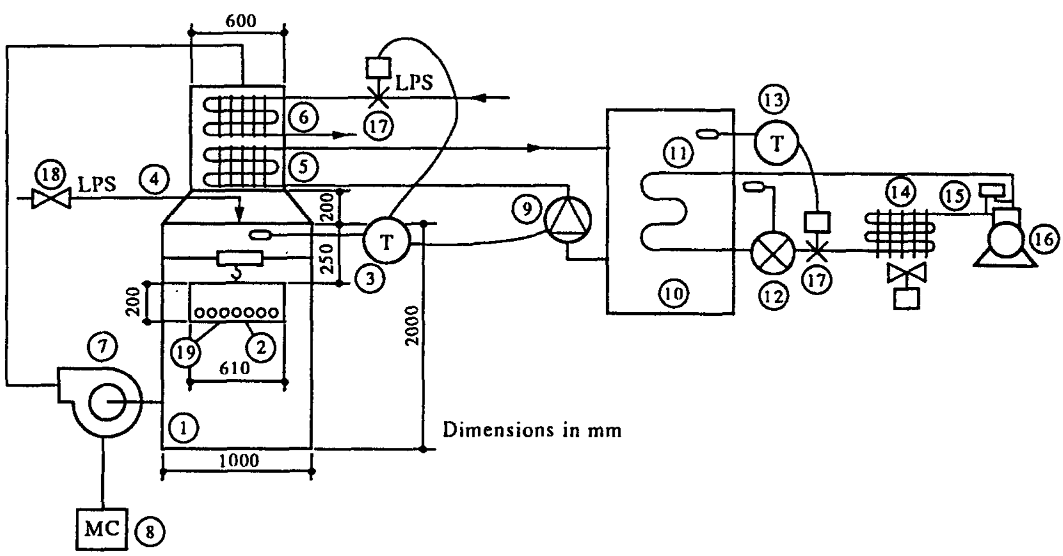

Fig. 2. A schematic drawing of the forced-air cooling system: 1, cooling chamber; 2, product; 3, thermostat; 4, low pressure steam inlet; 5, cold water heat exchanger; 6, steam heat exchanger; 7, radial fan; 8, fan speed controller; 9, water pump; 10, water tank; 11, evaporator; 12, thermostatic expansion valve; 13, thermostat; 14, air cooled condenser; 15, presostat; 16, compressor; 17, solenoid valve; 18, valve; 19, crate.

the products was hanged up to the hook and then the measurements were made. This procedure was repeated five times at the air-flow velocities of 1, 1.25, 1.50, 1.75, and 2 m s^{-1}, respectively. A detailed description of the experimental apparatus, instrumentation and procedure is given in detail in ref. [11].

ANALYSIS

Cooling parameters

Consider constant thermal and physical properties of the product and the cooling medium when operating under the unsteady-state conditions. The following analytical formulation is used as the technique for analyzing the cooling data during the cooling of food products [10, 12].

Dimensionless temperature is expressed using the product temperatures and the medium temperature, respectively,

$$\theta = (T-T_a)/(T_i-T_a). \quad (1)$$

The dimensionless temperature is generally expressed in the form of an exponential equation, including the cooling parameters in terms of the cooling coefficient (C), and lag factor (J_1), as

$$\theta = J_1 \exp(-Ct). \quad (2)$$

The cooling coefficient denotes the change in product temperature per unit change of cooling time for each degree temperature difference between the product and its surroundings.

By substituting $\theta = 0.5$ into equation (2), the half cooling time, which is one of the most meaningful in the practical applications, is defined as

$$Z = [\ln(2J_1)]/C. \quad (3)$$

Also, by substituting $\theta = 0.125$ into equation (2), the seven-eighths cooling time is found as

$$S = [\ln(8J_1)]/C. \quad (4)$$

Heat transfer parameters

To formulate the exact model we have to define the basic terms, and then proceed to the present model for determination of the heat transfer coefficients of the cylindrical products.

The governing heat conduction equation in one-dimensional cylindrical coordinate for unsteady-state with negligible internal heat generation and no moisture loss may be written as follows:

$$[(\partial^2 T/\partial r^2)+(1/r)(\partial T/\partial r)] = (1/a)(\partial T/\partial t). \quad (5)$$

The governing equation in terms of the excess temperature $\phi = T-T_a$ is

$$[(\partial^2 \phi/\partial r^2)+(1/r)(\partial \phi/\partial r)] = (1/a)(\partial \phi/\partial t). \quad (6)$$

The initial and boundary conditions are

$$\phi(r,0) = \phi_i = T_i - T_a,$$

$$\partial\phi(0,t)/\partial r = 0,$$

$$-k\,\partial\phi(R,t)/\partial r = h\phi(R,t).$$

The solution of equation (6) for estimating the dimensionless temperature distribution at any point of a cylindrical body is found in the literature [12–14]. The dimensionless temperature is

$$\theta = \sum_{n=1}^{\infty} \frac{2Bi}{[M_n^2+Bi^2]J_0(M_n)} J_0(M_n\Gamma)\exp(-M_n^2 Fo) \quad (7)$$

where $\Gamma = r/R$.

