

Development of a Formula for Predicting the Average Surface Heat Transfer Coefficient of Cylindrical Foods

Van Lai Dang^{1,*}

¹Dak Lak College, 594 Le Duan, Ea Kao Ward, Dak Lak province, Vietnam

*Author to whom correspondence should be addressed:

E-mail: laithpy@gmail.com

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Abstract: The development of a simplified formula and corresponding graphical representations for quickly estimating the average surface heat transfer coefficient (ASHTC) of cylindrical foods are presented. Data analysis shows that the proposed formula achieves good accuracy, with errors not exceeding 15% compared to the experimental data of Dincer, Dincer and Genceli, and errors not exceeding 7% compared to Dincer's empirical formula. Compared to Charan's formula, the error does not exceed 6%.

Keywords: cylindrical foods; formula; freezing time; heat transfer coefficient.

1. Introduction

In food processing, the freezing stage plays a key role in maintaining product quality, safety, and shelf life. Achieving an accurate assessment of the ASHTC is essential for enhancing the efficiency of this process. This parameter influences not only the heat exchange between the product and its environment, but also significantly affects the freezing time¹⁻³⁾ and the energy efficiency of the operation.

Various approaches have been developed to identify the ASHTC of food products, generally classified into three categories: experimental, analytical, and numerical methods⁴⁻⁷⁾. Experimental methods are widely used to determine ASHTC under controlled cooling, freezing⁸⁻¹⁰⁾ and other conditions¹¹⁻¹⁴⁾, for individual food types¹⁵⁻¹⁸⁾. Analytical and empirical correlations based on dimensionless parameters are commonly applied to simple geometries such as cylindrical and spherical foods¹⁹⁻²¹⁾, while numerical and CFD-based methods are suitable for complex airflow conditions²²⁻²⁵⁾. However, experiments are time-consuming; therefore, simple equations are needed for rapid ASHTC prediction, process optimization.

2. Materials and methods

2.1. Materials

To validate the accuracy of the proposed equation, several published experimental datasets and existing empirical formulas were selected for comparison:

Dincer I. conducted experiments on cooling grapes with a diameter of 11mm and a length of 12mm, as well as cooling unpeeled cucumbers with a diameter of 38mm and a length of 160mm, under conditions of 4°C temperature

and air velocity from 1 to 2m s⁻¹. From the results of these experiments, the author proposed an empirical formula to determine the ASHTC for these foods²⁶⁾:

$$Nu = 0,291 \cdot Re^{0,592} \cdot Pr^{0,333} \quad (1)$$

Dincer I. also used formula (1) to study the case of cooling bananas and carrots with $10^2 \leq Re \leq 10^5$ and got reasonably suitable results.

In this study, the experimental datasets used for comparison include those from Dincer and Genceli¹⁵⁾, which involve freezing cucumbers with a diameter of 38 mm at temperatures of -10°C, -18°C, and -25°C, with air velocities ranging from 0.5 to 5m s⁻¹; Dincer's data on cooling cucumbers of the same size at 4°C; and cooling data for grapes with a diameter of 11mm¹⁶⁾. These data sets were compared with the calculated results.

The author of the article²⁷⁾ predicts the ASHTC when freezing Tylose Gel cylinders with diameters from 52mm to 153.6mm in an air environment with air velocity of 2-5.5m s⁻¹ and air temperature of -18°C using the empirical formula:

$$Nu = 0,193 \cdot Re^{0,618} \cdot Pr^{0,333} \quad (2)$$

2.2. Theoretical basis

The ASHTC is contingent upon numerous elements²⁸⁻³⁰⁾, such as the thermal gradient between the food surface and the surrounding atmosphere, the food's form, and the fluid's thermophysical attributes. Most models today typically estimate the ASHTC during the cooling and freezing of food using an empirical equation^{31,32)}:

$$Nu = C \cdot Re^m \cdot Pr^n \tag{3}$$

Where, $Nu = \frac{\alpha \cdot D}{\lambda}$; $Re = \frac{\rho \cdot v \cdot D}{\mu}$; $Pr = \frac{\mu \cdot c_p}{\lambda}$

Numerous models exist for ascertaining the ASHTC during flow over a cylinder; however, Churchill and Bernstein's equation is the most widely used due to its broad calculation range and high reliability $Re \cdot Pr \geq 0,2^{33,34}$:

$$\alpha = \frac{\lambda}{D} \left(0,3 + \frac{0,62 \cdot Re^{1/2} \cdot Pr^{1/3}}{\left(1 + \left(\frac{0,4}{Pr}\right)^{2/3}\right)^{1/4}} \left(1 + \left(\frac{Re}{282000}\right)^{5/8}\right)^{4/5} \right) \tag{4}$$

Where,

α - ASHTC, $W/m^2 \cdot K$.

Properties of fluid are evaluated at the temperature

$$t = (t_a + t_w) / 2, \text{ } ^\circ C.$$

t_a, t_w - Fluid temperature and cylinder surface temperature, $^\circ C$.

