AN APPROACH TO OBTAIN THE HEAT TRANSFER COEFFICIENT OF AQUEOUS SUCROSE SOLUTIONS IN AGITATED BOILING VESSELS

by

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In this study, the heat transfer mechanism under agitated pool boiling was examined experimentally. Aqueous sugar solutions were used in a centrically agitated vessel. The effects of the gap which is between the impeller edge and the flat bottom of the agitated vessel, the rotational impeller speed and impeller size were studied on the boiling heat transfer coefficient. A new Nusselt function depending on the Peclet number was suggested for the heat transfer mechanism.

Key words: *heat transfer, agitated vessels, pool boiling, forced convection,
             aqueous sugar solutions*

Introduction

Foodstuffs produced from sugar (bonbon, *etc*.) must be in viscous liquid phase in order to give desired forms and to add additives (color, aroma or agent, *etc*.) in the confectionery industry. Because of the low thermal conductivity of the sucrose, it is difficult to heat white granulated sucrose directly in order to obtain viscous liquid phase. Therefore, the solution is composed by adding some water to sucrose in an agitated vessel then the solution is boiled to evaporate the water. In this way viscous sucrose solution can be heated up to high temperatures.

The viscous sucrose solutions are usually used producing "halva" type of desserts as a main ingredient. Halva is widely consumed in many Middle Eastern countries such as Turkey, Arabic countries, and Greece as well. It is a well-known fact that the transferred heat decreases as the sucrose concentration is getting higher on the boiling sucrose solutions. As a natural result, if the boiling temperature goes up to 130-150 °C, the sucrose concentration reaches a value of 90-95% [1, 2]. The main problem of sucrose melting is that the sucrose changes its color above 150 °C and its taste above 170 °C which results in decomposition chemically. In order to continue boiling, the heater surface temperature should not be higher than 150 °C. Therefore, it is necessary to evaporate the water within the solution in the fastest manner before reaching temperatures of 150 °C. The sucrose can be easily shaped after this process.

Due to mentioned reasons, agitated vessels are used very commonly in the industrial production in order to improve the heat transfer. Especially candy, halva, and many regional or modern confectionary foodstuffs are manufactured in the same technologies.

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It is very well known that agitating improves the heat transfer. But there are only a few researches on this particular subject. Mostly, pure substances, turbulent regime of the fluid flow and eccentricity were investigated in these studies. Some of these are presented below.

Adamiak and Karcz [3] investigated effects of type and number of impellers and liquid viscosity on the power characteristics of mechanically agitated gas liquid systems. They studied with water and glucose solutions of different concentrations which are 40%, 60%, and 70%. Different configurations of impellers were tested using baffled agitated vessels. Measurements of power consumption were carried out within the transitional and turbulent regime of the fluid flow. The relative power consumption was compared for the impellers. They did not investigate the heat transfer.

Cudak and Karcz [4] studied distribution of local heat transfer coefficient values in the wall region of an agitated vessel. The experiments were carried out within the turbulent regime of the Newtonian liquid flow in the agitated vessel equipped with the eccentrically located impeller. The experimental study showed that the distributions of the heat transfer coefficient values depend on the impeller eccentricity, impeller type and the direction of the liquid circulation in the agitated vessel. Here, the heat transfer coefficient was studied and a useful Nusselt function was proposed $Nu_m = C_{el} (e/R)Re^{0.67}Pr^{0.33}$ but they did not study on boiling conditions with the sucrose solutions.

Triveni *et al.* [5] studied on heat transfer for Newtonian and non-Newtonian fluids in the agitated vessel. They used anchor/turbine impeller and a coil for heating/cooling. They experimentally investigated effects of impeller geometry, rotational speed, and aeration to the heat transfer of few industrially important systems namely castor oil and its methyl esters, soap solution, and chalk slurries.

Peixoto and Nunhez [6] studied on improving heat transfer in stirred tanks cooled by helical coils numerically. They improved internal flow between tank wall and the coil avoiding placing any coil at the impeller height.

Lakghomi *et al.* [7] studied coil and jacket's effects on internal flow behavior on heat transfer in stirred tanks. They have indicated that coil ones more efficient.