For the center of the cylinder product, $\Gamma = 0$ and equation (7) is reduced to equation (8)

$$\theta = \sum_{n=1}^{\infty} \frac{2Bi}{[M_n^2+Bi^2]J_0(M_n)} \exp(-M_n^2 Fo). \quad (8)$$

Considering $Fo > 0.2$, the infinite sum can be approximated by the first term of the series and may be represented by the following expression

$$\theta = J_1 \exp(-M_1^2 Fo) \quad (9)$$

where $J_1 = [(2Bi)/(M_1^2+Bi^2)J_0(M_1)]$.

Dimensionless temperature values are derived using temperature measurements in equation (1) and a regression analysis for the dimensionless temperature distributions in the form of equation (2) was carried out using the least squares method.

The following equation is obtained by combining equations (9) and (2):

$$M_1^2 Fo = Ct. \quad (10)$$

The dimensionless numbers are introduced:

$$Fo = at/R^2 \quad (11)$$

$$Bi = hR/k \quad (12)$$

$$M_1^2 = (6Bi)/(2.85+Bi). \quad (13)$$

After making these substitutions, the present model for determining the heat transfer coefficient for a cylindrical product is developed as

$$h = [(2.85kRC)/(6a-CR^2)]. \quad (14)$$

The thermal conductivity (k), thermal diffusivity (a) and specific heat of the food products strongly depend on their water content and are given as follows [15, 16]

$$k = 0.148+0.493W \quad (15)$$

$$a = 0.088\times10^{-6}+(a_w-0.088\times10^{-6})W \quad (16)$$

$$C_p = 0.837+3.349W. \quad (17)$$

RESULTS AND DISCUSSION

Regression analyses were carried out on the dimensionless temperature data in the exponential form as given in equation (2). From the regression analyses, the lag factors (J_1) and cooling coefficients (C) were determined and hence, the half cooling times (Z) and seven-eighths cooling times (S) were calculated by

Table 1. Cooling process parameters of the individual cucumbers cooled with water ($D = 0.038 \pm 0.0010$ m, $L = 0.160 \pm 0.005$ m, $T_i = 22.0 \pm 0.5°C$, $T_e = 4°C$)

w (kg)	R^2	J_1	C (s^{-1})	Z (s)	S (s)
5	0.987	1.291389	0.001602	546.6	1457.6
10	0.996	1.177443	0.001567	592.3	1531.2
15	0.996	1.210404	0.001385	638.3	1639.2
20	0.991	1.250717	0.001243	737.6	1852.9

means of equations (3) and (4). The cooling parameters expressed in terms of J_1, C, Z, and S are given in Table 1.

It can be seen from Table 1 that the high regression coefficients were obtained in the regression analyses in the exponential form which were based on the least squares method and that the lag factors which are functions of the physical and thermal properties of the product. They are larger than 1 and indicate the certain internal resistance to the heat transfer within the product. The cooling coefficients decreased with increasing crate load from 5 to 20 kg. The values of cooling coefficient were obtained to be highly sensitive to the size of the products and their surfaces exposed to the cooling medium. As can be seen in Table 1, the half cooling time and the seven-eighths cooling time for the individual cucumbers from 5 to 20 kg increased 34.9 and 27.1%. As a result, the changes in the half cooling times and seven-eighths cooling times were found to be dependent on the crate load (batch weight) and this strongly indicates that the flow and temperature profiles around the product were influenced by the crate load and were found to be different for each batch.

Figure 3 presents the comparisons between the measured and regression center temperature distributions of the individual cucumbers in crates containing 5, 10, 15, and 20 kg of product. As the cooling time increases, the dimensionless measured and regression center temperature distributions are observed to decrease monotonically. Agreement is found to be very good between the measured and regression results and the maximum difference between them is 9.9% except for the dimensionless temperature value at $t = 0$. This is because the regression temperature values at $t = 0$ are larger than 1 and this situation shows the lag factor.

