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RESEARCH ARTICLE

POOL BOILING OF MILK IN A STAINLESS STEEL POT UNDER CLOSED CONDITION

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ABSTRACT

The present experimental study is concerned with the heat transfer during nucleate pool boiling of milk in a stainless steel pot under closed conditions. Reported are the results of the effect of the different heat rate of inputs varying from 240 to 360 watts on the heat transfer coefficient under pool boiling. The evaporated water condensed at the inner surface of the condensing cover was collected as fresh water. To quantify the effect of rate of heat input on the convective heat transfer coefficient, the Rohsenow correlation was applied with the constants from the experiments. The convective heat transfer coefficients were estimated in the range of 160.51 to 374.52 W/m^2 ^{o}C for the given heat inputs. The nucleate boiling heat flux was predicted to vary exponentially with the excess temperature of the stainless steel pot surface above the saturation temperature of the milk. The experimental errors in terms of percent uncertainty were also evaluated.

INTRODUCTION

Pool boiling occurs under quiescent fluid conditions. It has been investigated by many researchers during the last seven decades [1-10]. Rohsenow [1] proposed constant values of the exponents in dimensionless numbers and provided a list of values of constant for some surface-fluid combinations. Later on, Vachon *et al.* [3] performed various experiments by taking several fluid-surface combinations to obtain the associated values of constants (C_{sf} & n). Rohsenow pool boiling correlation has been evaluated by many researchers at sub-atmospheric, atmospheric, or higher pressure [2-8]. Tiwari et al., [9] have evaluated the convective heat and mass transfer coefficient for pool boiling of sugarcane juice during jaggery preparation.

Khoa is an Indian traditional heat coagulated, partially dehydrated milk product. It has considerable economic and dietary importance to the Indian population. It forms an important base for preparation of milk sweets which are an integral part of Indian food heritage. Khoa production involves boiling of milk with an aim of evaporating the large quantity of water present in it.

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Recently, Kumar *et al.* [10, 11] have experimentally studied the pool boiling of milk in an aluminum pan under open and closed conditions for khoa production by conventional heating method. In the open batch method (conventional method) of khoa making the evaporated mass of water from the milk is lost in the atmosphere. If the evaporated mass is allowed to condense, then the condensed water can be reutilized for human consumption or other use. Thus, the present study has been set forth to experimentally investigate nucleate pool boiling of milk in a circular stainless steel pan under closed conditions for the different heat inputs varying from 240 to 360 W. Experimental data obtained for pool boiling of milk were analyzed by using the Rohsenow correlation for the surface boiling of liquids to determine the constants and the convective heat transfer coefficient. Evaluation of the convective heat transfer coefficient is required for the proper design of an evaporator. The present research work would be highly useful in designing a distillation cum khoa making system.

MATERIALS AND METHODS

2.1 Experimental set-up, observations and procedure

The schematic diagram of the experimental unit is shown in Fig. 1. It consists of an electric hot plate (178 mm in diameter) of 1000 W capacity connected through a variac to control the rate of heating of the milk in a closed stainless steel pot of 3.2 liters capacity. The pot was closed by a vertical cylinder (192 mm high) covered by a hemi-spherical shaped condensing cover (60 mm high) brazed at its top. Both the vertical cylinder and the condensing cover were made of 24 gauge thick galvanized sheet. An arrangement for collection of the condensate was made by welding a copper channel inside the condensing cover around it. It is important to mention here that the distillate output during heating of milk under closed conditions was observed at temperatures greater than 90 °C. This range is generally termed as pool or nucleate boiling condition which is preferred for khoa production [10, 11].