2.3. Regression and Development of Formula

Although accurate, the Churchill–Bernstein equation is complex, requiring detailed air property data and iterative calculations. To make the method more practical for engineering use, a simplified formula was developed using the following steps:

- a) Averaging air properties
Air properties such as viscosity, conductivity, specific heat, density and Prandtl number were considered constant, using average values corresponding to the typical food freezing range from $-50^\circ C$ to $10^\circ C^{35}$.
- b) Computational dataset generation
The Churchill–Bernstein equation was used to calculate ASHTC values for cylindrical foods across a range of diameters from 5mm to 80mm and air velocities from 0.5 to 25m s^{-1} . This dataset provides the basis for regression to find simpler equations that allow rapid prediction of ASHTC.
- c) Introducing a new dimensionally variable
It was observed that the combined term $(v \cdot D)$ had a strong nonlinear influence on ASHTC. Therefore, a dimensionless parameter was introduced: $X = (v \cdot D)^{5/8}$.
- d) Regression modeling
The computed data were fitted using nonlinear regression to obtain a simplified empirical expression.

The final form of formula is:

$$\alpha = \frac{1}{D} [0,0055 + (2,2 \cdot X^2 + 4,4 \cdot X)^{0,8}] \tag{5}$$

Formula (5) was developed based on the Churchill–Bernstein equation, with an R^2 value of 0.99, confirming

the reliability of the regression model. It allows engineers to estimate ASHTC quickly and accurately without requiring the air thermophysical property tables.

2.4. Method

The ASHTC values were calculated using the proposed simplified formula (5), and then compared to the results obtained from Dincer’s and Charan’s empirical formulas (Equations 1 and 2), as well as to experimental measurements from published datasets.

The comparison was performed by computing ASHTC over a range of:

- Food diameters from 11 to 153.6mm.
- Air velocities from 0.5 to 5.5m s^{-1} .
- Air temperatures from $-25^\circ C$ to $+4^\circ C$.

The predicted results were tabulated and the percentage deviations from experimental values were determined, in order to evaluate the accuracy, stability, and practical applicability of formula (5) across different food types and thermal conditions.

3. Results and discussion

3.1. Results

Table 1: Comparison of calculated results and experimental data set of the ASHTC $\alpha, W m^{-2} K^{-1}$ by Dincer for cucumbers and grapes at $4^\circ C^{16,26}$

Velocity v, m/s	This study	Cucumbers D = 38mm		Grapes D = 11 mm	
		By Dincer's formula	Dincer's exp.data	This study	Dincer's exp.data
1.0	17.79	18.35	18.2	32.44	29.57
1.25	20.02	20.95	19.9	36.33	32.81
1.50	22.06	23.17	21.3	39.87	35.27
1.75	23.96	25.56	23.1	43.16	38.39
2.0	25.76	27.67	26.6	46.23	40.85

Table 2: Comparison of calculated results and experimental data set of the ASHTC $\alpha, W m^{-2} K^{-1}$ by Dincer and Genceli for cucumbers with a diameter of 38mm^{15,26}

Velocity v, m/s	This study	Experimental data set of Dincer and Genceli		
		$-25^\circ C$	$-18^\circ C$	$-10^\circ C$
0.5	12.24	11.02±0.01	10.82±0.005	11.19±0.07
1.0	17.79	15.16±0.001	15.04±0.01	15.25±0.009
1.25	20.02	-	-	-
1.50	22.06	18.73±0.06	18.81±0.04	19.10±0.04
1.75	23.96	-	-	-
2.0	25.76	22.46±0.09	22.08±0.05	22.17±0.04
5.0	42.90	40.19±0.13	39.98±0.09	40.00±0.07

Formula (5) is used to calculate the ASHTC of foods during the cooling and freezing of cucumbers with a diameter of 38mm and the cooling of grapes with a diameter of 11mm under different temperature and air velocity conditions. The findings are subsequently benchmarked against experimental data from Dincer and Dincer and Genceli, as presented in their publication, and also against the calculation results derived from formulas (1) and (2):

Graphics of the ASHTC when cooling and freezing cylindrical foods depending on air velocity and size are constructed using formula (5) as shown in Figure1.

Table 3: Comparison of calculation results of the ASHTC α , $W m^{-2} K^{-1}$ with Charan’s formula²⁷⁾ when freezing cylindrical Tylose Gel at $-18^{\circ}C$

Velocity v , m/s	Diameter D , m	This study	By Charan’s formula
2.0	0.1536	14.05	13.87
3.0	0.1536	17.96	17.81
4.0	0.1536	21.50	21.28
5.0	0.1536	24.80	24.43
5.5	0.1536	26.39	25.91
2.0	0.1045	16.48	16.06
3.0	0.1045	20.90	20.63
4.0	0.1045	24.87	24.65
5.0	0.1045	28.54	28.29
5.5	0.1045	30.29	30.01
2.0	0.0520	22.34	20.97
3.0	0.0520	28.02	26.94
4.0	0.0520	33.03	32.18
5.0	0.0520	37.61	36.94
5.5	0.0520	39.78	39.18