In addition to the results obtained in the hydrocooling experiments, the cooling process parameters of the cylindrical products subjected to the forced-air cooling are given in Table 2.

It can be seen from Table 2 that the cooling process parameters were strongly affected by the increase in the flow velocity of air. The cooling coefficients increased with an increase in the flow velocity of air during cooling of the individual products. We found that the half cooling times and seven-eighths cooling times also decreased by 27.6 and 32.3% for an individual cucumber with increasing flow velocity of air from 1 to 2 m s^{-1}. As presented above, the cooling process parameters were found to be dependent upon the experimental conditions including different flow velocities. This would seem to be due to changes in the heat transfer environment in forced-air cooling.

Figures 4–8 show the measured and regression center temperature distributions of the individual

Table 2. Cooling process parameters of the individual cucumbers cooled with air

U (m s^{-1})	R^2	J_1	C (s^{-1})	Z (s)	S (s)
1.00	0.964	1.243384	0.0005595	1628.2	4105.9
1.25	0.960	1.254941	0.0006286	1463.9	3669.3
1.50	0.978	1.293050	0.0006907	1375.6	3382.7
1.75	0.964	1.598894	0.0009026	1287.9	2823.8
2.00	0.967	1.391872	0.0008680	1179.5	2776.6

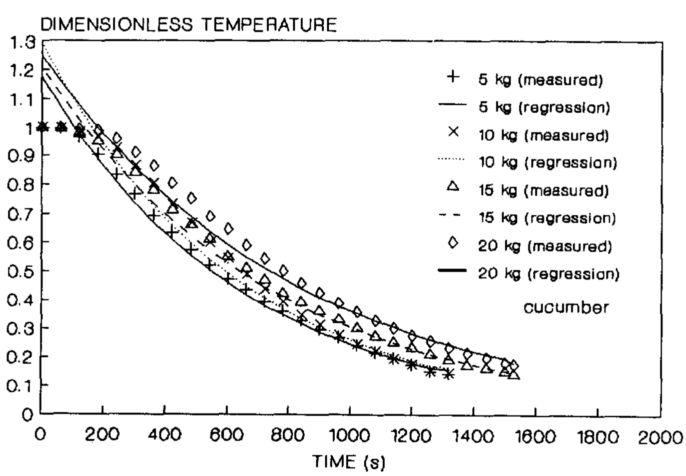

FIG. 3. Measured and regression temperature distributions of an individual cucumber in batches of 5, 10, 15 and 20 kg.

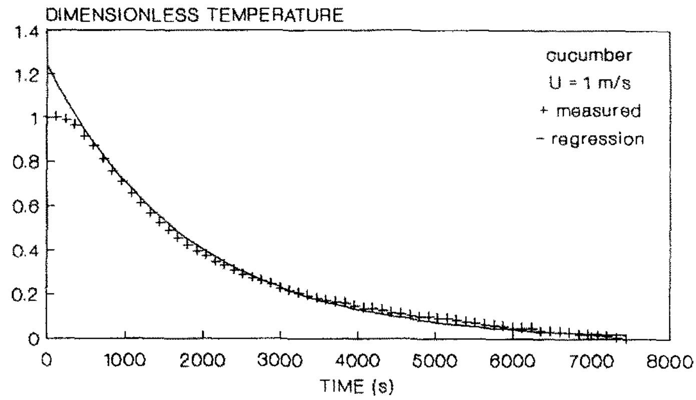

FIG. 4. Measured and regression temperature distributions of an individual cucumber in batch of 5 kg at air-flow velocity of 1 m s^{-1}.

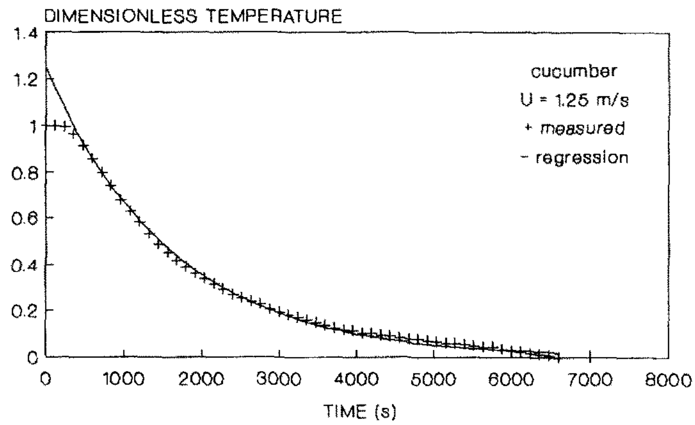

FIG. 5. Measured and regression temperature distributions of an individual cucumber in batch of 5 kg at air-flow velocity of 1.25 m s^{-1}.