Kawase *et al.* [8] examined on the heat transfer experimentally and theoretically in a jacketed, stirred tank with various non-Newtonian fluids and different large-scale impeller.

Adib *et al.* [9] described the boiling heat transfer coefficient h for the vertical tube falling film evaporator in function of the experimental parameters which are concentration in, temperature, heat flux and mass flow rate.

Gabsi *et al.* [10] studied on a CFD model of date-water diffusion in agitated vessel to predict mass transfer. The model predicted the sugar mass transfer from date to water as the function of impeller speed, date: water ratio and the varieties of date. The numerical results were compared with the experimental data for mass transfer which indicated a good agreement.

As a result of detailed literature survey, a special study was not found about the effects of agitating on heat transfer during the pool boiling. Aforementioned studies were not examined within the laminar regime of the aqueous sucrose solutions at high sucrose concentration.in the centrically agitated vessels.

Heat transfer characteristics of pool boiling on pure substances have been studied for many years. One of the frontiers in this field is Rohesnow [11] and his basic calculations are used in many later studies. Nukiyama [12] was focused on experimental study of pool boiling

and came up with a boiling curve that is known by his name. However, most of these equations are applicable for pure liquids.

Ozdemir and Pehlivan [13] have suggested a function depending on the concentration of sucrose to calculate the heat transfer coefficient and boiling point for non-agitated solutions during pool boiling. The suggested functions are not applicable for agitated vessels used in industrial applications. This study is a continuation of the previous study [13] and the aim is determined the boiling heat transfer coefficient in centrically agitated vessels experimentally.

Impeller blades are used to improve on the heat transfer in the vicinity of the agitated vessel wall and they are produced within the 0-12 mm distance from the inner surface.

Pool boiling heat transfer mechanism

Vapor bubble which grows on the heating surface blocks the contact of liquid and the heating surface. Thus make the heat transfer more difficult. However, as vapor bubbles are leaving from the surface with the impact of the buoyant force, they cause the liquid to move. This improves the heat transfer a bit.

The combined effect on heat transfer of these opposite situations relate to the structure of heating surface, the size of vapor bubbles, the surface tension of the solution and viscosity [14-16]. These physical conditions of aqueous sucrose solutions also change in accordance with sucrose concentration. Naturally vapor bubbles in high-sucrose-concentrated solutions are bigger and long lived. It is possible to remove this condition with negative effect on heat transfer partly by agitating. It is also known that the agitation supports the heat transfer.

Non agitating pool boiling heat transfer mechanism

In general, boiling is a process that fluid changes from liquid phase to vapor phase. The process starts at a saturation temperature of liquid with certain pressure. According to Newton's law of cooling the heat is transferred from the surface to the saturated liquid phase is given:

$$\dot{q} = h(T_w - T_{sat}) \tag{1}$$

The heat transfer of pure fluids for bubble formation region [14] can be defined as:

$$\dot{q} = C(T_w - T_{sat})^n \tag{2}$$

Following equations can be used for the boiling of the sucrose-water solutions with different concentrations and non-agitating conditions [11]:

$$\dot{q} = C(1 - c_s)(T_w - T_b)^{1,3} \tag{3}$$

where C is a constant and $(1 - c_s)$ – the water concentrations. Saturation temperature of sucrose water solution for a given mass concentration can be calculated by using the equation [13]:

$$T_b = T_{sat} + \left(\frac{c_s T_{sat}}{2,1}\right)^{c_s^{2,1}} \tag{4}$$

The heat transfer coefficient can be calculated by the following equation for non-agitated situation [13]:

$$h = C(1 - c_s)\left\{T_w - \left[T_{sat} + \left(\frac{c_s T_{sat}}{2,1}\right)^{c_s^{2,1}}\right]\right\}^{0,3} \tag{5}$$