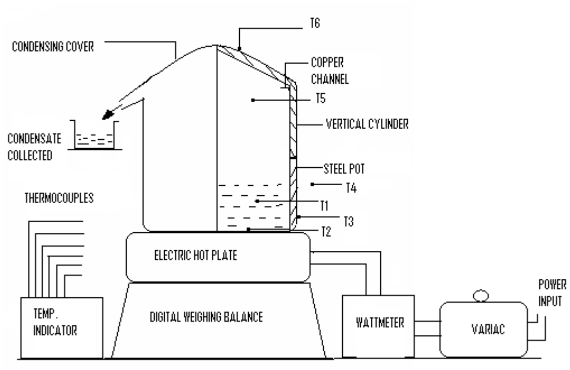

Fig. 1: Schematic view of experimental set up

Six calibrated copper-constantan thermocouples connected to a ten channel digital temperature indicator with least count of 0.1 °C (accuracy ± 0.1%; range of -50 to 200 °C) were used to measure the milk temperature (T_1), pot bottom temperature (T_2), outer pot side temperature (T_3), room temperature (T_4), vapor temperature (T_5) and condensing cover temperature (T_6). The heat input was measured by a calibrated wattmeter (accuracy within ±0.5% of full scale value 1500 watts), having a least count of 1 watt. The mass of water evaporated during heating of milk has been measured by using an electronic weighing balance of 6 kg capacity (Scaletech, model TJ-6000) with a least count of 0.1g with an accuracy ± 2% on the full scale.

In order to determine the convective heat transfer coefficients during pool boiling of milk under closed conditions the following procedure was employed: Fresh sample of milk obtained from a herd of 15 cows was heated in a stainless steel cylindrical pot covered by a vertical cylinder for different values of heat inputs ranging from 240 to 360 W. The necessary data of temperature and other parameters during heating of milk were started to record once milk temperature becomes equal to 90 °C (i.e. pool boiling mode range). These data were recorded before the solidification of concentrated milk. Temperatures were measured at various locations as shown in Fig. 1.The mass of water evaporated during heating of milk for each set of observations was obtained by subtracting two consecutive readings in a given time interval. All the experimental parameters were recorded after every 10 minute time interval. Different sets of heating of milk were obtained by varying the input power supply from 240 to 360 W to the electric hot plate with the help of the variac. The experiments followed a path of increasing heat inputs. For every run of the milk heating, constant mass of the milk sample was taken i.e. 935g. But at higher value of heat input (360 W) the quantity of the milk sample was reduced to 735g because of the spillover due to high rate of bubbles formation. For each run of the test, fresh sample of milk was taken. The experimental results for different sets of heating are reported in Appendix-A. In order to make a comparison the same process was also repeated for water.

2.2. Computation procedure

The experimental data obtained for pool boiling of milk were analyzed by using the well known expression given by Rohsenow [1].

$$C_{pl}\left[\frac{T_s - T_{sat}}{h_{fg}\,\mathrm{Pr}^n}\right] = C_{sf}\left[\frac{q_{nucleate}}{\mu_l h_{fg}}\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}\right]^{\frac{1}{3}} \quad (1)$$

The Eq. (1) can also be written as

$$q_{nucleate} = \mu_l h_{fg}\left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{1/2}\left[\frac{C_{pl}(T_s - T_{sat})}{C_{sf} h_{fg}\,\mathrm{Pr}^n}\right]^3 \quad (2)$$

The average convective heat transfer coefficient is given by

$$h = \frac{q_{nucleate}}{T_s - T_{sat}} \quad (3)$$

The Rate of water evaporated is determined by dividing Eq. (2) by enthalpy of vaporization and multiplying the area of pan

$$\dot{m}_{ev} = \frac{Q_{boiling}}{h_{fg}} = \frac{A q_{nucleate}}{h_{fg}} \quad (4)$$

Now with the help of Eq. (4), the Eq. (2) can be rearranged as follows

$$C_{sf}\,\mathrm{Pr}^n = \frac{C_{pl}(T_s - T_{sat})}{h_{fg}}\left(\frac{A\mu_l}{\dot{m}_{ev}}\right)^{1/3}\left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{1/6} \quad (5)$$

