Evaporative Heat Transfer Coefficients During Sensible Heating of Milk

Mahesh Kumar [1*], Sudhir Kumar [2], Om Prakash [3] and K.S. Kasana [4]

ABSTRACT

In this article, the evaporative heat transfer coefficients for sensible heating phase of milk in a stainless steel pot during khoa making by conventional heating method have been reported. Various indoor experiments were performed for sensible heating of milk in a stainless steel pot under open condition by varying heat inputs from 240 watts to 420 watts. The experimental data were used to determine the values of evaporative heat transfer coefficients which were observed to decrease with an increase in rate of heating. It is also observed that the evaporative heat transfer coefficient increases significantly with the increase in operating temperature for each rate of heat inputs. The experimental error in terms of percent uncertainty was also evaluated.

***Key words*: Sensible heating of milk; Khoa; Khoa making; Evaporative heat transfer coefficients**

1. INTRODUCTION

Dunkle [1] formulated a semi-empirical relation to determine the rate of evaporation for distillation under indoor conditions with few limitations. Clark [2] also developed a thermal model for a higher operating temperature range under simulated conditions for a small inclination of the condensing surface. Later on, Tiwari and Lawrence [3] attempted to incorporate the effect of inclination of the condensing surface by choosing the values of constants (C & n) as proposed by Dunkle. Adhikari et al., [4-6] attempted to modify the values of these coefficients under simulated conditions. Kumar and Tiwari [7] and Tiwari et al., [8] have developed a thermal model for heat and mass transfer for indoor as well as outdoor conditions by using simple regression analysis. Tiwari et al., [9] studied the heat and mass transfer behavior of sugar cane juice during natural convective heating for preparation of jaggery under the open and closed conditions. They observed that the convective and evaporative heat transfer coefficients increase significantly with an increase in heat input. Later on, Kumar et al., [10] experimentally evaluated the performance of aluminum and stainless steel pots during sensible heating of sugarcane juice under open condition for jaggery making, which confirmed the findings by Tiwari et al., [9].

Khoa is an important indigenous heat coagulated, partially dehydrated milk product which is obtained by heat desiccation of whole milk to 65 to 70 percent milk solids without the addition of any foreign ingredients [11]. The heating of milk during khoa making involves sensible heating and boiling convection heat transfer phases. Recently, Kumar et

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al., [12, 13] experimentally evaluated the convective heat transfer coefficients during sensible heating of milk in aluminum [12] and stainless steel pots [13] for khoa making by varying the heat inputs from 240 watts to 420 watts. The convective heat transfer coefficients for milk heating in an aluminum pot were reported to decrease from 5.25 W/m^2 ^{o}C to 3.09 W/m^2 ^{o}C with the increase in heat inputs, whereas it decreased from 4.70 W/m^2 ^{o}C to 2.68 W/m^2 ^{o}C in the case of stainless steel pot. The evaporative heat transfer coefficients during milk heating in an aluminum pot were reported to decrease from 63.83 W/m^2 ^{o}C to 27.8 W/m^2 ^{o}C with the increase in given heat inputs.

This experimental study was performed to evaluate the evaporative heat transfer coefficients during sensible heating of milk under open condition in a circular stainless steel pot for different heat inputs varying from 240 watts to 420 watts. The temperature range for sensible heating phase of milk was considered up to 90 ^{o}C [12, 13]. The present research work may be helpful in designing an evaporator for khoa production.

2. MATERIALS AND METHODS

2.1 Experimental set up details and procedure

The schematic view of the experimental set-up is shown in Fig. 1. It consisted of an electric hot plate of 1000W capacity which is connected through a variac to control the rate of heating of the milk in a stainless steel pot of capacity 3.2 liters. The milk temperature (T_c) and pot inner bottom temperature (T_1) were measured by a digital temperature indicator (least count of 0.1 ^{o}C; accuracy ± 0.1%) with calibrated copper-constantan thermocouples. The relative humidity (RH) and temperature above the milk surface (T_e) were measured by a digital humidity/temperature meter (model Lutron-HT3006 HA). It had a least count of 0.1% relative humidity (accuracy of ± 3%) and 0.1 ^{o}C temperature (accuracy of ±0.8 ^{o}C). The heat input was measured by a calibrated digital wattmeter having a least count of 1 watt. The mass of moisture evaporated during heating of milk was measured by an electronic weighing balance (capacity 6 kg; Scaletech, model TJ-6000; accuracy of ± 2%) having a least count of 0.1g.