Agitating pool boiling heat transfer mechanism

The heat transfer rate on agitated pool boiling is higher than non-agitated pool boiling. This case can be written for the heat flux as:

$$\dot{q}_a = \dot{q}_o + q_g \tag{6}$$

$\dot{q}_o$ and $\dot{q}_g$ can be written separately as:

$$\dot{q}_o = h_o \Delta T \tag{7}$$

$$\dot{q}_g = h_g \Delta T \tag{8}$$

This situation is also applicable for the boiling heat transfer coefficient and the Nusselt number. So, h_a and Nu_a can be written separately as:

$$h_a = h_o + h_g \tag{9}$$

$$Nu_a = Nu_o + Nu_g \tag{10}$$

where h_o can be calculated by using eq. (5) and the Nu_o can be obtained by the equation:

$$Nu_o = \frac{h_o l}{k} \tag{11}$$

where h is the boiling heat transfer coefficient, l – the characteristic length which is one of the experimental parameters, and k is the thermal conductivity. The thermal conductivity of pure water, liquid sucrose, and aqueous sucrose solution are given separately in tab. 1. The value of the thermal conductivity varies from 0.594 to 0.574 in concentration between 70-85% in experiments. Because of that it was taken as 0.58 $Wm^{-1}K^{-1}$ for aqueous sucrose solution.

Table 1. The thermal conductivity of aqueous sucrose solutions

Material	Temperature [°C]	Value [$Wm^{-1}K^{-1}$]	Concentration [%]
Pure water	80-140	0.670-0.688 [17]	100
Liquid sucrose	140	0.555 [18]	100
Aqueous sucrose solution	100-140	0.594-0.574 [21]	70-85

Experimental set-up and uncertainty analysis

The Nusselt functions and the Nusselt numbers change according to the material specification (μ, ρ, c_p, and k) due to temperature. Therefore, it is necessary to perform experiments at different saturated pressures. However, it is not easy performing these experiments at high pressures due to the leaking problems in agitating vessels. Therefore, the heat transfer mechanism relating to the sucrose concentration can be investigated at about 30 °C temperature range for aqueous sucrose solutions whose material properties are well known. It is possible to obtain different saturated conditions under constant pressures for different temperatures therefore aqueous sucrose solutions were used in experiments. The experimental set-up is given in fig. 1.

The 30 mm glass wool is used for the vessel isolation. Inner diameter of the vessel is 172 mm. Turbine type impeller which has two blade is used. Impeller blade length is 168 mm and it is constant for all impeller blades. Impeller widths are 16 mm for size 1, 26 mm for size 2 and 39 mm size 3, respectively.

The experiments were performed for three different speeds which are 40-80-120 rotations per minute of agitator and two different gaps (4 and 12 mm) between the impeller blade and the heating bottom surface. Four different concentrations of aqueous sucrose solutions (70%, 75%, 80%, and 85%) were examined. Height of the liquid level is 60 mm.

The transferred heat flux was determined by using the mass and energy balance. The change of solution mass was obtained by gravimetric analyses. The heat transfer rate was calculated by using phase change enthalpy and the mass changing.

Kline and McClintock [19] suggested the accurate method called uncertainty analysis. According to Holman [20], if R is given function of the independent variables $x_1, x_2, x_3, \ldots, x_n$, $R = R(x_1, x_2, x_3, \ldots, x_n)$, and $W_1, W_2, W_3, \ldots, W_n$ are the uncertainties in these independent variables, the uncertainty of R can be evaluated by;

Figure 1. Experimental set-up

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} W_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} W_2 \right)^2 + \ldots + \left(\frac{\partial R}{\partial x_n} W_n \right)^2 \right]^{1/2} \qquad (12)$$

In the experiments, the maximum errors were expressed in this way. Here, W is the absolute error of the parameters. Table 2 gives absolute and relative errors of measured variables.

Thermocouples were calibrated (2 point calibration; boiling pure water and ice water) for every cycle of experiment. Temperature measuring error is verified as ±0,1 °C. The relative and the absolute errors were calculated by taking into account for maximum 30 °C and minimum 12 °C temperature differences.

Table 2. Uncertainties of parameters

Uncertainties	Relative error range [%]	Absolute error range
ΔT	0.47-1.17	0.140-0.141 °C
Δm	0.49-20.2	1.413-1.414 g
$\dot{q}_a$	7.44-20.2	55.8-151.5 W/m^2
h_a	7.5-20.2	127.5-343.4 W/m^{2}K
Nu_a	7.5-20.2	4.5-12.12

A digital scale was used for mass balance. It has an accuracy of ±1 g. The relative and the absolute errors were calculated by taking into account for maximum 290 g and minimum 7 g mass differences.