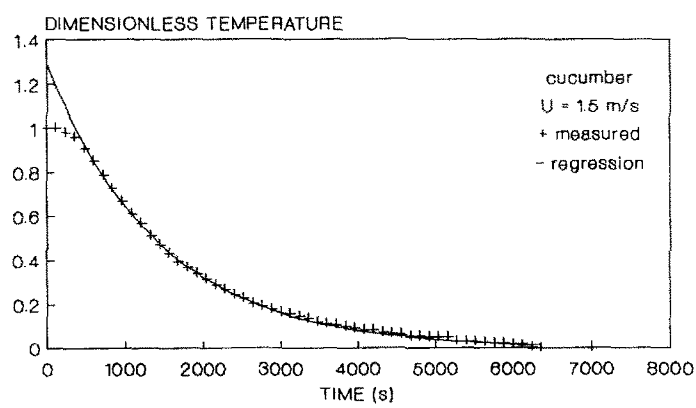

FIG. 6. Measured and regression temperature distributions of an individual cucumber in batch of 5 kg at air-flow velocity of 1.5 m s^{-1}.

cucumbers in the crates containing the batches 5 kg of product subjected to air cooling at the flow velocities of 1, 1.25, 1.5, 1.75, and 2 m s^{-1}, respectively. As can be seen in these figures, the measured and regression temperature profiles follow the same trend and decrease with increasing the cooling time. In comparison, very good agreement was found between the measured and regression dimensionless temperature values. For a clearer presentation, all the regression temperature distributions of the individual

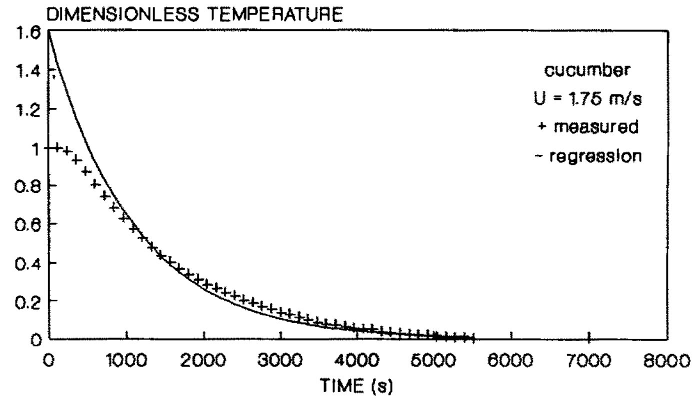

FIG. 7. Measured and regression temperature distributions of an individual cucumber in batch of 5 kg at air-flow velocity of 1.75 m s^{-1}.

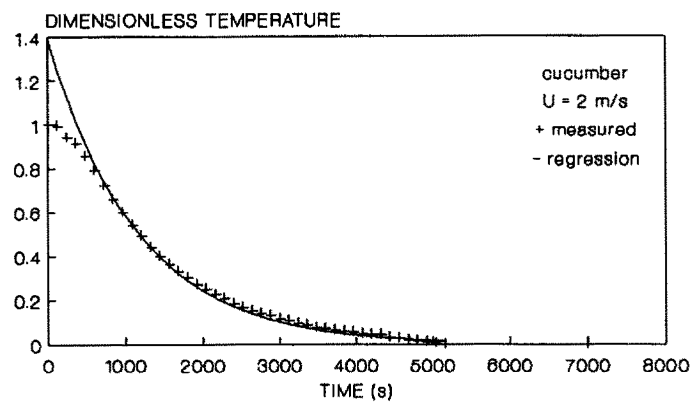

FIG. 8. Measured and regression temperature distributions of an individual cucumber in batch of 5 kg at air-flow velocity of 2 m s^{-1}.

products at different flow velocities are plotted in Fig. 9.

The results indicated that the present methodology can easily be used in order to determine cooling process parameters.

In addition to the cooling process parameters presented above, the thermal conductivities, thermal diffusivities and specific heats of the products which are some heat transfer parameters were determined using equations (15)–(17). The present model (equation (14)) was used in order to determine the heat transfer coefficient for an individual cylindrical product in each batch. The experimental conditions and some heat transfer parameters of the products within the uncertainty bands are summarized as follows: $\rho = 964.40 \pm 27$ kg m^{-3}, $W_i = 0.96$, $W_e = 0.95$, $k = 0.6212$ W m^{-1} K^{-1}, $a = 1.456 \times 10^{-7}$ m^2 s^{-1}, $C_p = 4052.04$ J kg^{-1} K^{-1}.

