Evaluation of Convective Heat Transfer Coefficient for Pool Boiling of Milk Under Closed Condition

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

ABSTRACT

This research paper reports the study on heat and mass transfer during pool boiling of milk in an aluminum pan under closed conditions. Various indoor experiments were conducted for different heat inputs varying from 240 to 360 W. During heating of milk the evaporated water was condensed at the inner surface of the condensing cover and collected as fresh water. Experimental data were analyzed by using Rohsenow pool boiling correlation with the help of simple linear regression analysis. The convective heat transfer coefficients were estimated in the range of 186.32 to 567.56 W/m^2 ^{o}C for the heat inputs varying from 240 to 360 W. The nucleate boiling heat flux was observed to increase exponentially with the increase in excess temperature. The experimental errors in terms of percent uncertainty were also evaluated.

Keywords: *Milk; Khoa; Khoa making; Pool boiling; Convective heat transfer coefficient.*

1. INTRODUCTION

BOILING is a very effective and efficient mode of heat transfer, and it is encountered in various engineering applications. Khoa making is one of the important applications which involves boiling of milk with an aim of evaporating the large quantity of water present in it. Khoa is a heat desiccated milk product which forms an important base for the preparation of variety of milk sweets [1]. During the last seven decades, many theoretical and empirical correlations have been proposed to estimate the heat transfer coefficients as well as critical heat fluxes, under boiling in different conditions [2]. Rohsenow proposed constant values of the exponents in dimensionless numbers and provided a list of values of constant for some surface-fluid combinations for nucleate boiling which was further extended [3, 4]. Rohsenow pool boiling correlation has been evaluated experimentally by many researchers [2, 4-11]. The convective heat and mass transfer coefficient for pool boiling of sugarcane juice during preparation of jaggery were reported to vary from 50.65 to 345.20 W/m^2 ^{o}C for heat inputs ranging from 160 to 340 watts [12].

Recently, the pool boiling behavior of milk for khoa making under open conditions have been experimentally studied [13]. The values of the constants and were determined as 0.941 and -1.472 respectively for the heat inputs ranging from 240 to 360 watts. The convective heat transfer coefficient was reported to vary from 334.48 to 837.78 W/m^2 ^{o}C and the heat flux was observed to vary from 272.711 to 34089.27 W/m^2 for the excess temperatures ranging from 4 to 20 ^{o}C. During khoa making under open conditions 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. The aim of the present experimental work is to investigate nucleate pool boiling of milk in a circular aluminum pan under closed conditions for the different heat inputs. Experimental data were analyzed by using the Rohsenow correlation for the surface boiling of liquids to determine the convective heat transfer coefficient which is required

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for the proper design of an evaporator. Several indoor experiments were performed for pool boiling of milk in a closed cylindrical aluminum pan by varying the heat inputs from 240 to 360 watts and the condensed water was collected as fresh water. The present research work would be useful in designing a distillation cum khoa making system.

2. MATERIALS AND METHODS

2.1 Experimental set-up and observations

The schematic view of the experimental set-up is shown in Fig. 1. It consists of a hot plate (1000W capacity; 178 mm in diameter) connected through a variac to control the rate of heating of the milk in a closed aluminum pot (200 mm in diameter, 102 mm deep and 1.6 mm thick). 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 condensing cover were made of 24 gauge thick galvanized sheet. An arrangement for collection of the condensed water was made by welding a copper channel inside the condensing cover around it. It is pertinent to mention here that the distillate output during heating of milk under closed conditions was observed at a higher temperature (>90 °C). This range is generally referred as pool/nucleate boiling conditions which is preferred for making khoa [13, 14].