After substituting

$$K = \frac{C_{pl}(T_s - T_{sat})}{h_{fg}}\left(\frac{A\mu_l}{\dot{m}_{ev}}\right)^{1/3}\left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{1/6}$$ Eq. (5) becomes

$$K = C_{sf}\,\mathrm{Pr}^n \quad (6)$$

Taking the logarithm both sides of the Eq. (6),

$$\log K = n\log \mathrm{Pr} + \log C_{sf} \quad (7)$$

The above equation represents the straight line in the following form,

$$y = mx + c \quad (8)$$

Where, $y = \log K$, $m = n$, $x = \log \mathrm{Pr} = \log(\mu_l C_{pl}/k_l)$

and $c = \log C_{sf}$

K in the above expression was calculated for various excess temperatures, (T_s -T_{sat}) recorded during the pool boiling experiments by using the thermal physical properties of milk. Thus the values of *m* and *c* in equation (8) were obtained by using the following formulae obtained by linear regression method

$$m = \frac{N\sum xy - \sum x\sum y}{N\sum x^2 - \left(\sum x\right)^2} \quad (9)$$

$$c = \frac{\sum x^2\sum y - \sum x\sum xy}{N\sum x^2 - \left(\sum x\right)^2} \quad (10)$$

The following expressions were used for calculating the different thermal physical properties of milk such as specific heat C_{pl} [12], surface tension σ [13], density ρ_l [14], viscosity μ_l [15], thermal conductivity k_l [16], and enthalpy of vaporization h_{fg} [17] which were determined at an average temperature in the given time interval.

$$C_{pl} = 2.976T + 3692 \tag{11}$$

$$\sigma = 1.8\times10^{-4}T^2 - 0.163T + 55.6 \tag{12}$$

Where σ is in $N.m^{-1}\times10^{-3}$

$$\rho_l = -0.2307\times10^{-2}T^2 - 0.2655T + 1040.51 - F(-0.478\times10^{-4}T^2 + 0.969\times10^{-2}T + 0.967) \tag{13}$$

$$\ln\mu_l = 4.03\times10^{-5}T^2 - 2\times10^{-2}T + 0.827 \tag{14}$$

Where μ_l is in Pa.s $\times10^{-3}$

$$k_l = 0.356439\,\bar{X}_w + 0.223544 \tag{15}$$

$$h_{fg} = (h_{fg}\ of\ water)\times\bar{X}_w$$

The experimental error was evaluated in terms of percent uncertainty (internal + external) for the mass of moisture evaporated. The following two equations were used for internal uncertainty [18]:

% internal uncertainty = (U_I/mean of the total observations) ×100

where

$$U_I = \frac{\sqrt{sd_1^{\,2} + sd_2^{\,2} + \ldots sd_n^{\,2}}}{N_o} \tag{18}$$

For external uncertainty, the least counts and the accuracies of all the instruments used in measuring the observation data have been taken [10].

RESULTS AND DISCUSSION

The experimental data given in Tables A1 to A5 (Appendix-A) were used to evaluate the values of m and c. After determining m and c, the values of C_{sf} and n were obtained as $C_{sf} = e^c$ and $n = m$. The values of the constants C_{sf} and n for milk were found to vary from 0.945 to 0.972 and -1.309 to -1.490 respectively. These results are reported in Table 1. The convective heat transfer coefficients were computed from Eq. (3) by using the values of C_{sf} and n for different values of heat inputs which are also given in Table 1. The average values of the constants C_{sf} and n were determined as 0.964 and -1.396 respectively. The variation of convective heat transfer coefficient for the different values of heat input is illustrated in Fig. 2. It was observed to increase from 160.51 to 374.52 W/m^2 °C for the heat inputs increasing from 240 to 360 W. This may be due to higher surface temperature of the pan and activation of more nucleation sites which results in increased evaporation rate. The results obtained for convective heat transfer coefficients are compared with the Rohsenow correlation which are also

Table 1: Values of C_{sf}, n and convective heat transfer coefficients for milk and water

Heat input (W)	C_{sf}	n [-]	h (W/m^2 °C)
	Milk		
240	0.971	1.309	160.51
280	0.972	1.354	205.25
320	0.969	1.432	285.06
360	0.945	1.490	374.52
	Water		
240	1.000	3.761	273.16