Material properties (μ, ρ, c_p), phase change enthalpy related with the concentration and the temperature were taken from corresponding tables [21, 22].
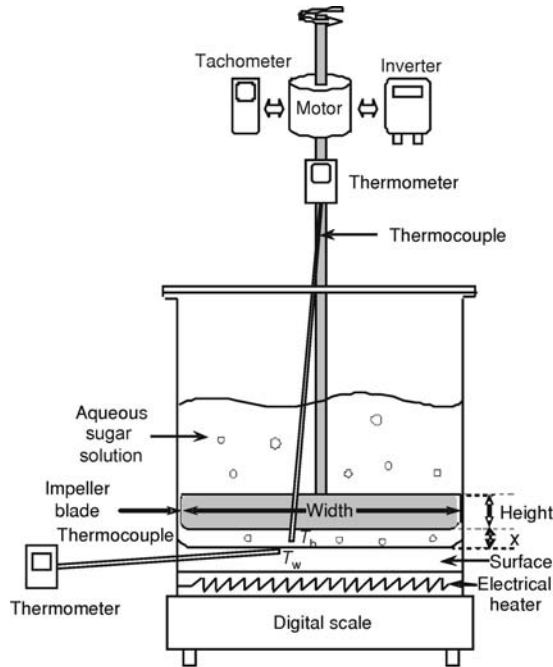
Heat loss to the environment was calculated as 17 W by using laminar natural convection heat loss calculation method [23].
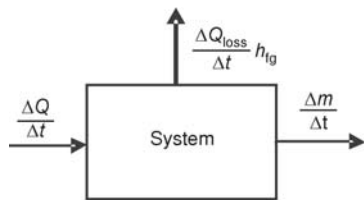
Mass and energy balance

Taking Q_{loss} into account, mass and energy balance for aqueous sucrose solution are shown in fig. 2.

By using partial mass balance, the mass concentration of sucrose (c_s) and the mass concentration of water (c_{wt}) are equal to:

$$c_s = \frac{m_s}{m_s + m_{wt}} \tag{13}$$

Figure 2. Mass and energy balance

$$c_{wt} = \frac{m_{wt}}{m_s + m_{wt}} \tag{14}$$

The difference between the initial and final masses in a time interval was defined as:

$$\Delta m = m_1 - m_2 \tag{15}$$

Based on gravimetric analyze in a time interval, the sucrose concentration can be obtained. By writing the energy balance for each time interval, the continuous regime for boiling is give, eq. (16). Here, the heat transfer area (A) is known and the transferred heat flux can be calculated using the equation:

$$\frac{\dot{Q}}{A} = \dot{q} \frac{\Delta m}{\Delta t} \frac{h_{fg}}{A} \tag{16}$$

Obtaining the boiling heat transfer coefficient

The boiling heat transfer coefficient for each sucrose concentration (from 70% to 90%) can be calculated by using eq. (17):

$$h = \frac{\dot{q}}{T_w - T_b} \tag{17}$$

Also the boiling heat transfer coefficient can be expressed as:

$$h = \frac{Nuk}{l} \tag{18}$$

The Nusselt numbers should be determined by using a Nusselt function. Therefore the goal of this study is to find out a useful Nusselt function for the valid heat transfer mechanism.

The Nusselt numbers can be obtained using the boiling heat transfer coefficients which are calculated for each experimental result. Hence, the Nusselt numbers which are calculated through the experimental results can also be calculated through the suggested Nusselt function.