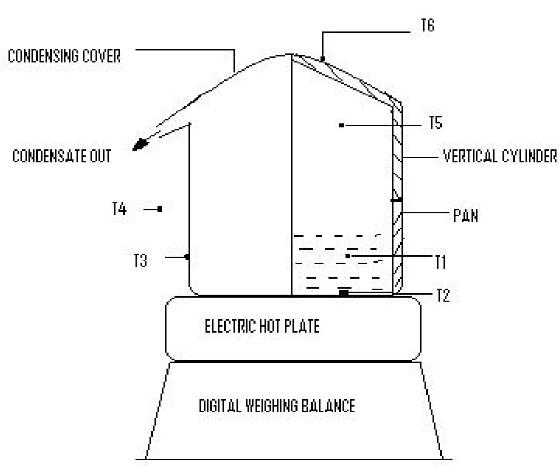

Fig. 1: Schematic view of experimental set up

Temperatures were measured at various locations as shown in Fig. 1 by calibrated copper-constantan thermocouples using a ten channel digital temperature indicator with least count of 0.1^{0}C (accuracy ± 0.1%; range of -50 to 200 °C). The heat input was measured by a calibrated wattmeter having a least count of 1 watt. An electronic weighing balance of 6 kg weighing capacity (Scaletech, model TJ-6000) with a least count of 0.1g was used to measure the evaporated mass of the milk.

2.2 Experimental procedure

Locally available fresh milk (obtained from a herd of 15 cows) was heated in an aluminum cylindrical pot covered by a vertical cylinder for different values of heat inputs ranging from 240 to 360 watts. The experimental data were recorded for pool boiling range (>90 °C) and were taken before the solidification of concentrated milk. The following parameters were recorded after every 10 minute time interval: milk temperature (T_1), pot bottom temperature (T_2), outer pot side temperature (T_3), room temperature (T_4), vapor temperature (T_5), condensing cover temperature (T_6), and mass of the milk evaporated. Temperatures measured at various locations have also been shown in Fig. 1. The mass of water evaporated during heating of milk for each set of observations has been obtained by subtracting two consecutive readings in a given time interval. Different sets of heating of milk have been obtained by varying the input power supply from 240 to 360 watts to the electric hot plate with the help of the variac. The experiments follow 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 heat inputs of 360 watts 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 from the same herd of cows. The experimental results for different sets of heating are reported in Appendix-I. In order to make a comparison the same process was also repeated for water.

2.3 Thermal model

The experimental data obtained for pool boiling of milk were analyzed by using the correlation proposed by Rohsenow [3] which is expressed as

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

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 Prandtl number is calculated by using the following expression,

$$\mathrm{Pr} = \frac{\mu_l C_{pl}}{k_l} \quad (3)$$

The average convective heat transfer coefficient can be given by

$$h = \frac{q_{nucleate}}{T_s - T_{sat}} \quad (4)$$

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

$$\dot{m}_{ev} = \frac{Q_{boiling}}{h_{fg}} = \frac{A q_{nucleate}}{h_{fg}} \quad (5)$$

Now with the help of Eq. (5), the Eq. (2) can be rearranged as follows

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

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. (6) becomes

$$K = C_{sf}\,\mathrm{Pr}^n \quad (7)$$

Taking logarithm both sides of the Eq. (7),

$$\log K = n\log \mathrm{Pr} + \log C_{sf} \quad (8)$$

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

$$y = mx + c \quad (9)$$

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, (Ts -Tsat) recorded during the pool boiling experiments by using the thermal physical properties of milk. The corresponding values of x and y were also computed.

Thus the values of m and c in equation (9) were obtained by using the following formulae obtained by linear regression method

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

$$c = \frac{\sum x^2 \sum y - \sum x \sum xy}{N\sum x^2 - \left(\sum x\right)^2} \quad (11)$$

Where N is the number of observations in each set of heat input.

2.4 Thermal physical properties of milk

The following expressions were used for calculating the different thermal physical properties of milk such as specific heat (C_{pl}), surface tension (σ), density (ρ_l), viscosity (μ_l), thermal conductivity (k_l), and enthalpy of vaporization (h_{fg}) which were determined at an average temperature in the time interval [15-20].

$$C_{pl} = 2.976T + 3692$$

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

Where σ is in N.m$^{-1}\times10^{-3}$

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

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

Where μ_l is in Pa.s $\times10^{-3}$

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

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

2.5 Experimental error

The experimental method used is an indirect approach for determining the convective heat transfer coefficient based on the mass of the water evaporated. This indirect method is certainly has a considerable degree of experimental uncertainty. The experimental error was evaluated in terms of percent uncertainty (internal + external). The following two equations were used for internal uncertainty [21]:

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

Where N_0 is the number of sets and *sd* is the standard deviation which is given as

$$sd = \sqrt{\frac{\sum\left(X - \bar{X}\right)^2}{N}}$$

Where $X - \bar{X}$ is the deviation of observation from the mean *N* and is the number of observations in each set of heat input.