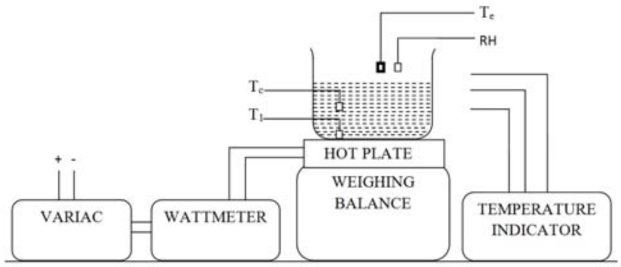

Fig. 1: Schematic view of experimental unit

2.2 Experimental procedure

Fresh cow milk sample of 935g mass was heated in a stainless steel cylindrical pot (200 mm in diameter, 102 mm deep, 1.6 mm thick, and weight = 1191g) for different heat inputs ranging from 240 watts to 420 watts. For every run of the milk heating, constant mass of the milk sample was taken i.e. 935g. To avoid the scaling and burning of the product, light manual stirring and scraping of milk was carried out with the help of a Teflon scraper. The data for temperature, mass evaporated, and relative humidity were recorded up to 90 ^{o}C (i.e., sensible heating phase range) after every 10 minute time interval. By varying the input power supply from 240 watts to 420 watts, different sets of milk heating were obtained. The experimental data obtained for milk heating are reported in Appendix-A (Tables A1-A5). For comparison purpose, this experimentation was also repeated for water under the same working conditions at 240 watts. The experimental data for water heating is given in Table A6 (Appendix-A). The mass evaporated during heating of milk and water for each set of observations were obtained by subtracting two consecutive readings in a given time interval.

2.3 Computation procedure

The evaporative heat transfer coefficient (h_e) was calculated from Equation (1) which is given as [12, 14]:

$$h_e = \frac{0.016\, h_c \left[P(T_c) - \gamma\, P(T_e)\right]}{T_c - T_e} \tag{1}$$

The data obtained from experimentation were used to determine the values of the convective heat transfer coefficients. The details of the convective heat transfer coefficient values used for determining the evaporative heat transfer coefficients are given elsewhere [13].

The different physical properties of humid air, such as specific heat (C_v), thermal conductivity (K_v), density (ρ_v), viscosity (μ_v), and and partial vapor pressure, *P(T)* were determined by using following expressions [12, 13]:

$$C_v = 999.2 + 0.1434 T_i + 1.101\times10^{-4} T_i^2 - 6.7581\times10^{-8} T_i^3 \tag{2}$$

$$K_v = 0.0244 + 0.7673\times10^{-4} T_i \tag{3}$$

$$\rho_v = \frac{353.44}{(T_i + 273.15)} \tag{4}$$

$$\mu_v = 1.718\times10^{-5} + 4.620\times10^{-8} T_i \tag{5}$$

$$P(T) = \exp\left[25.317 - \frac{5144}{(T_i + 273.15)}\right] \tag{6}$$

Where $T_i = (T_c + T_e)/2$

The experimental errors were evaluated in terms of percent uncertainty (internal + external) for the mass of water vapor evaporated. The following equations were used for internal uncertainty [15]:

$$U_I = \frac{\sqrt{\sigma_1^{\,2} + \sigma_2^{\,2} + \ldots \sigma_N^{\,2}}}{N_o} \tag{7}$$

Where σ is the standard deviation and N_o are the number of sets.

Therefore, the percent internal uncertainty was determined using the expression: % internal uncertainty = (U_I/mean of the total observations) ×100 (8)

For external uncertainty, the least counts of all the instruments used in measuring the observation data were considered.

