Flow Boiling Heat Transfer of Water and Sugar Solutions in an Annulus

Hong Yu and Roya Sheikholeslami
School of Chemical Engineering and Industrial Chemistry, The University of New South Wales, Sydney, New South Wales 2052, Australia

William O. S. Doherty
Sugar Research Institute, Mackay, Queensland 4740, Australia

DOI 10.1002/aic.10111
Published online in Wiley InterScience (www.interscience.wiley.com).

The subcooled flow boiling heat-transfer characteristics of water and sugar solutions in an annulus have been investigated under operating conditions similar to those found in the sugar mill evaporators. The variations in the effects of heat flux, fluid velocity, and subcooling on the observed heat-transfer coefficients over a range of sugar concentrations implied an enhanced contribution of nucleate boiling heat transfer in the partial flow boiling regime, where both forced convection and nucleate boiling heat transfer occurred. Increasing the sugar concentration led to a significant drop in the observed heat-transfer coefficient because of a mixture effect, which resulted in a local rise in the saturation temperature of sugar solution at the vapor-liquid interface. The reduction in the heat-transfer coefficient with increasing sugar concentration is also attributed to changes in the fluid properties (for example, viscosity and wettability) of solutions with different sugar content. The experimental data were compared with predictions by various flow boiling models and a modified Chen model incorporating the effect of sugar concentration. The new model provided a better prediction of heat-transfer coefficients of sugar solutions in an annulus. © 2004 American Institute of Chemical Engineers *AIChE J,* 50: 1119–1128, 2004
Keywords: nucleate boiling, heat-transfer coefficient, sugar, subcooled flow boiling, forced convection

Introduction

Flow boiling takes place in various industrial applications. In multieffect sugar mill evaporators, juice concentration occurs via forced convective nucleate flow boiling in vertical calandrias. The performance of these evaporators, which accounts for ~70% of energy consumption in sugar mills, is important for efficient running of a sugar factory. Thus, the ability to accurately predict the flow boiling heat-transfer coefficients in sugar mill evaporators is desirable, not only for the optimal design and operation of equipment, but also as a means to help analyze and interpret the mechanisms involved in such heat-transfer processes. This article describes an approach to correlate the heat-transfer coefficients of sugar solutions during subcooled flow boiling in a vertical annulus, based on modifications of existing models developed for pure water.

Analysis of flow boiling heat transfer has been attempted by many workers (Celata et al., 1993; Chen and Tuzla, 1995; Muller-Steinhagen et al., 1986) with a widely-recognized Chen (1966) model, which was developed for saturated flow boiling but could be conveniently extended to subcooled boiling. The Chen model assumed that the flow boiling heat-transfer coef-

Correspondence concerning this article should be addressed to R. Sheikholeslami at r.sheikholeslami@eng.unsw.edu.au.

ficient was a modified sum of forced convection and nucleate boiling heat-transfer coefficients. The convective and nucleate boiling terms were obtained by the Dittus-Boelter correlation (Winterton, 1998), and the Forster-Zuber (1955) pool boiling correlation, respectively. An enhancement factor F, representing the ratio of the effective two-phase Reynolds number to the liquid Reynolds number, was included into the convective term to account for the enhanced convection because of bubble dynamics, whereas a suppression factor S was included into the nucleate boiling term to account for the reduced thermal boundary layer because of flowing conditions.

A number of variations on Chen's additive method have been tested for water and other organic fluids (Bjorge et al., 1982; Liu and Winterton, 1991; Steiner and Taborek, 1992). Liu and Winterton (1991), for example, used an asymptotic-type addition model for analyzing both saturated and subcooled flow boiling data. They replaced the Forster-Zuber correlation with Cooper's pool boiling correlation (Cooper, 1984) for deriving the nucleate boiling term. The enhancement and suppression factors were also redefined. Another Chen-type model was that described by Bjorge et al. (1982), which was an extension of the Bergles and Rohsenow (1964) correlation to cover subcooled and saturated regions with pure water. The authors used a superposition equation similar to that described by Liu and Winterton, except that an incipient boiling term suggested by Bergles and Rohsenow was included instead of the suppression factor. This resulted in good correlation for both saturated and subcooled boiling data.