The % internal uncertainty was determined by using the following expression:

% internal uncertainty =

$(U_I/\text{mean of the total observations}) \times 100$ (20)

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

3. RESULTS AND DISCUSSION

The values of m and c were evaluated from Eqs. (10) and (11) by using the experimental data from Tables A1- A5. After determining the m and c, the values of C_{sf} and n were calculated as $C_{sf} = e^c$ and $n = m$. The values of the constants C_{sf} and n were observed to vary from 0.899 to 0.976 and -1.363 to -1.496 respectively for the given heat inputs which are reported in Table 1. The convective heat transfer coefficients were computed from Eq. (4) by using the values of C_{sf} and n for different values of heat inputs which are also given in Table I. The average values of the constants C_{sf} and n were determined as 0.952 and -1.432 respectively.

Table - I

Values of the constants and convective heat transfer coefficients

Heat input (W)	C_{sf}	n [-]	h (W/m^2 °C)
Milk			
240	0.976	1.363	186.32
280	0.963	1.375	249.85
320	0.971	1.492	343.04
360	0.899	1.496	567.56
Water			
240	1.000	3.879	316.51

The variation in convective heat transfer coefficient for the different values of heat input is illustrated in Fig. 2. It increases from 186.32 to 567.56 W/m^2 °C for the given heat inputs ranging from 240 to 360 watts. The increase in values of convective heat transfer coefficient with the increase in the heat input could be due to higher surface temperature of the pan and activation of more nucleation sites. This causes rapid formation of the vapor bubbles at the pan-liquid surface resulting in increased evaporation rate. The experimentally determined convective heat transfer coefficients are also compared with the Rohsenow correlation (Fig 2). It is found that the convective heat transfer coefficients are lower than that of Rohsenow correlation and are observed to vary in a range of 0.56 to 20.07%.

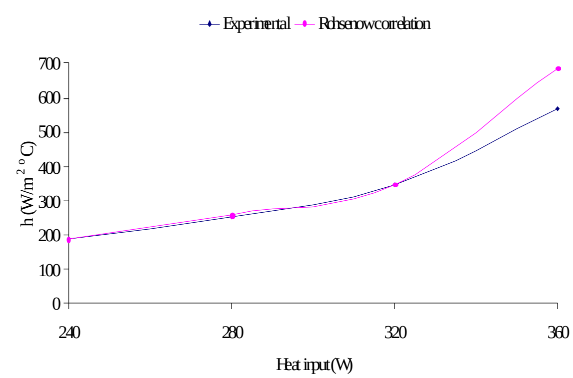

Fig. 2: Variation in convective heat transfer coefficient with heat inputs

Fig. 3 illustrates the prediction for variation of heat flux with excess temperature ranging from 4 to 20 °C for different values of heat inputs. From Fig. 3 it can be seen that the heat flux increases with the increase in heat inputs which could be due to increased mass evaporation rate. The general trend is that heat flux rises exponentially with the increase in excess temperature. These results are in accordance with those reported in the literatures [12, 13, 22, and 23]. The average value of heat flux was found to vary from 115.17 to 14394.70 W/m^2 for the given excess temperature range.

