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THERMAL COOLING DATA FOR FIGS EXPOSED TO AIR COOLING

Ibrahim Dincer *
TUBITAK-Marmara Research Center, Gebze 41470, Kocaeli-Turkey

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ABSTRACT

This paper implies the presentation of a methodology for determining the thermal cooling data in terms of the cooling coefficients, lag factors, half cooling times and seven-eighths cooling times, as well as the heat transfer coefficients of the food products. This methodology was employed to determine the thermal cooling data for the individual figs being cooled with air at the flow velocities of 1.1, 1.5, 1.75, and 2.5 m/s. The results of this study show that the cooling coefficient and lag factor varied linearly, the half cooling time and seven-eighths cooling time decreased by 21.5% and 20.9% and the heat transfer coefficient increased by 27.3% with increasing air-flow velocity from 1.1 to 2.5 m/s.

Introduction

Precooling is a cooling operation in which the field temperature of fruits and vegetables is reduced to the storage or transportation temperature as quickly as possible in order to maintain the quality and to prevent spoilage as well as to extend the storage period after harvest in the field. The four types of precooling methods, namely hydrocooling, air cooling, hydraircooling, and vacuum cooling are widely used in practice. One of these precooling methods may be selected by considering some criteria, such as cost, convenience, effectiveness, applicability, efficient use, operation conditions and personal preference as well as product requirements [1,2,7].

In practice, there is a need to determine the thermal cooling data expressed in terms of the cooling time, lag factor, half cooling time and seven-eighths cooling time for the food products in

* Present address: Department of Mechanical Engineering, University of Victoria
Victoria, B.C. V8W 3P6, Canada.

order to design cooling systems properly and to establish optimum cooling conditions. Some investigations on the determination of the cooling rate data of the food products both theoretically and experimentally have been undertaken (e.g., see [3-6]). In this study, the changes in the thermal cooling data for the individual figs, as test samples, subjected to different flow velocities in air cooling were observed.

Methodology

The heat transfer is assumed to be one dimensional and unsteady-state. It is further considered that the thermal and physical properties of both the product and the air medium are constant with time and that there is a perfect contact between the individual product and air flow. Under these conditions, the variation in the dimensionless temperature against the cooling time becomes exponential in the form of Eq.(1) after a while:

$$\theta = J\exp(-Ct) \tag{1}$$

The dimensionless temperature which is a function of the product and medium temperatures is expressed as

$$\theta = (T - T_a)/(T_i - T_a) \tag{2}$$

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 θ=0.5 into Eq.(1), the half cooling time, which is one of the most meaningful in practical applications, is found to be

$$H = [\ln(2J)]/C \tag{3}$$

Also, by substituting θ=0.125 into Eq.(1), the seven-eighths cooling time is found as

$$S = [\ln(8J)]/C \tag{4}$$

The lag factor is defined in terms of the Biot number as follows [5]:

The following model developed earlier [8] is used to determine the heat transfer coefficients of the spherical products subjected to cooling:

$$h = (3.2kRC)/(10.3a - CR^2) \tag{5}$$

The thermal conductivity and thermal diffusivity are estimated using the equations given below [9]:

$$k = 0.148 + 0.493W \tag{6}$$

$$a = 0.088x10^{-6} + (a_w - 0088x10^{-6})W \quad (7)$$

where a_w is the thermal diffusivity of water at the product temperature, (=0.148x10^{-6} m^2/s).

Experimental

The experimental apparatus and procedure used for the present investigation is similar to that described earlier by Dincer [7]. For this reason, a brief explanation on how to measure the center temperatures of spherical shaped figs during air-cooling will be presented.

An experimental investigation was conducted to measure the center temperatures of the individual figs at the air flow velocities of 1.1, 1.5, 1.75, and 2.5 m/s. The figs (0.047 m in average diameter) were treated as spherical test samples. For each test, a 5 kg batch of similar figs was selected and placed into a polyethylene case. The eight temperature probes were embedded at the centers of eight samples in each batch. The other probes were provided to measure air medium temperatures inside the cooling chamber. After the air medium temperature in the chamber reached 4°C, the polyethylene case containing the samples was attached to the hook (Fig.1), and

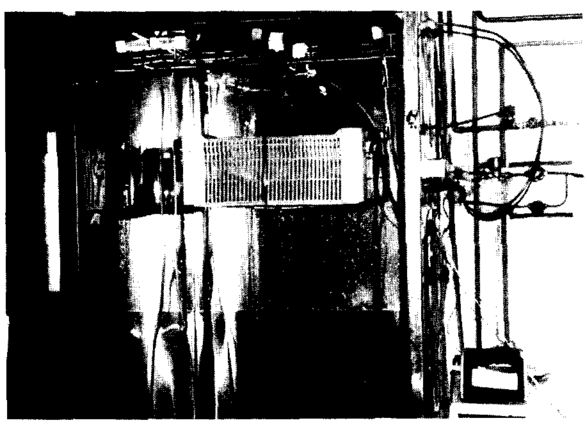

FIG. 1
A photograph representing the cooling chamber before commencing experiment

test samples were cooled until their center temperatures reached 7°C. The center temperatures of the samples were recorded at every 30 s overall the experiment. This procedure was repeated for each flow velocity. Eight temperature readings for each batch were averaged to minimize the measurement errors.