Apart from the superposition models derived from mechanistic analysis (such as, those of Chen (1966) and Rohsenow (1953)), much work has been published on empirical correlations for flow boiling heat-transfer applications. Shah (1983) developed a model for the quick assessment of subcooled flow boiling heat transfer in annuli with a wide range of experimental parameters and a variety of fluids. The model divided the flow boiling curve beyond the single-phase region into partial and fully developed regions, where a dimensionless term ψ_o was introduced to represent the ratio between two-phase boiling heat-transfer coefficient, and the liquid only coefficient as a function of the Boiling number. The expressions of ψ_o varied depending on the subcooled boiling region.

A dimensionless group model was developed by Moles and Shaw (1972) to correlate boiling heat transfer to subcooled liquids under forced convection, based on the data from various heating surfaces and geometries. Dimensionless terms such as the Boiling number, Jacob number, and Prandtl number were incorporated into the model to account for the effects of heat flux, liquid velocity, and subcooling. The pressure effect was considered by the density ratio. Although models of this type provided a simple and comprehensive approach for evaluating and predicting the boiling heat-transfer coefficients, their validity is often limited to the range of fluids and conditions used to formulate the correlations (Butterworth and Shock, 1982).

Most boiling heat-transfer studies of sugar solutions reported so far have been based on pool boiling (Garyazha and Kulinchenko, 1975; Mayinger and Hollborn, 1977; Quraishi and Varshney, 1975), and little work has been conducted to apply the existing models, whether analytical or empirical, to the estimation of boiling heat-transfer coefficient data relevant to the multiple effect evaporators in sugar mills. This article, therefore, characterized the subcooled flow boiling heat-transfer performance of water and sugar solutions in an annular arrangement under thermal hydraulic conditions frequently found in the sugar mill evaporators. In particular, the effects of operating conditions were evaluated, including fluid velocity, heat flux, subcooling and sugar concentration on heat-transfer coefficients. The experimental data were compared with selected models and a modified Chen model proposed to provide a better fit to measured heat-transfer coefficients for both water and sugar solutions.

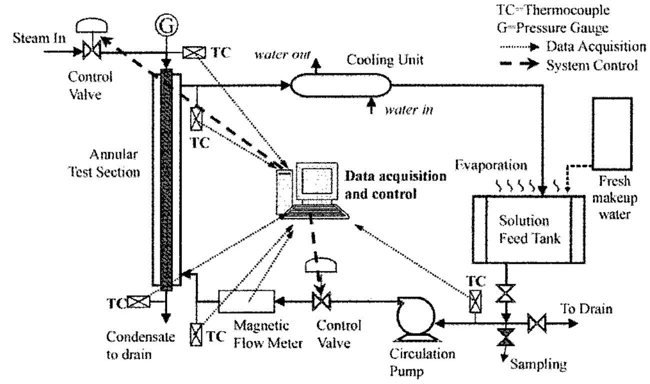

Figure 1. Test rig.

Experimental

Figure 1 shows the experimental set up used in this work. The test fluid was circulated in a closed loop consisting primarily of a storage tank, centrifugal pump, annular test section, cooling unit, freshwater makeup tank, and other measurement and control devices. Details of the test loop and procedures have been described elsewhere (Yu et al., 2002).

The annular test section is a vertical double pipe heat exchanger, where the heating steam flows inside an inner tube made of stainless steel (19.0 mm O.D., 0.9 mm wall thickness, and 1.6 m length; Sandvik, Australia P/L), and the working fluid runs through the outer annulus made of glass (38.0 mm O.D.; Pegasus, Canada) to allow a visual observation of boiling surface during the experiment. (As a result, this arrangement is slightly different from that of a sugar mill where the sugar juice is inside the inner tube, whereas the steam flows through the annulus.) All other pipings and fittings in the water systems were manufactured from stainless steel to prevent corrosion. Two PID controllers (Spirax Sarco P/L) were used in conjunction with a magnetic flowmeter (COPA-XE 400®, Elsag Bailey) to maintain a constant flow rate and heat flux during the run. An in-line cooling unit (Diecon, Marine Products, Inc.) was used to obtain the heat balance within the flow loop, and to keep the bulk temperature of the feed tank constant. Distilled water was periodically added into the storage tank to make up the water loss because of evaporation. The data acquisition and control system (Genie, American Advantech Co.) collected the inlet and outlet temperatures of both streams and bulk temperature from thermocouples embedded around the system (Figure 1) and the flow rates of the fluid from the magnetic flowmeter, which were constantly displayed on the computer screen and recorded into the computer's hard disk at certain time intervals. All measurements were taken after the system had stabilized for a given operating condition. Table 1 shows the range of