Obtaining the Nusselt function

The Nusselt function is defined depending on the Reynolds and the Prandtl numbers for plane surface as [24]:

$$Nu = a \, Re^b \, Pr^c \tag{19}$$

If eq. (19) is linearized, eq. (20) can be written as:

$$\ln \text{Nu} - \ln a + b \ln \text{Re} + v \ln \text{Pr} \tag{20}$$

The Nusselt number values which are depending on the Reynolds and the Prandtl numbers were obtained for all configurations by using experimental data. One of these configurations is given in fig. 3.
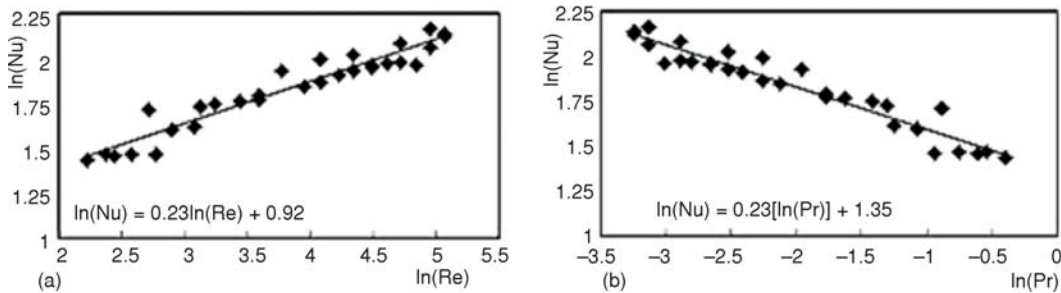

Figure 3. For the first size blade, 4 mm gap and 80 rpm; (a) lnRe – lnNu, (b) lnPr – lnNu

Experimental studies show that the coefficient b is equal to the coefficient c in eq. (20). That is also seen in fig 3. This observation concerns all of the configurations investigated. Therefore, it was concluded that the Peclet number can be written as eq. (21) instead of RePr.

$$\text{Pe} = \text{Re Pr} \tag{21}$$

Thus, the Nusselt function takes the following form:

$$\text{Nu} = a\,\text{Pe}^{\,b} \tag{22}$$

Already, the Nusselt function associated with the Peclet number has been given for developing laminar flow at the thermal entrance region. This subject takes place as the forced convection in the fundamental literature. Several Nusselt functions have been given for such like heat transfer situations in the literature. The average Nusselt function is defined as follow for the thermal entrance region in a circular L length of pipe with constant surface temperature for laminar flows [25]:

$$\text{Nu} = 3.66 + \frac{0.065\left(\dfrac{D}{L}\right)\text{Re Pr}}{1 + 0.04\left[\left(\dfrac{D}{L}\right)\text{Re Pr}\right]^{2/3}} \tag{23}$$

"The average Nusselt number for the thermal entrance region of flow between isothermal parallel plates of length L is expressed as below:

$$\text{Nu} = 7.54 + \frac{0.03\left(\dfrac{D_{\text{h}}}{L}\right)\text{Re Pr}}{1 + 0.016\left[\left(\dfrac{D_{\text{h}}}{L}\right)\text{Re Pr}\right]^{2/3}} \tag{24}$$

where D_{h} is the hydraulic diameter, which is twice the spacing of the plates. This relation can be used for Re $\leq$ 2800" [25].

Equations (23) and (24) have constant values which are 3.66 and 7.54. In this study, these constant values are the Nusselt numbers, Nu_o, as seen in eq. (10). These Nu_o are referring to non-agitating condition that the fluid velocity or the agitator speed is equal to zero. In order to calculate Nu_o, h_o can be obtained by using eq. (5).
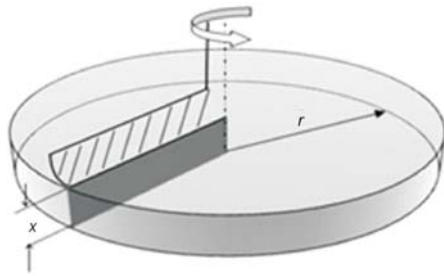

Figure 4. Assumption of differential channel width in circular rotation moving
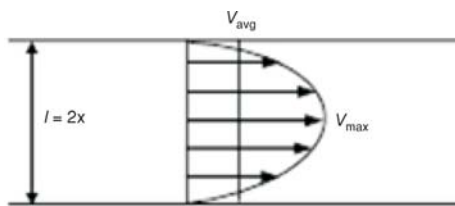

Figure 5. Fully developed velocity profile for a pipe flow

There is a hydro-dynamically developed flow because of the constant agitation speed. The impeller blades move the fluid repetitively at each rotation in an agitated vessel. However the flow characteristic repeats itself for every rotation in the gap. It can be assumed that the flow is at thermal entrance region for a pipe flow. A simple diagram that depicts this situation is given in fig. 4.