Results and Discussion

The thermal cooling data, namely cooling coefficient, lag factor, half cooling time, seven-eighths cooling time, as well as the heat transfer coefficient are the parameters for evaluating and representing a cooling process. After non-dimensionalizing experimental center temperature measurements by using Eq.(2), regression analyses were carried out on these dimensionless temperature data in the exponential form as given in Eq.(1). From the regression analyses, the lag factors (J), cooling coefficients (C) were determined and hence the half cooling times (H) and seven-eighths cooling times (S) were calculated using Eqs.(3) and (4). The thermal conductivity and thermal diffusivity were estimated from Eqs.(6) and (7). By using the values of a ,C, R, and k in Eq.(5), the heat transfer coefficients were determined. These values expressed in terms of J, C, H, S, and h for the individual figs cooled at different air-flow velocities are given in Table 1.

TABLE 1.
Thermal cooling data for figs (W=0.78, T_i=22.2±0.5°C, T_f=7°C, T_a=4±0.1°C, ρ=1076±2 kg/m^3, k=0.53254 W/mK, a=1.35x10^{-7} m^2/s)

U(m/s)	r^2	J	C(1/s)	H(s)	S(s)	h (W/m^{2}K)
1.10	0.9904	1.20755	0.0006217	1418.2	3648.1	23.77±0.17
1.50	0.9941	1.18989	0.0006677	1298.4	3374.7	26.16±0.20
1.75	0.9945	1.17942	0.0006907	1242.4	3249.5	27.41±0.20
2.50	0.9930	1.19522	0.0007828	1113.2	2884.2	32.71±0.27

It can be seen from Table 1 that a sensitive regression analysis in the exponential form by using the least squares method implies the high regression coefficients over 0.99 and the cooling thermal parameters were strongly affected by the increase in the air flow velocity. The cooling coefficients increased with an increase in the flow velocity of air during cooling of the individual products. Also, it can be seen from Table 1 that the lag factors which are the function of the physical and thermal properties of the product are larger than 1 and indicate the certain internal resistance to the heat transfer within the product. The cooling coefficients decreased with an increase in the flow velocity from 1.1 to 2.5 m/s. The values of C were obtained to be highly sensitive to the size of the products and their surfaces exposed to the cooling medium. We found that the half cooling times and seven-eighths cooling times also decreased to be 21.5% and 20.9%, and that the heat transfer coefficient increased by 27.3%, for an individual fig, with increasing flow velocity of air from 1.1 to 2.5 m/s. As presented above, the thermal cooling data were found to be dependent upon the experimental conditions including different flow velocities. Therefore, this would seem to be due to changes in the heat transfer environment in forced-air cooling.The variations in the thermal cooling parameters and especially their variation with respect to an increase in the air-flow velocity strongly indicates that the flow and temperature profiles as well as thermal and physical properties around the product were influenced by the air-flow velocity and were different for each experiment.

Figures 2-5 present the experimental and regression center temperature distributions of the individual figs in the batches containing 5 kgs of product subjected to air cooling at the flow velocities of 1.1, 1.5, 1.75, and 2.5 m/s, 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 comparisons, a very good agreement was found between the measured and regression dimensionless temperature values. The maximum difference between the experimental and regression temperature values is about 10.7 % for four cases of air-flow velocity, except initially. Because the regression temperature values at t=0 are larger than 1, this situation shows the lag factor.

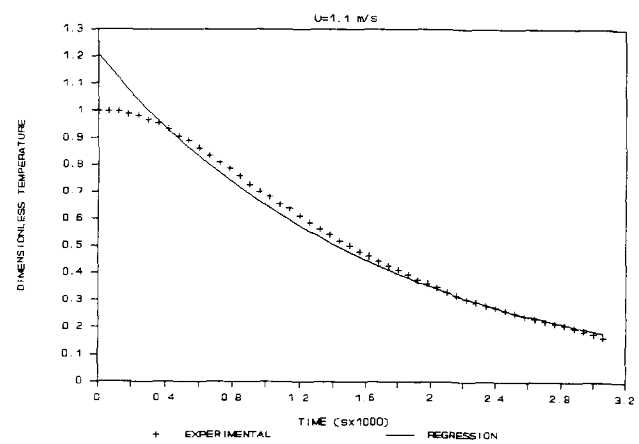

FIG. 2
Measured and regression temperature distributions of an individual fig at air-flow velocity of 1.1 m/s