The heat transfer coefficients and the Biot numbers for the individual products in crates containing the batches of 5, 10, 15, and 20 kg of product cooled with water are given in Table 3.

As can be seen in Table 3, the heat transfer coefficients strongly depend on the cooling coefficient and, therefore, the values of h and Bi decreased with increasing crate load from 5 to 20 kg during cooling in water. Increasing the crate loading from 5 to 20 kg decreased the heat transfer coefficient by 47.7% for cucumbers. This would seem to be because of the changes in the heat transfer environments of the individual products in each crate. The Biot numbers ranged between 0 and 100. This situation includes the boundary condition of the third kind in transient heat transfer and shows the finite internal and external resistances to the heat transfer from the products. The values of Bi, therefore, supports the present approach which considered the boundary condition of the third kind (the convection boundary condition).

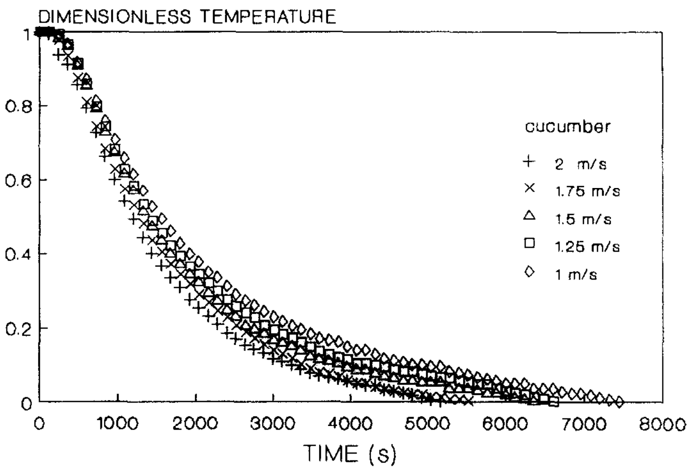

FIG. 9. Regression temperature distributions of the individual cucumbers at air-flow velocities of 1, 1.25, 1.5, 1.75 and 2 m s^{-1}.

Table 3. Heat transfer coefficients for individual cucumbers cooled with water

w (kg)	h (W m^{-2} K^{-1})	Bi
5	182.52±26	5.6±1
10	171.20±23	5.2±1
15	124.71±13	3.8±0.5
20	98.42±8	3.0±0.2

The heat transfer coefficients for the individual products in crates containing 5 kg of product during cooling in forced-air at the temperature of 4°C and at the flow velocities of 1, 1.25, 1.5, 1.75 and 2 m s^{-1} are given in Table 4.

It can be seen from Table 4 that the heat transfer coefficients strongly depend on the air-flow velocity and the values of h and Bi increased with an increase in the flow velocity from 1 to 2 m s^{-1} during cooling in air. The increase in the heat transfer coefficient was found to be 46.2% for cucumbers. The increase rate in the heat transfer coefficient was also found to be similar to the increase rate in the Biot numbers. The variations in the heat transfer coefficient and especially its increase with respect to an increase in the air-flow velocity strongly indicate that the flow and temperature profiles as well as thermal and physical properties of the air around the product were influenced by the flow velocity and were different for each experiment. The increase in the heat transfer coefficient from $U = 1.75$ to 2 m s^{-1} was found to be larger than the other flow cases probably due to the sudden changes in the experimental cooling medium condition.

Table 4. Heat transfer coefficients for individual cucumbers cooled with air

U (m s^{-1})	h (W m^{-2} K^{-1})	Bi
1.00	28.02±1.20	0.85±0.067
1.25	32.69±1.50	1.00±0.073
1.50	37.21±1.81	1.14±0.085
1.75	55.42±3.33	1.69±0.154
2.00	52.11±3.02	1.59±0.140

The results indicated that the present model is capable of determining the heat transfer coefficients for the individual cylindrical products in a simple and accurate way. On the other hand, this approach can be extended to different geometrical objects.

CONCLUSIONS

Transient heat transfer from the individual cylindrical products to the water and air streams was analyzed and the heat transfer experiments were employed to measure the center temperatures of these products. These temperature data were used in the present models for determining cooling process parameters and the heat transfer parameters. The results of the present study showed that the half cooling times and seven-eighths cooling times increased with increasing batch weight in water cooling and decreased with increasing the flow velocity in air cooling and that the heat transfer coefficients decreased with an increase in the batch weight in water cooling and increased with an increase in the flow velocity in air cooling.

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