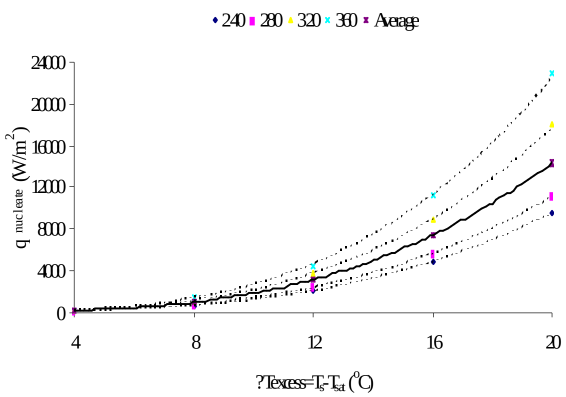

Fig. 3: Variation in heat flux with excess temperatures

For comparison purpose, the convective heat transfer coefficient and the heat flux values for water have also been determined at 240 watts. The results for convective heat transfer coefficient of water are also reported in Table1 from which it is observed that the convective heat transfer coefficient of milk is 69.87% lower than that of water. The variation in heat flux with excess temperature for milk and water has been shown in Fig 4. It can be seen from Fig 4 that the values of heat flux for milk is about 4 times lower than that of water. This may be due to the presence of fat, sugar and other milk solids particulates.

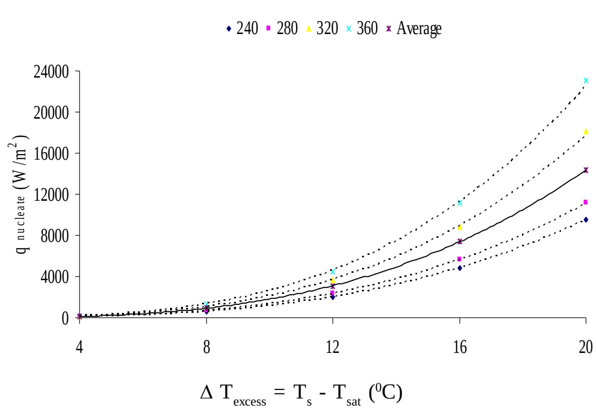

Fig. 4: Variation in heat flux for milk and water at 240 watts

The percent uncertainty (internal + external) was evaluated in the range of 7.85 to 19.15% and the different values of convective heat transfer coefficients were found to be within this range. The experimental percent uncertainties are reported in Table II. Error bars for convective heat transfer coefficients are depicted in Fig. 6.

Table - II

Experimental percent uncertainties

Heat input (W)	Internal uncertainty (%)	External uncertainty (%)	Total uncertainty (%)
	Milk		
240	11.95	1.3	13.25
280	17.85	1.3	19.15
320	6.55	1.3	7.85
360	17.30	1.3	18.6
	Water		
240	12.04	1.3	13.34