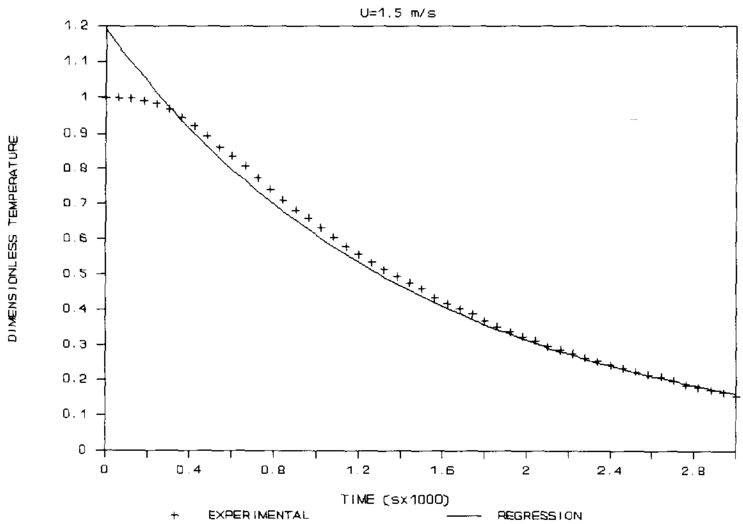

FIG.3
Measured and regression temperature distributions of an individual fig at air-flow velocity of 1.5 m/s

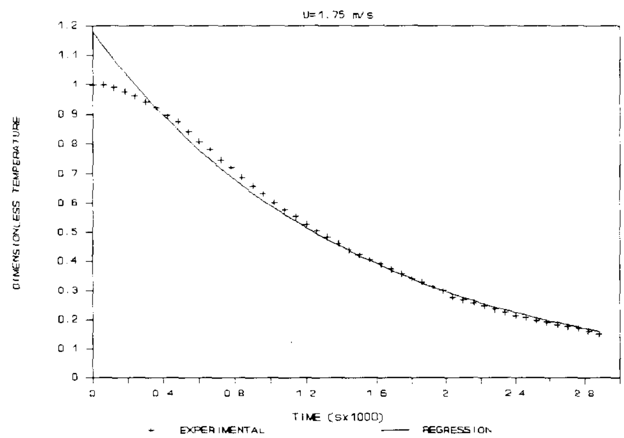

FIG. 4
Measured and regression temperature distributions of an individual fig at air-flow velocity of 1.75 m/s

The results indicated that this approach is capable of determining the thermal cooling data for the individual products in a simple and accurate way. On the other hand, this approach can easily be extended for the regular and irregular shaped products as well.

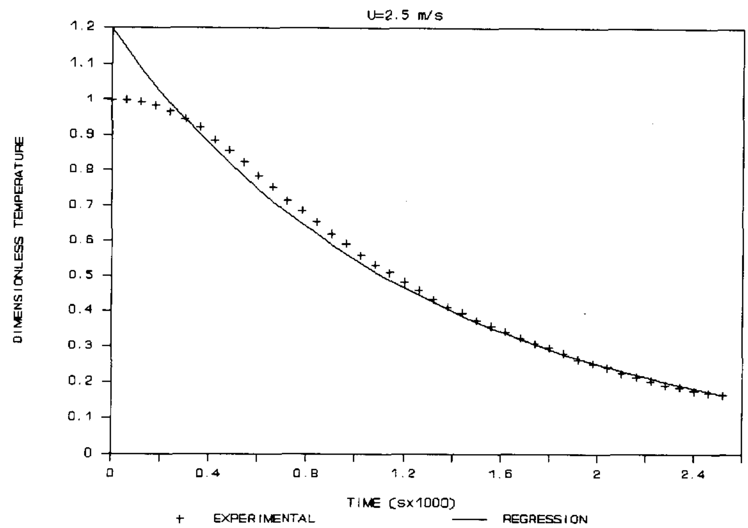

FIG. 5
Measured and regression temperature distributions of an individual fig at air-flow velocity of 2.5 m/s

Conclusions

A methodology was presented to determine the thermal cooling data, such as cooling coefficient, lag factor, half cooling time and seven-eighths cooling time, as well as the heat transfer coefficient for the individual figs cooled in air medium at the flow velocities of 1.1, 1.25, 1.5, and 2.5 m/s. The half cooling times and seven-eighths cooling times decreased, and the heat transfer coefficient increased with increasing the flow velocity in air cooling. It can be concluded that the present methodology is a simple and useful tool to determine the thermal cooling data in the practical cooling applications.

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Nomenclature

a	thermal diffusivity, m^2/s
C	cooling coefficient, 1/s
h	heat transfer coefficient, W/m^2K
H	half cooling time, s
J	lag factor
k	thermal conductivity, W/mK

r^2	correlation coefficient
R	radius, m
S	seven-eighths cooling time, s
t	time, s
T	product temperature at any time, °C
T_a	cooling medium temperature, °C
T_f	final product temperature, °C
T_i	initial product temperature, °C
W	water content by mass, decimal
θ	dimensionless temperature
ρ	density, kg/m^3

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