The maximum flow velocity occurs at the center of the pipe as seen in fig. 5 [26]. In this study, the maximum flow velocity occurred at the bottom edge of the impeller blade as expected. So, the heat transfer mechanism between the bottom surface and the impeller blade can be thought as the laminar forced pipe flow. Taking the similarity to pipe flow into account, the bottom surface where the flow velocity is zero is accepted as the inner wall of the pipe. The bottom edge of the impeller blade where the maximum flow velocity occurs is accepted as the center of the pipe. Ultimately, the gap between the blade and the bottom surface is accepted as equal to the radius of the pipe. This means that the characteristic length is thought as twice the gap ($x = l/2$).

In experiments, maximum linear velocities, average linear velocities and the Reynolds numbers were calculated by the equations:

$$\vec{V}_{max} = \vec{V}_{r/2} \tag{25}$$

$$\vec{V}_{avg} = \vec{V}_{r/2}\left(\frac{l_x}{l}\right) \tag{26}$$

$$Re = \frac{\rho \vec{V}_{avg} l}{\mu} \tag{27}$$

The maximum Reynolds number was obtained under 1127. Hence the experiments were carried out within the laminar regime of the liquid solution flow in the agitated vessel.

In this study, taking everything into account aforementioned the local Nusselt number for the agitating situation was described using the equation:

$$Nu_{local} = \frac{a\,Pe}{l + b\,Pe^{c}} \tag{28}$$

where the Peclet number depends on the Reynolds number and the Reynolds number on the fluid flow speed. Also the fluid flow speed is associated with the radius for a constant agitation speed. The average Nusselt function was obtained by integrating the local Nusselt function from $r = 0$ to $r = r$:

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$$\text{Nu}_a = \text{Nu}_o + \int_{r=0}^{r=r} \frac{a\text{Pe}}{1 + b\text{Pe}^c} \, dr \qquad (29)$$

Assuming $a = b\,c$ equality in eqs. (29) and (30) can be obtained as:

$$\text{Nu}_a = \text{Nu}_o + \ln(1 + b\text{Pe}^c) \qquad (30)$$

In this study, an approach which is similar to the laminar forced pipe flow was proposed with eq. (30). How well the measured values match up with this approach is discussed in the results section.

Results and discussions

The results of this experimental study which is conducted to determine heat transfer rate in an agitated boiling vessel were investigated with engineering approach. As also mentioned previously, the heat transfer rate and the boiling temperature are very important for fast evaporation. The boiling and the surface temperatures should not be higher than 150 °C because of caramelize. For this reason, the heat transfer rate must be increased at small temperature differences. The heat transfer increases regressively with the Peclet number depending on the agitation speed.

The results showed that there is a good correlation between the experimental results and calculated values of the heat transfer coefficients using:

$$\text{Nu}_a = \frac{h_o l}{k} + \ln(1 + \text{Pe}^{2.5}) \qquad (31)$$

The overall Nusselt numbers obtained experimentally and calculated using proposed expression eq. (31), – solid line, are shown from fig. 6 to fig. 8 for impeller blade sizes 1, 2, and 3, and 4-12 mm gaps and 70% (■), 75% (▲), 80% (◆), and 85% (●) concentration of sucrose solutions. The results were obtained by substituting $b = 1$ and $c = 2.5$ in eq. (30). The characteristic length is twice the gap. Temperature range is between 100-120 °C. Blade velocity range is 0-120 rpm. The Reynolds number is <1100 and the Prandtl number is <1. The results revealed that, for proposed Nusselt function, the numerical data were in good agreement with the experimental data indicating the R^2 of 0.99.

Due to experimental the Nusselt number is directly proportional to the characteristic length, the values of the Nusselt number are higher for larger gap. It can be seen in fig. 6.