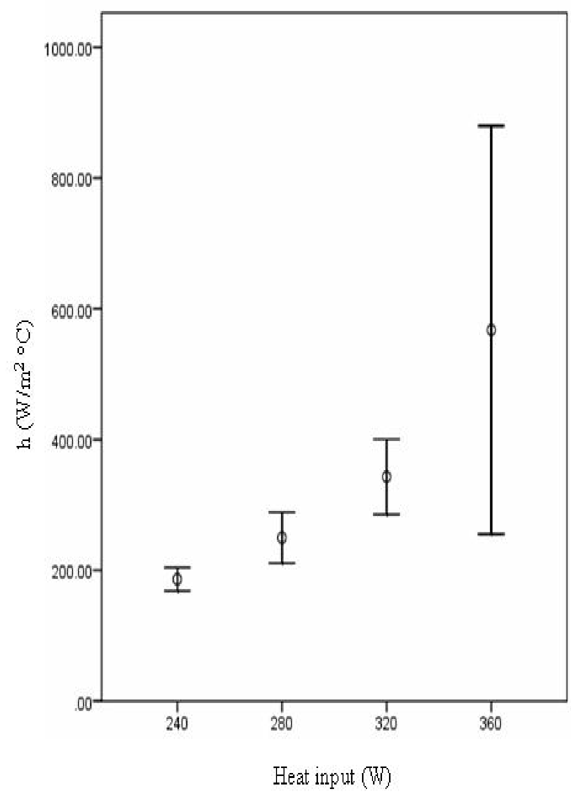

Fig. 5: Error bars for convective heat transfer coefficients

4. CONCLUSIONS

The convective heat transfer coefficients for pool boiling of milk in an aluminum pan under closed conditions were determined by using Rohsenow correlation with the help of simple linear regression analysis. The values of the constants C_{sf} and *n* were determined as 0.941 and -1.472 respectively. The values of convective heat transfer coefficients were found to increase from 186.32 to 567.56 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 rapid formation of the vapor bubbles at the pan-liquid surface. The variation of heat flux with excess temperature of milk have also been predicted which were found to vary exponentially with increasing excess temperature and were observed to vary from 115.17 to 14394.70 W/m^2. The present study would be useful in designing a distillation cum khoa making unit. The experimental errors in terms of percent uncertainty were found in the range of 7.85 to 19.15%.

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	Experimental constant that depends on fluid
Pr	Prandtl number
$q_{nucleate}$	Nucleate boiling heat flux, W/m^2
T	Temperature, ^{o}C
T_s	Average surface temperature, ^{o}C
T_{sat}	Saturation temperature, ^{o}C
w	Weight of milk, 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

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APPENDIX - I

Table.A1 : Observations for pool boiling of milk under closed conditions at heat input=240 W

Time interval (min)	T_1 (°C)	T_2 (°C)	T_3 (°C)	T_4 (°C)	T_5 (°C)	T_6 (°C)	m_{ev} (g)
10	95.6	98.6	57.8	27.1	88.3	57.0	9.9
10	100.1	100.6	58.4	27.2	93.6	61.4	22.1
10	100.1	100.8	58.8	27.4	94.8	60.6	21.9
10	100.0	100.7	58.8	27.5	95.0	61.4	21.2
10	100.3	100.7	58.5	27.8	95.7	61.4	21.1
10	100.2	100.7	59.0	27.9	95.9	62.4	21.2
10	100.1	100.9	58.5	27.9	96.6	62.2	21.4
10	100.1	100.8	58.9	28.0	96.6	63.3	20.9
10	100.2	100.6	59.2	28.2	96.3	64.2	21.4
10	100.1	100.7	59.0	28.3	96.3	64.3	21.9
10	100.3	101.0	59.5	28.4	97.3	63.9	21.2
10	100.3	100.8	59.2	28.3	97.5	64.2	21.7
10	100.3	100.7	58.9	28.6	98.1	62.8	21.3
10	100.3	100.7	59.2	28.6	97.8	63.0	21.2
10	100.4	101.0	59.4	28.8	98.3	65.3	21.9
10	100.2	100.7	60.0	28.6	98.2	63.1	20.9
10	100.3	100.8	60.1	28.6	98.5	64.0	21.4
10	100.4	100.7	60.4	28.6	98.4	64.4	21.5
10	100.5	100.9	60.1	28.7	98.6	63.5	22.6
10	100.4	101.0	60.1	28.7	98.7	61.1	20.7
10	100.4	100.9	60.1	28.7	98.7	61.7	21.3

Table.A2 : Observations for pool boiling of milk under closed conditions at heat input=280 W

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	93.1	93.9	57.6	27.5	90.9	56.2	8.8
10	100.1	100.6	58.3	27.7.	97.2	64.4	28.9
10	100.4	100.9	58.4	28.0	98.3	64.3	30.1
10	100.3	100.8	58.8	28.2	98.6	63.0	29.4
10	100.3	100.8	58.9	28.4	98.7	63.3	29.3
10	100.4	100.8	59.0	28.2	98.6	63.1	29.7
10	100.3	100.8	59.7	28.5	98.6	62.6	24.1
10	100.4	101.1	58.6	28.4	98.6	62.9	28.6
10	100.1	101.0	60.1	28.7	98.7	62.8	29.2
10	100.3	101.0	58.5	28.5	99.0	63.3	29.1
10	100.5	101.2	60.3	28.9	98.8	61.3	29.8
10	100.5	101.2	60.9	28.9	98.9	62.9	29.2
10	100.6	101.3	61.0	28.9	98.8	64.6	29.9
10	100.6	101.2	60.9	28.9	99.0	63.6	30.2
10	100.6	100.8	61.2	29.0	98.9	64.3	30.8
10	100.6	100.9	60.7	29.2	98.9	61.6	29.4
10	100.6	101.0	61.6	29.3	98.9	64.3	30.0