Table 1. The Ranges of Operating Parameters Used in This Work in Comparison to Those in the Sugar Mill Evaporator (Doherty, 2000; Lavarack, 2001)

Condition	This Work		Sugar Mill Evaporator (1st–5th Effect)
	Water	Sugar Solution	
Heat flux (kW/m^2)	45.6–112.7*	50.7–86.9*	16.7–23.3
Velocity (m/s)	1.0–1.8	0.8–1.6	0.8–2.8
Subcooling (K)	12.0–35.0#	16.0–35.0#	0–17.0
Superheat (K)	4.6–17.4	4.1–24.7	12.0–26.0
Sugar conc. (%(w/w))	0	25–50	15–68

*Higher ranges used due to flow boiling operation without vacuum system.
#Higher subcooling values used due to limited temperature range of equipments.

variables used in the experiments as compared to those used in sugar mill evaporators. Before the flow boiling experiment, the fluid wettabilities were analyzed under room-temperature by taking photographs of single droplets (>10) of water and sugar solutions on the heat exchange tube with a CCD camera, and measuring the static contact angle of each fluid.

The subcooled flow boiling heat-transfer (water-side) coefficient h was obtained, based on the resistance equation including the system geometry (Kreith 1973)

$$\frac{1}{U_o} = \frac{1}{h} + \frac{\delta_w D_o}{k_w \bar{D}_L} + \frac{D_o}{D_i h_{st}} \tag{1}$$

where k_w and δ_w are the wall thermal conductivity and thickness, respectively. D_i is the inside wall diameter, D_o is the outside wall diameter and $\bar{D}_L$ is the log mean diameter. The steam-side heat-transfer coefficient hst was calculated assuming film-type condensation of steam (see Appendix B). The overall heat-transfer coefficient Uo was calculated from the heat-transfer rate q, the heat-transfer surface area A, and ΔT_m, the log mean temperature difference for a countercurrent flow (Eq. 2).

$$U_o = \frac{q}{A \Delta T_m} \tag{2}$$

$$q = \dot{m} c_p \Delta T_l \tag{3}$$

where $\dot{m}$ is the mass-flow rate c_p is the specific heat of heating fluid and ΔT_l is the temperature difference of fluid along the annulus. The measurement uncertainty of temperatures was ± 0.3°C and for velocity measurements this was about 0.5%. The uncertainties involved in heat flux and heat-transfer coefficients were less than 9%, which was a typical range for this type of experiment.

Results and Discussion

Flow boiling heat-transfer data

Subcooled flow boiling regions. The regime of subcooled nucleate boiling is known to consist of two sub-regions depending on the levels of heat flux and wall superheat involved (Shah 1983; Dhir 1998; Prodanovic et al., 2002):

- partial or highly subcooled boiling region; and
- fully developed or low subcooled boiling region

The former region starts at low to moderate wall superheat and heat flux values, where heat transfer is controlled by both forced convection and surface nucleate boiling, because only a limited number of bubble nucleation sites are available on the boiling surface. The latter occurs at higher heat flux levels, where the contribution of forced convection diminishes with an increase in the number of active nucleation sites. Thus, the liquid velocity and subcooling are generally found to affect the heat-transfer coefficient in the partial boiling region, but become negligible in the fully developed boiling region, where the heat-transfer coefficient is controlled primarily by heat flux (Shah, 1983; Sivagnanam et al., 1994).