Figures 6(b) and 7(b) show the best fit for the first and the second size impeller blade with 4 mm gap. The deviations in fig. 8(a) are due to the reason that the upper level of the solution is below the third size impeller height which is the highest. Therefore, the solution accumu-
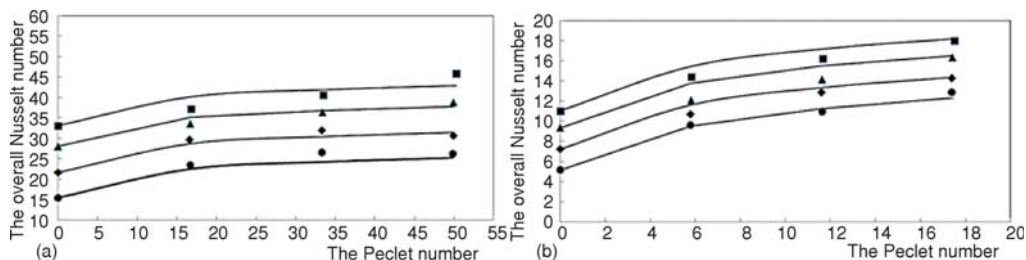

Figure 6. Comparison of the experimental and calculated values of the Nusselt numbers in eq. (31), impeller blade size 1; (a) 12 mm gap, (b) 4 mm gap
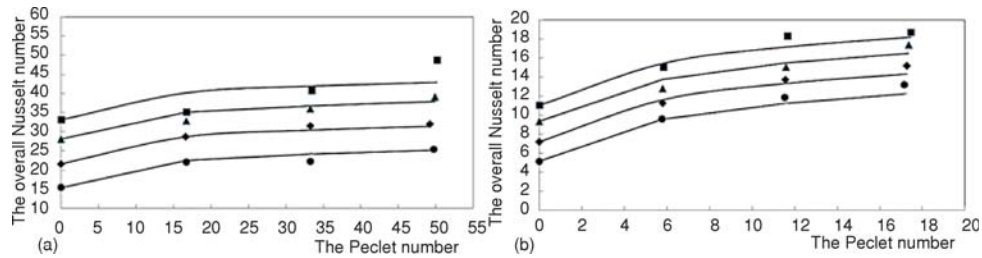
Figure 7. Comparison of the experimental and calculated values of the Nusselt numbers in eq. (31), impeller blade size 2; (a) 12 mm gap, (b) 4 mm gap
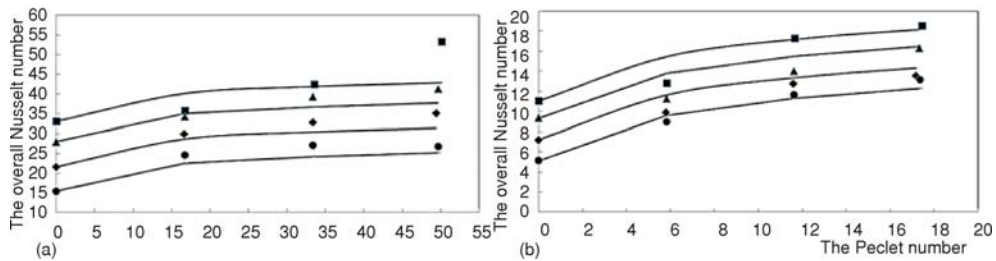

Figure 8. Comparison of the experimental and calculated values of the Nusselt numbers in eq. (31), impeller blade size 3; (a) 12 mm gap, (b) 4 mm gap

lates in front of the impeller blade. A good agitation is not achieved at low concentration and low rpm conditions. For this reason, experimental results are lower than calculated using expression:

$$h_a = h_o + \left(\frac{k}{l}\right)\ln(1 + Pe^{2.8}) \tag{32}$$

The overall heat transfer coefficient obtained experimentally and calculated by eq. (32) (solid lines) are shown on fig. 9 for impeller blade sizes 1, 12, and 4 mm gaps, 70% (■), 75% (▲), 80% (◆), and 85% (●) concentration of sucrose solutions and for 40, 80, and 120 rpm. In eq. (32), h was calculated using eq. (5). The characteristic length is twice the gap. Temperature range is between 100-120 °C. Blade velocity range is 0-120 rpm. The Reynolds number is <1100 and the Prandtl number is <1.