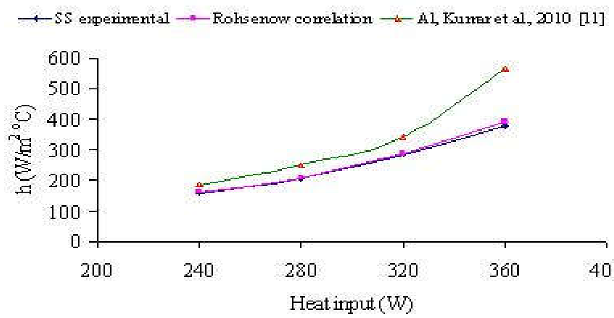

Fig. 2: Variation in convective heat transfer coefficient with heat inputs

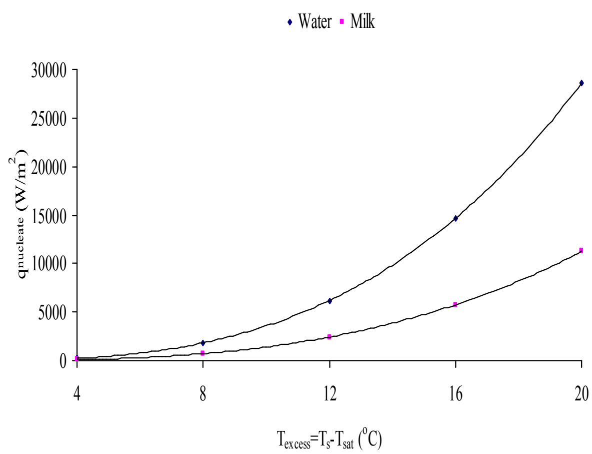

Fig. 3: Variation in heat flux with heat inputs

depicted in Fig 2. It is observed that the convective heat transfer coefficients are lower than that of Rohsenow correlation and are observed to vary in a range of 1.04 to 4.10%. The values of convective heat transfer coefficients obtained for pool boiling of milk in stainless steel pot are also compared with the values reported for aluminum pot by Kumar *et al.* [11].

Table 2: Experimental percent uncertainties

Heat input (W)	Internal uncertainty (%)	External uncertainty (%)	Total uncertainty (%)
	Milk		
240	12.50	1.3	13.8
280	20.62	1.3	21.92
320	4.13	1.3	5.43
360	4.52	1.3	5.82
	Water		
240	11.74	1.3	13.04

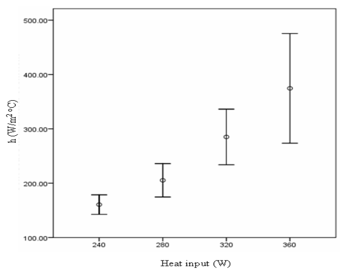

Fig. 4: Error bars for convective heat transfer coefficients

These results are also illustrated in Fig. 2. It can be seen form Fig. 2 that the convective heat transfer coefficients during pool boiling of milk in stainless steel pot are lower than that of aluminum pot and were observed 27.42% lower for the given range of heat inputs. Fig. 3 illustrates the variation of predicted heat flux with excess temperature ranging from 4 to 20 ^{o}C. The heat flux was observed to increase exponentially with the increase in excess temperature. These results are in accordance with those reported in the literature [9, 10, 11, 17 and 19]. The average value of heat flux was found to vary from 89.89 to 11236.4 W/m^2 for the mentioned excess temperatures range. In order to make a comparison, the convective heat transfer coefficient and the heat flux values for water were also determined at 240 W. The results for convective heat transfer coefficient of water are given in Table1 from which it is observed that the convective heat transfer coefficient of water is 70.18% higher than that of milk. The variation in heat flux with excess temperature for water is also shown in Fig 3**.** It was observed about 2.55 times higher than that of milk. This may be due to the purity of water. The experimental errors in terms of percent uncertainty (internal + external) were estimated in the range of 5.43 to 21.92% and the different values of convective heat transfer coefficients were found to be within this range. The experimental percent uncertainties are reported in Table 2. Error bars for convective heat transfer coefficients are shown in Fig. 4.