3. RESULTS AND DISCUSSION

The experimental data given in Tables A1 to A5 (Appendix-A) were used to determine the values of evaporative heat transfer coefficients. The results for the evaporative heat transfer coefficients during sensible heating of milk in a stainless steel pot are presented in Table 1. It is noted that the values of evaporative heat transfer coefficients decrease with the increase in heat inputs. This is due to decrease in convective heat transfer coefficients with the increase in heat inputs. The details of the convective heat transfer coefficients values used for determining the evaporative heat transfer coefficients are presented elsewhere [13]

Table 1: Evaporative heat transfer coefficients values for sensible heating of milk

Heat input, (W)	Weight of milk, (g)	h_e, (W/m^2 °C)
240	935	17.50-86.81
280	935	19.28-75.56
320	935	16.29-67.83
360	935	12.57-51.96
420	935	11.43-40.12

To show the variation of evaporative heat transfer coefficients with respect to change in heat inputs, average values of evaporative heat transfer coefficients have been calculated which are plotted in Figure 2. It can be clearly seen from Figure 2 that the evaporative heat transfer coefficients decrease with the increase in heat inputs. The evaporative heat transfer coefficients were observed to decrease 129.23% for the given range of heat inputs. The evaporative heat transfer coefficients obtained for sensible heating of milk in a stainless steel pot were compared with the values reported by Kumar et al., [12] for sensible heating of milk in an aluminum pot (Figure 2). It can be seen that the evaporative heat transfer coefficients during sensible heating of milk in a stainless steel pot follows the same trend as reported for the case of an aluminum pot. The evaporative heat transfer coefficients during sensible heating of milk in a stainless steel pot were found 12.60% lower for the given range of heat inputs than in the case of an aluminum pot.

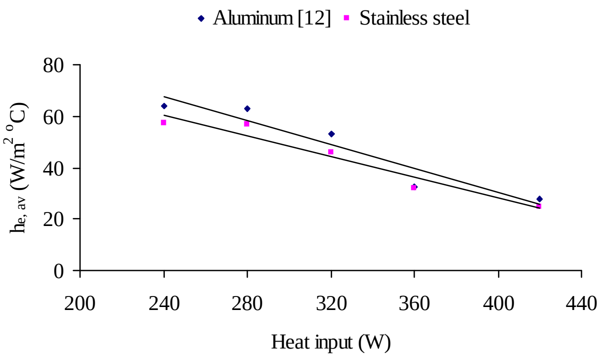

Fig 2: Variation of the evaporative heat transfer coefficients with heat inputs.

Figure 3 illustrates the variation of evaporative heat transfer coefficients with operating temperature for the given range of heat inputs. It can be noticed that evaporative heat transfer coefficients increase significantly for every rate of heating with an increase in operating temperature.

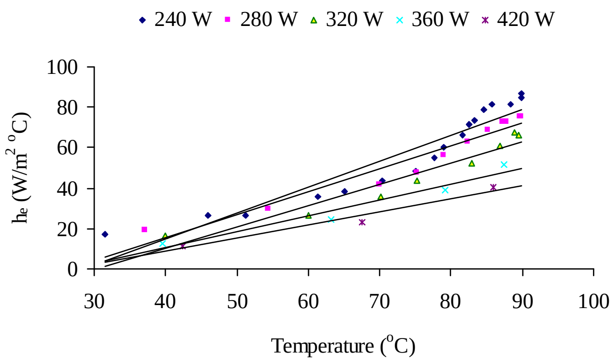

Fig 3: Variation of the evaporative heat transfer coefficients with temperature.

In order to make a comparison, the evaporative heat transfer coefficients for water have also been determined at 240 W, the results of which are given in Table 3. These results are also illustrated in Figure 4. The evaporative heat transfer coefficients of milk were found 23.22% lower than the water at 240 watts. Thus, it is inferred that the evaporative heat transfer coefficients for milk are lower in comparison to water which may be due to the presence milk solids, fat, proteins and salts.

The percent uncertainty (internal + external) was observed in the range 28.06% to 37.84%, and the different values of evaporative transfer coefficients were found to be within this range. The error bars for evaporative heat transfer coefficients are given in Figure 5.