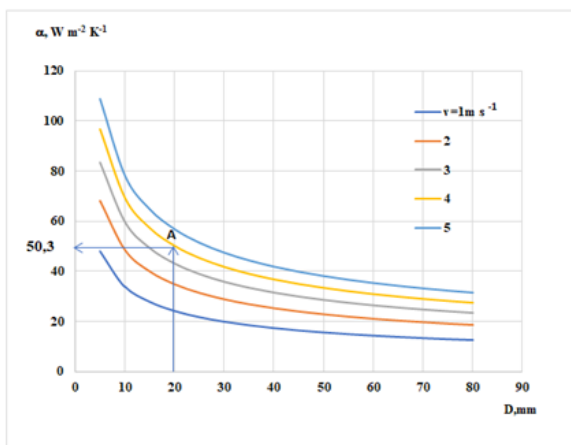


Fig. 1(a): ASHTC's reliance on diameter and velocity from 1 to 5m s⁻¹ for cylindrical foods

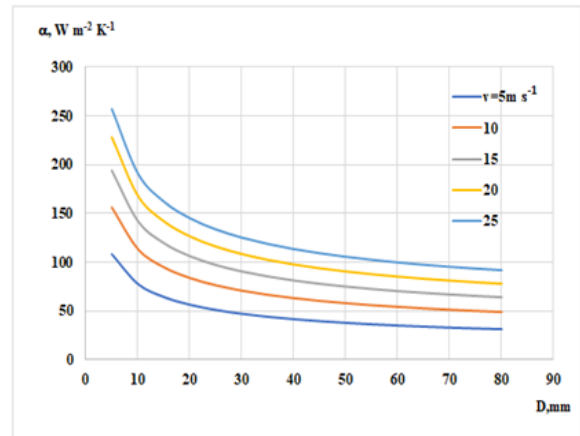


Fig. 1(b): ASHTC's reliance on diameter and velocity from 5 to 25m s⁻¹ for cylindrical foods

3.2. Discussion

Analysis of data in Table 1 shows that the ASHTC of cucumbers with a diameter of 38 mm, calculated according to this study is always smaller than the value predicted by Dincer's formula (1), the error is not more than 7% at an air velocity of 2m s⁻¹; the error compared to Dincer's experimental data is not more than 4% with the smallest error at an air velocity of 1.25m s⁻¹. The calculated results of the ASHTC when cooling grapes with a diameter of 11mm compared to Dincer's experimental data have a gradually increasing difference as the air velocity increases with the largest difference being about 12% at a velocity of 2m s⁻¹; However, when compared to the experimental data set of Dincer and Genceli in Table 2, the error in calculating the ASHTC when freezing cucumbers is about 15%;

Meanwhile, Table 3 shows the results of calculating the ASHTC when cooling compared with the formula of author Charan is quite similar with an error of no more than 6% for a small size of 0.052m at a air velocity of 2m s⁻¹.

Analysis of the graphics in Figure 1 shows the following notable observations:

For all air velocities, the ASHTC decreases as the food size increases. However, when the food diameter $D \geq 60mm$, the ASHTC becomes relatively stable and appears to have little change.

The ASHTC tends to increase as the air velocity increases. This is shown by the curves moving upwards as the air velocity increases from 1 to 25m s⁻¹. Compared to the graph in Figure 1a, the ASHTC in Figure 1b is much larger, showing a stronger impact of air velocity on the ASHTC capacity of the food.

Point A in Figure 1a illustrates how to use the graph to determine the ASHTC of the food: when freezing food with a diameter of 2mm at an air velocity of 4m s⁻¹, the graph allows determining the ASHTC of the food as 50.3W m⁻² K⁻¹.

4. Conclusion

For the first time a simplified formula were developed based on the Churchill–Bernstein equation to describe the dependence of ASHTC on air velocity and diameter of cylindrical foods. The calculation results, when compared to the experimental data sets from Dincer and Dincer and Genceli, show discrepancies of no more than 15%. The difference relative to Dincer’s empirical formula is within 7%, and the difference compared to Charan’s formula is within 6%, confirming the reliability and practical applicability of the formula (5).

An important contribution of the authors of the paper is the conversion of a complex heat transfer equation into a simplified formula and easy-to-use practical graphs. This toolkit allows engineers to estimate ASHTC values quickly without the need for the air thermophysical data.

The proposed formula can be used to determine the ASHTC for non-circular cylindrical food. For these cases, the equivalent diameter is calculated using the formula $D=4F/U$ where, F is the cross-sectional area and U is the wetted perimeter.

Using this research method, simplified formulas and graphs for determining the ASHTC of spherical and flat foods items can be developed based on well-known empirical correlations./.

Nomenclature

t	temperature (°C)
c_p	specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
v	velocity ($m\ s^{-1}$)
ρ	density ($Kg\ m^{-3}$)
d	diameter of food (m)
C	consant (–)
Nu	Nusselt Number (–)
Re	Reynolds Number (–)
Pr	Prandtl Number (–)

Greek symbols

α	ASHTC ($W\ m^{-2}\ K^{-1}$)
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
μ	dynamic viscosity (Pa s)

Subscripts

a	fluid
w	cylinder surface
m	consant
n	consant

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