Conclusions

The research reported herein was set forth in order to determine the convective heat transfer coefficients for pool boiling of milk in a stainless steel pot under closed conditions. Experimental data were analyzed by using Rohsenow correlation with the help of simple linear regression analysis. The average values of the constants 'C_{sf}' and 'n' were determined as 0.964 and -1.396 respectively. The values of convective heat transfer coefficients were found to increase from 160.51 to 374.52 W/m^2 ^{o}C for the heat inputs ranging from 240 to 360 watts. This could be due to higher heating surface temperature which results in formation of more active nucleation sites and thus rapid formation of the vapor bubbles at the pan-liquid surface. The variation of heat flux with excess temperature of milk was predicted to increase exponentially with the increase in excess temperature. The average values of heat flux was observed to vary from 89.89 to 11236.4 W/m^2 for the given heat inputs. The experimental errors in terms of percent uncertainty were evaluated in the range of 5.43 to 21.92%.

Nomenclature

A	Area of pan, m^2
C_{pl}	Specific heat, J/kg ^{o}C
C_{sf}	Experimental constant that depends on surface-fluid combination
F	Fat content %
g	Gravitational acceleration, m/s^2
h	Convective heat transfer coefficient, W/m^2 ^{o}C
h_{fg}	Enthalpy of vaporization, J/kg
k_l	Thermal conductivity of milk, W/m ^{o}C
m_{ev}	Mass evaporated, kg
$\dot{m}_{ev}$	Rate of mass evaporated, kg/s
N	Number of observations
N_o	Number of sets
n	Experimental constant that depends on fluid
Pr	Prandtl number $(\mu_l C_{pl} / k_l)$
$q_{nucleate}$	Nucleate boiling heat flux, W/m^2
sd	Standard deviation
T	Temperature, ^{o}C
T_s	Surface temperature, ^{o}C
T_{sat}	Saturation temperature, ^{o}C
W	Watts
w_1	Weight of fluid, g
w_2	Weight of pot, g
$\bar{X}_w$	Average water content % in time interval
μ_l	Viscosity of milk, kg/m.s
ρ_l	Density of milk, kg/m^3
ρ_v	Density of vapor, kg/m^3
σ	Surface tension of milk, N/m

Table A2: Observations for pool boiling of milk in closed conditions (heat input=280 W, w_1=935g, w_2=1191g)

Time interval (min)	T_1 (ºC)	T_2 (ºC)	T_3 (ºC)	T_4 (ºC)	T_5 (ºC)	T_6 (ºC)	m_{ev} (g)
10	94.2	95.3	53.4	26.1	60.1	42.8	7.9
10	99.2	100.3	57.8	26.6	90.7	56.9	12.9
10	99.8	100.5	58.7	26.7	97.2	59.7	24.7
10	100.0	100.6	59.0	26.9	98.7	60.0	25.7
10	100.1	100.7	59.5	27.0	99.0	60.0	24.7
10	100.3	100.7	59.2	27.0	99.3	60.4	24.0
10	100.5	100.9	58.9	27.0	99.2	60.1	23.6
10	100.1	100.8	59.0	27.2	99.3	59.5	23.9
10	100.1	100.7	57.6	27.2	99.3	60.4	24.3
10	100.0	100.7	56.9	27.3	99.3	61.0	24.4
10	100.1	100.7	57.4	27.4	99.5	61.0	25.1
10	99.9	100.8	56.4	27.3	99.2	61.1	25.2
10	100.1	100.7	56.4	27.4	99.3	62.3	25.1
10	100.1	100.7	57.0	27.6	99.2	63.8	25.6
10	100.0	100.8	57.3	27.8	99.3	65.3	26.0
10	100.1	100.9	57.0	27.9	99.3	64.6	25.3
10	100.1	100.9	57.7	28.2	99.3	63.7	25.0

Table A3: Observations for pool boiling of milk in closed conditions (heat input=320 W, w_1=935g, w_2=1191g)