The method used to determine the region of subcooled boiling data in this work (Figure 2) was that proposed by Shah (1983), which distinguishes different subcooled boiling regions based on the ratio between subcooling and wall superheat $\Delta T_{sc}/\Delta T_{sat}$, with the transition point characterized by the following equations

$$\Delta T_{sc}/\Delta T_{sat} = 2 \tag{4}$$

$$\Delta T_{sc}/\Delta T_{sat} = 6.3 \times 10^4 Bo^{1.25} \tag{5}$$

that is, the region is high subcooling if $\Delta T_{sc}/\Delta T_{sat} > 2$ or $\Delta T_{sc}/\Delta T_{sat} < 2$ and $\Delta T_{sc}/\Delta T_{sat} \geq 6.3 \times 10^4\ Bo^{1.25}$, otherwise the region is low subcooling. As shown in Figure 2, all boiling data lay within the high subcooling or partial boiling region under the current experimental conditions, indicating that both the thermal hydraulic conditions of fluid, such as velocity and subcooling, and heat flux are important factors in determining the flow boiling heat-transfer coefficients of water and sugar solutions.

Effects of operating parameters

The variations of the heat-transfer coefficients as a function of fluid velocity and subcooling were evaluated at comparable superheat levels for water and sugar solutions (Figures 3 and 4). Figure 3 shows that the heat-transfer coefficient of water and sugar solutions increased with increasing fluid velocity (Figure 3) and could be described by a power law relation

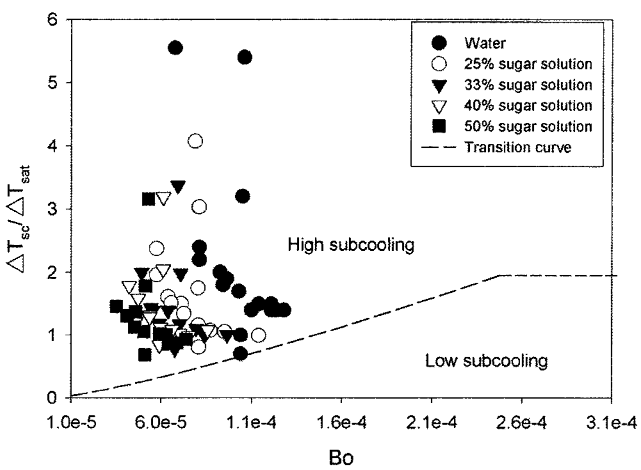

Figure 2. Identification of subcooled boiling regions for water and sugar.

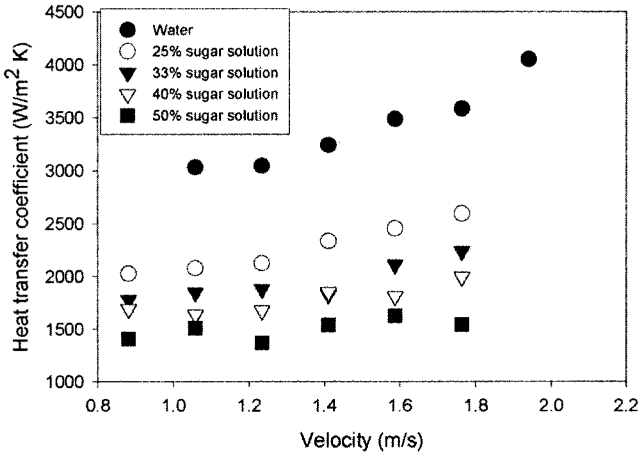

Figure 3. Effect of fluid velocity on heat-transfer coefficients of water and sugar solutions at 20 K subcooling and ~ 16 K superheat.

$$h \sim (\nu)^n \tag{6}$$

The slope n was found to be 0.49 for water and reduced from 0.38 to 0.17 as the sugar concentration increased from 25 to 50% (Table 2). A value of 0.8 would be expected if the heat transfer were in the nonboiling region, as indicated by the Dittus-Boelter equation (Wenzel et al., 1994). Thus, the reduced dependence of the heat-transfer coefficient on fluid velocity with increasing sugar concentration signified an increased contribution from the nucleate boiling term of heat transfer, which might be associated with reduced forced convective heat transfer because of lower Reynolds numbers of sugar solutions (Bao et al., 2000).

Figure 4 shows that the heat-transfer coefficients of water and sugar solutions decreased with increasing fluid subcooling, consistent with results obtained in previous studies with water and various organic mixtures (Muller-Steinhagen et al., 1986; Sivagnanam et al., 1994; Sivagnanam and Varma, 1990; Thom et al., 1965; Wenzel et al., 1994). The variations in the dependence of heat-transfer coefficient on subcooling showed behavior similar to that observed for fluid velocity, with the effect of subcooling being less pronounced in more concentrated sugar solutions (Figure 4).