Although the heat transfer coefficient is directly proportional to the Nusselt number, inversely proportional to the characteristic length. So, while the Nusselt number and the characteristic length increase in value, the characteristic length increases at a higher rate than the
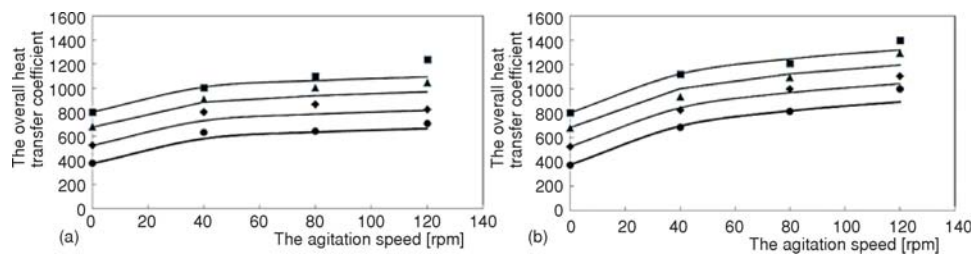

Figure 9. Comparison of the experimental and calculated values of the heat transfer coefficient in eq. (32), impeller blade size 1; (a) 12 mm gap, (b) 4 mm gap

Nusselt number. Thus, the values of heat transfer coefficient decrease with the increase of the gap. It can be seen in fig. 9 that in the case of 4 mm gap has higher heat transfer coefficients than in the case of 12 mm gap.

Conclusions

The heat transfer depends on substantially sucrose concentration during the boiling process for aqueous sucrose solutions. The heat transfer coefficient has a constant value which can be calculated depending on concentration for non-agitated conditions. It increases depending on agitation intensity. It decreases whereas the sucrose concentration increases. The boiling process is possible with smaller temperature differences without caramelize at higher heat transfer rate in agitated tanks.

Here, the heat transfer mechanism shows an analogy with the laminar forced convection in pipes. The flow was accepted as a thermal entrance region in the pipe in order to describe this phenomenon, a Nusselt function was proposed.

The comparison indicated that a good consistency was obtained between the Nusselt numbers determined through the experimental data and calculated through the suggested function. The proposed Nusselt function is suitable within the laminar flow regime and it is valid for $Re < 1100$.

On basis of the performed experimental studies it can be stated that the heat transfer coefficient increases with the decrease of the gap size.

It is observed that the impeller blade sizes do not have a great impact on the heat transfer in the case of the width of impeller blade is larger than the gap as used in industrial applications.

Acknowledgments

Nomenclature

A – surface area, [m^2]
C – constant, [–]
c – concentration, [kgkg^{-1}]
c_p – constant pressure specific heat, [kJkg^{-1}K^{-1}]
D – diameter of pipe, [m]
h – boiling heat transfer coefficient,   (eq. 17), [Wm^{-2}K^{-1}]
h – enthalpy, [kJkg^{-1}]
k – thermal conductivity, [Wm^{-1}K^{-1}]
l – characteristic length, [m]
m – mass, [kg]
Nu – Nusselt number ($= a\mathrm{Pe}^b$), [–]
Pe – Peclet number ($= \mathrm{RePr}$), [–]
Pr – Prandtl number ($= c_p\mu/k$), [–]
Re – Reynolds number ($= \rho/V_{avg}/\mu$), [–]
Q – heat, [kJ]
$\dot{Q}$ – heat transfer rate, [kW]
$\dot{q}$ – heat flux, [Wm^{-2}]
T – temperature, [°C]
t – time, [s]
V – axial velocity of fluid, [ms^{-1}]
x – gap between bottom edge of the impeller blade and the bottom surface of vessel, [mm]

Greek symbols

μ – dynamic viscosity, [Pa·s],[kgm^{-1}s^{-1}]
ρ – density, [kgm^{-3}]

Subscripts and superscripts

a – agitated
avg – average
b – boiling
fg – difference in property between saturated liquid and saturated vapor
g – gain
h – hydraulic
max – maximum
o – non-agitated
r – radius
s – sucrose
sat – saturation
t – total
w – surface, wall
wt – water

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