Time interval (min)	T_1 (ºC)	T_2 (ºC)	T_3 (ºC)	T_4 (ºC)	T_5 (ºC)	T_6 (ºC)	m_{ev} (g)
10	97.7	98.8	58.1	26.7	97.3	64.8	28.1
10	98.7	100.7	58.4	26.9	98.7	66.4	32.9
10	99.0	100.8	58.4	27.0	98.8	65.0	31.8
10	99.1	100.8	58.3	27.0	98.7	67.3	31.5
10	99.2	101.0	58.1	27.2	98.9	67.0	31.4
10	99.4	101.0	57.9	27.4	98.9	65.3	31.6
10	99.5	101.1	59.0	27.3	98.9	66.2	32.2
10	99.4	101.1	60.1	27.4	98.9	67.1	31.1
10	99.4	101.2	60.5	27.6	98.9	66.9	32.8
10	99.5	101.3	60.8	27.6	99.0	68.0	32.2
10	99.0	101.5	60.1	27.6	99.0	69.1	32.6
10	99.9	101.6	60.7	27.8	99.0	68.6	32.1
10	100.0	101.9	60.6	28.0	99.1	69.4	33.6

Table A4: Observations for pool boiling of milk in closed conditions (heat input=360 W, w_1=735g, w_2=1191g)

Time interval (min)	T_1 (ºC)	T_2 (ºC)	T_3 (ºC)	T_4 (ºC)	T_5 (ºC)	T_6 (ºC)	m_{ev} (g)
10	97.3	97.6	59.0	26.9	96.2	57.9	33.2
10	100.4	100.5	59.7	27.1	98.7	62.9	37.2
10	100.4	101.1	60.0	27.3	98.8	62.6	38.8
10	100.7	101.2	60.6	27.4	98.7	63.8	38.3
10	100.7	101.2	61.1	27.6	98.8	62.1	38.4
10	100.8	101.3	61.0	27.6	98.8	62.5	39.0
10	100.3	101.7	64.1	27.8	98.8	61.6	39.4
10	100.4	102.0	64.5	27.9	98.8	64.1	40.3
10	100.7	101.9	64.3	27.9	98.9	63.5	39.8
10	100.3	101.8	63.5	28.0	98.9	62.5	38.1
10	101.2	102.7	64.2	28.0	99.1	62.9	37.9
10	101.5	102.5	63.9	28.1	99.0	62.7	38.9

Table A5: Observations for pool boiling of water in closed conditions (heat input=240 W, w_1=935g, w_2=1191g)

Time interval (min)	T_1 (ºC)	T_2 (ºC)	T_3 (ºC)	T_4 (ºC)	T_5 (ºC)	T_6 (ºC)	m_{ev} (g)
10	91.0	93.6	49.6	25.5	90.6	55.1	10.6
10	94.4	96.5	51.2	25.8	93.0	58.1	14.4
10	95.7	97.3	51.1	26.0	94.1	59.5	15.7
10	96.0	98.3	52.3	26.0	95.6	60.4	16.8
10	96.5	98.2	53.3	26.2	94.5	61.1	17.9
10	96.8	98.3	53.8	26.4	95.9	62.3	17.6
10	96.9	98.6	54.0	26.6	95.9	62.4	17.9
10	96.9	98.4	54.0	26.6	96.1	63.8	18.0
10	96.7	98.8	53.9	26.7	96.1	63.9	18.1
10	97.0	99.7	54.6	26.8	96.2	62.5	18.4
10	96.9	99.5	55.9	26.9	96.1	63.3	18.7
10	97.0	99.6	55.3	27.0	96.2	63.6	18.8
10	96.9	99.5	55.2	27.0	96.2	64.4	19.2
10	96.9	99.5	54.9	27.2	96.3	63.3	19.4
10	97.0	99.9	55.9	27.2	96.3	62.4	19.1
10	96.7	99.3	56.0	27.3	96.2	62.1	18.9
10	96.5	99.6	56.5	27.3	96.2	64.1	19.8
10	96.3	99.2	56.0	27.5	96.0	63.4	19.5
10	96.4	99.7	56.3	27.6	96.0	63.1	19.1
10	96.4	99.7	56.7	27.4	96.1	65.0	19.7
10	96.5	99.9	56.8	27.4	96.2	65.1	19.6

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