Table 2. The Dependence of Heat-Transfer Coefficient on Fluid Velocity and Heat Flux for Water and Sugar Solutions

	Exponent	
Condition	$h \sim (\nu)^n$	$h \sim (q'')^m$
Water	0.49	0.60
25% sugar solution	0.38	0.60
33% sugar solution	0.32	0.69
40% sugar solution	0.25	0.61
50% sugar solution	0.17	0.72

Figure 5 depicts the effect of heat flux on the heat-transfer coefficients of water and sugar solutions. For a given fluid velocity and subcooling, a general increase in the heat-transfer coefficient with increasing heat flux was observed in all solutions tested, as expected for nucleate boiling regime (Thom et al., 1965). Similarly, the extent of heat flux effect could be represented with the following relationship

$$h \sim (q'')^m \tag{7}$$

It has been reported in the literature (Wenzel et al., 1994) that exponent values of 0 and ~0.8 are commonly distinguishable for forced convection controlled and nucleate boiling controlled regions, respectively. The values of m obtained in this work for water and sugar solutions were found to be between 0.60 and 0.72 (Table 2), consistent with the findings that all data were extracted from the partial boiling region. An increase in the effect of heat flux could also be noticed with increasing sugar concentrations, which again constituted a transition to more nucleate boiling heat-transfer controlled region.

For a constant heat flux, the heat-transfer coefficients of sugar solutions were considerably lower than that of water and decreased with increasing sugar concentration (Figure 5). The reduction in the heat-transfer coefficients with increasing sugar concentrations have been reported in the previous studies

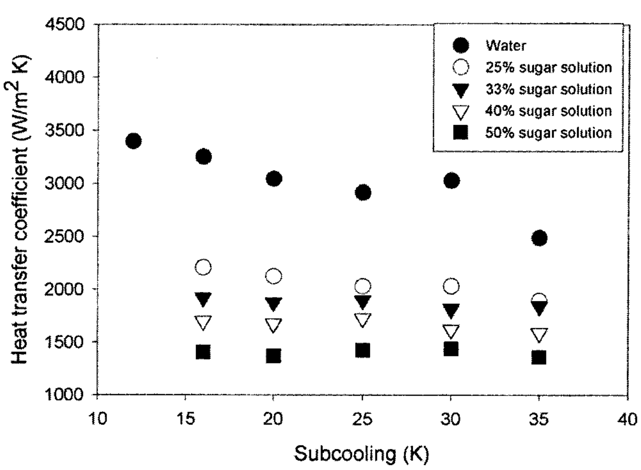

Figure 4. Effect of subcooling on heat-transfer coefficients of water and sugar solutions at 1.2 m/s velocity and ~ 14 K superheat.

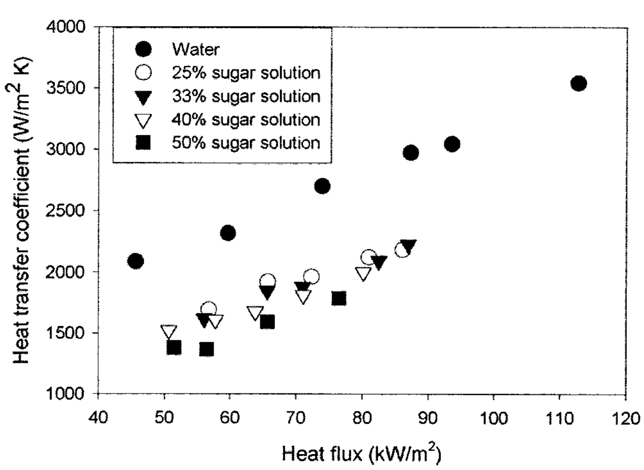

Figure 5. Effect of heat flux on the heat-transfer coefficients of water and sugar solutions at 20 K subcooling and 1.2 m/s velocity.