Table 3: Values of the evaporative heat transfer coefficients for sensible heating of water at 240 watts

Heat input (W)	Weight of water (g)	h_e (W/m^2 °C)
240	935	29.20-88.48

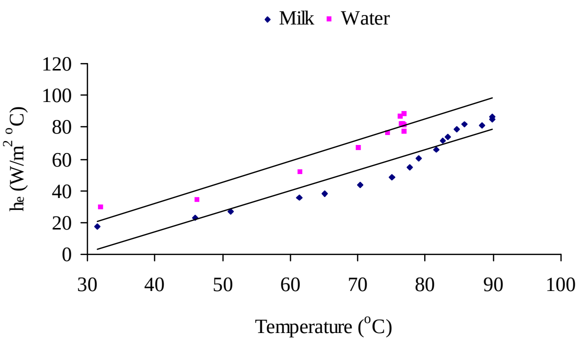

Fig.4: Comparison of the evaporative heat transfer coefficients for milk and water at heat input = 240 W.

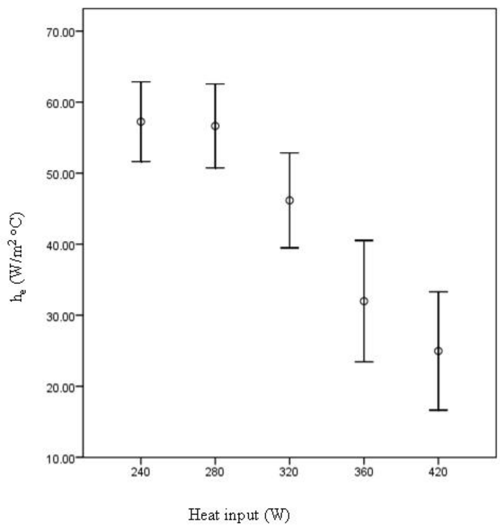

Fig. 5: The error bars for evaporative heat transfer coefficients during sensible heating of milk in a stainless steel pot.

CONCLUSIONS

The following results have been drawn from the present research work in which the evaporative heat transfer coefficients for sensible heating phase of milk during khoa making in a stainless steel pot under open conditions were investigated.

- The values of evaporative heat transfer coefficients decrease with an increase in rate of heat inputs from 240 watts to 420 watts. It was observed to decrease about 129.23% for the given range of heat inputs.
- The evaporative heat transfer coefficients were observed to vary between 11.43 W/m^2 ^{o}C to 86.81 W/m^2 ^{o}C for the given range of heat inputs and the experimental errors in terms of percent uncertainty were found in the range of 28.06 % to 37.84%.
- The evaporative heat transfer coefficient increases significantly with an increase in operating temperature.
- The evaporative heat transfer coefficients of milk were observed 23.22% lower in comparison to water which may be due to the presence of milk solids particulates.

Nomenclature

C_v Specific heat of humid air, J/kg ^{o}C

g Acceleration due to gravity, m/s^2

Gr Grashof number = $= \beta g X^3 \rho_v^2 \Delta T / \mu_v^2$

h_c Convective heat transfer coefficient, W/m^2 ^{o}C

h_e Evaporative heat transfer coefficient, W/m^2 ^{o}C

$h_{e,av}$ Average evaporative heat transfer coefficient, W/m^2 ^{o}C

K_v Thermal conductivity of humid air, W/m ^{o}C

m_{ev} Mass evaporated, kg

N Number of observations in each set of heat input

Pr Prandtl number = $\mu_v C_v / K_v$

$P(T)$ Partial vapor pressure at temperature T, N/m^2

ΔT Effective temperature difference, ^{o}C

w_1 Weight of milk/water, g

w_2 Weight of empty pot, g

W Heat input, watts

X Characteristic dimension, m

Greek symbols

β Coefficient of volumetric expansion (K^{-1})

γ Relative humidity (%)

μ_v Dynamic viscosity of humid air, N s/m^2

ρ_v Density of humid air, kg/m^3

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