Table.A3 : Observations for pool boiling of milk under closed conditions at heat input=320 W

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	96.2	97.9	58.9	27.3	91.8	64.1	29.3
10	99.9	100.4	58.4	27.6	98.2	65.6	39.0
10	100.0	100.5	58.4	27.6	98.4	65.4	39.1
10	100.2	100.6	57.3	28.0	98.4	67.0	37.4
10	100.1	100.6	57.6	28.0	98.5	67.4	36.9
10	100.3	100.7	58.7	28.3	98.4	67.0	37.7
10	100.3	100.7	59.2	28.4	98.5	66.1	37.9
10	100.3	100.7	58.9	28.4	98.6	66.9	38.1
10	100.2	100.8	58.7	28.3	98.7	65.6	37.2
10	100.4	100.7	59.1	28.4	98.7	67.3	37.3
10	100.3	100.7	59.3	28.5	98.8	67.2	39.7
10	100.3	100.7	59.2	28.5	98.7	67.3	38.0
10	100.4	100.7	59.3	28.4	98.8	67.5	37.6

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Table.A4 : Observations for pool boiling of milk under closed conditions at heat input=360W

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	95.8	96.5	59.5	27.4	90.4	61.6	21.8
10	99.8	100.2	58.6	27.4	98.6	64.7	46.1
10	100.0	100.6	59.5	27.5	98.5	65.6	48.1
10	100.1	100.7	60.2	27.6	98.7	65.4	46.8
10	100.1	101.0	59.7	27.8	98.6	66.8	47.7
10	100.1	100.9	59.6	27.8	98.6	66.1	46.3
10	100.2	101.2	59.4	28.0	98.6	66.4	45.4
10	100.1	101.1	60.3	28.2	98.7	66.3	45.6
10	100.4	100.6	59.8	28.2	98.7	65.1	46.9
10	100.4	101.0	60.0	28.2	98.7	64.0	47.4
10	100.6	104.1	61.6	28.3	98.4	65.4	41.6
10	100.6	109.1	67.2	28.3	98.8	65.7	33.7

Table.A5 : Observations for pool boiling of water under closed conditions at heat input=240 W

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	93.2	94.6	54.9	25.9	88.2	54.4	11.7
10	96.2	97.3	56.5	25.9	93.6	57.3	17.1
10	96.9	98.0	57.0	25.9	96.0	60.2	19.6
10	97.2	98.1	57.3	25.9	97.1	60.2	20.3
10	97.8	98.6	57.2	26.0	97.6	61.2	21.3
10	97.7	98.4	56.7	26.0	97.5	61.6	21.2
10	98.1	98.6	57.4	26.2	97.9	61.3	20.9
10	98.4	98.9	57.2	26.1	97.9	61.7	20.4
10	97.3	98.6	57.3	26.1	97.1	62.9	21.4
10	97.4	99.1	57.1	26.2	97.1	62.0	21.8
10	97.4	98.6	57.1	26.4	97.2	62.6	21.3
10	97.2	98.4	57.0	26.5	97.1	63.0	21.0
10	97.4	99.0	58.3	26.8	97.2	63.3	21.2
10	97.5	98.9	58.6	26.8	97.2	63.5	22.0
10	97.4	98.4	59.1	27.0	97.3	64.0	22.4
10	97.7	98.9	59.0	27.0	97.3	64.1	22.9
10	97.5	98.7	59.1	27.0	97.2	64.5	23.0
10	97.4	98.9	59.0	27.0	97.2	63.8	22.2
10	97.0	98.7	58.9	27.0	96.5	64.6	23.6
10	96.7	98.7	58.9	27.1	96.2	64.5	22.9
10	96.7	98.9	58.9	27.2	96.2	64.5	23.6