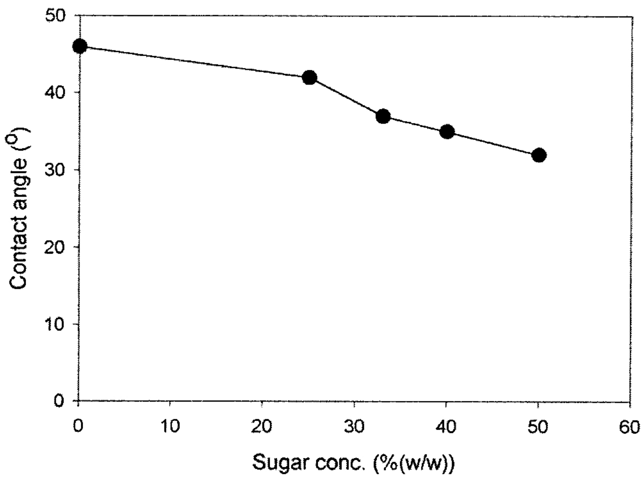

Figure 6. Variations of the static contact angles of water and sugar solutions on stainless steal tube as a function of sugar concentration.

(Cordiner et al., 1969; Mayinger and Hollborn, 1977), and could be attributed to several factors including mixture effect, which arised from preferential evaporation of the light component (that is, water) from a multicomponent mixture (that is, sugar-water binary mixture) at the liquid-vapor interface (for example, bubble interface), and differences in the physical properties, such as viscosity and wetting characteristics, between the water and sugar solution. The loss of solvent at the vapor-liquid interface resulted in a concentration gradient of solute (that is, sugar) close to the interface, which drove a counterdiffusion of water molecules to minimize the sugar concentration at the interface, as well as a local rise in the saturation temperature. This resulted in a decrease in the available wall superheat, and, hence, boiling heat-transfer coefficient in sugar solutions (Vadekar and Hills, 2001). Furthermore, the high viscosities of sugar solutions, particularly at the vapor-liquid interfacial layer, may impact on the heat-transfer coefficient by suppressing the bubble growth rate and bubble-induced turbulence, as well as diminishing heat transport by the liquid because of an additional mass-transfer resistance in solution (Mayinger and Hollborn, 1977; Sivagnanam and Varma, 1990). Also, previous studies (Butterworth and Shock, 1982; Fujita, 1992; Wen and Wang, 2002) have shown that an increase in the wettability of a fluid could affect the heat-transfer coefficient during nucleate boiling through its effect on the active nucleation site density on the surface. The more wettable fluids, which have smaller contact angles, as has been observed with increasing sugar concentration in solution (Figure 6), are more likely to "snuff out" cavities on heating surface thereby reducing the number of active nucleation sites available and heat-transfer coefficient (Butterworth and Shock, 1982).

Data correlation

The experimental data were correlated with a number of subcooled flow boiling models available in the literature, together with a new model based on a modification of the Chen model (see Appendix A), which has been widely used in the design of heat exchangers in the process industry (Butterworth and Shock, 1982). Various modified versions of the Chen model have previously been proposed to improve its predictive ability for the different heating surfaces and fluids of interest. Peacock and Starzak (1996) developed a boiling model for climbing film evaporator system in sugar mill with the Chen correlation, and found improved model performance when a Forster-Zuber constant was correlated with heat flux. Bao et al. (2000) also obtained a better correlation of the data for organic fluids when the Forster-Zuber equation was replaced with the Cooper correlation. In our current work, the Chen correlation was modified by deriving the nucleate boiling components with the Rohsenow (1951) boiling correlation. This correlation was developed based on the transient conduction mechanism and microconvection because of subsequent replacement of the superheated liquid layer by the departing bubbles from the surface, expressed in the form of dimensionless groups

$$\frac{\mathrm{Re}_B \mathrm{Pr}}{Nu_B} = \frac{c_p \Delta T_{sat}}{h_{fg}} \tag{8}$$

or in the final form

$$\frac{\Delta T_{sat} c_p}{h_{fg}} = C_{SF}\left[\frac{q''}{\mu h_{fg}}\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}\right]^{0.33}\left[\frac{c_p \mu}{k}\right]^n \tag{9}$$

where the exponent $n = 1.0$ for water and 1.7 for all other fluids (Rohsenow 1972). The surface coefficient C_{SF}, which is a function of a particular heating surface-fluid combination, takes into account the effects of surface conditions, fluid properties (for example, viscosity and wettability) and their interactions on nucleate boiling heat transfer (Benjamin and Balakrishnan, 1997). In our current study, the influence of fluid properties on the values of C_{SF} was represented by the following relationship with nonlinear regression

$$C_{SF} = \frac{0.04}{1 + (C/14.75)^{2.02}} \tag{10}$$

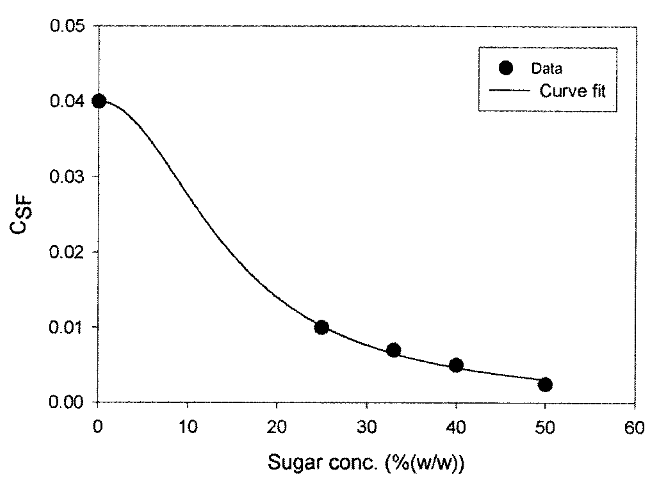

Figure 7. Variation of C_{SF} values as a function of sugar concentration.

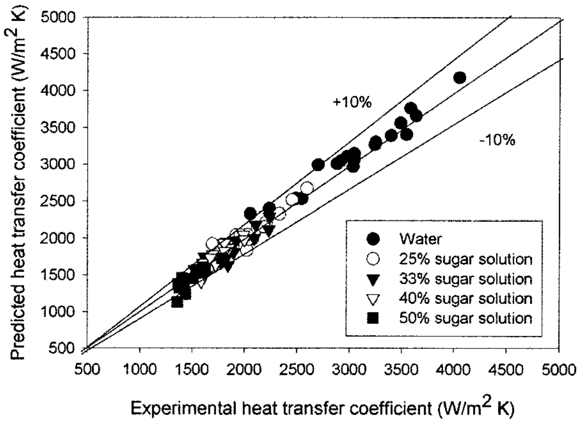

Figure 8. Comparing measured and calculated heat-transfer coeffficients for water and sugar solutions using the proposed model based on Chen's approach.

where C is the sugar concentration. Many studies (Nishikawa and Fujita, 1976; Pioro 1999; Vachon et al., 1968) have found that the C_{SF} values for water is generally higher than those for the organic/inorganic solutions, corresponding well with data obtained in this work (Figure 7).

A revised Dittus-Boelter equation (Eq. 11) was used in conjunction with the Rohsenow equation to correlate experimental data for water, because it was found that those data did not compare well with the proposed model based on Chen's approach, even when the effect of C_{SF} was incorporated.

$$\frac{h_l D}{k} = 0.020\ \mathrm{Re}_l^{0.8}\mathrm{Pr}_l^{0.4} \tag{11}$$

This may be because of a greater contribution of forced convective heat transfer in water in comparison to those in the sugar solutions under the partial boiling condition (see Figure 3/Eq. 6), and so an accurate prediction of heat-transfer coefficient depended strongly on the proper choice of forced convection correlation. In fact, the use of the original Dittus-Boelter equation in Chen's correlation has always been questionable as the flow velocity distribution that normally occurs under the nonboiling conditions would often be disturbed by the bubble activities during nucleate boiling (Rohsenow 1953).

Figure 8 shows the comparison of measured and calculated heat-transfer coefficients for water and sugar solutions with the proposed model. Comparisons of all model fits to the data obtained in this work are summarized in Tables 3 and 4. In addition to modifying the Dittus-Boelter equation, the Gnielinski correlation, which was shown to be more accurate than the Dittus-Boelter equation (Muller-Steinhagen et al., 1986), was also tested with slightly better data fits (mean deviation ~10% for water) than those of the Dittus-Boelter equation. This was, however, considerably worse than the data fits by the modified Dittus-Boelter equation proposed. Thus, the authors used the proposed model with modified Dittus-Boelter equation to account for flow development under nucleate boiling.

Overall, the model proposed in this work fitted the data better than the other models tested, with a mean deviation of 3.8% and over 90% of the data points having less than 10% deviation (Table 3; Figure 8). This was not surprising because the prediction of nucleate boiling coefficient by the other models did not account for the mixture effect and variations in the fluid properties, that is, wetting characteristics and viscosity because of changes in sugar concentrations, which was shown to significantly affect nucleate boiling (Figures 3–5). The above effects were lumped into one surface coefficient C_{SF} in this study, because the relative contribution of each of these phenomena in nucleate boiling was still not determined; also, the contact angles of water and sugar solutions (Figure 6) could not be corrected for equivalent flow boiling conditions because of the lack of temperature coefficient data. As a result, the proposed model was not applicable to media other than water and sugar solution. For further improvement of the model, separate terms for viscosity, wettability and mixture effects may be considered.

The Liu and Winterton model, and the Bjorge et al. model gave data fits only slightly lower than that obtained for the proposed model (mean deviation ~7%). A detailed analysis, however, indicated that the data fits by the Liu and Winterton model and the Bjorge et al. model were rather unevenly distributed over different sugar concentrations and appeared to deteriorate at either the lowest or the highest limit of sugar concentrations (that is, for water or 50% sugar solution, see Table 4). The lower model fits for water by these two correlations, as noted earlier, might be the result of an inaccurate prediction of forced convection coefficient by the Dittus-Boelter equation. The Chen model and the Shah model were found to overpredict the flow boiling heat- transfer coefficient by an average of ~20%, considerably higher than those achieved for three aforementioned models. The poor performance by the Chen model was consistent with results obtained previously (Campbell et al., 2000; Kandlikar 1983; Prodanovic et al., 2002), which showed that the Chen model typically overpredicted the effect of nucleation resulting in a large de-

Table 3. Comparison of Model Fits to Subcooled Flow Boiling Data for Water and Sugar Solutions

Model	Mean Dev.* (%)	Avg. Dev.** (%)	Max. Dev. (%)	Calc. Data % Within ±10% Dev. Range
Chen	21.9	21.8	41.4	9.5
Liu & Winterton	7.3	0.7	19.7	70.2
Moles & Shaw	39.6	−39.6	60.7	0
Shah	17.8	17.6	29.5	13.1
Bjorge et al.	7.1	−1.7	19.2	77.4
Proposed	3.8	0.2	16.7	91.7

*Mean deviation is calculated as: $1/n_n|[h_{cal} - h_{\exp}]/h_{\exp}| \times 100\%$.
**Average deviation is calculated as: $1/n_n[h_{cal} - h_{\exp}]/h_{\exp} \times 100\%$, where n is the number of data.

Table 4. Comparison of Mean and Average Deviations in Fitting the Experimental Data to Various Models

Model	Water	Sugar Solutions			
		25%	33%	40%	50%
Chen	15.6/15.5	23.2/23.2	23.4/23.4	23.9/23.9	24.8/24.8
Liu & Winterton	12.3/12.2	4.0/2.8	4.5/−1.2	4.8/−3.7	9.6/−9.6
Moles & Shaw	37.6/36.6	38.8/38.3	38.9/39.6	41.2/40.8	43.5/43.5
Shah	17.7/17.6	22.9/22.9	20.2/20.2	17.6/17.6	10.6/10.1
Bjorge et al.	8.3/5.2	5.2/3.3	5.2/−1.5	6.3/−4.7	13.0/−12.8
Proposed	3.7/3.1*	3.2/1.0	4.1/−1.2	3.9/0.5	4.2/−3.3

*Mean deviation/average deviation.

viation. However, Prodanovic et al. (2002) reported that the Shah model exhibited good agreement with data in the fully developed boiling region, but tended to over-predict the heat transfer rate in the partial boiling region. The Moles and Shaw model showed the worst data fit with under-predictions by as much as 61%, demonstrating the limited range of applicability characteristic of the dimensionless group correlations (Guglielmini et al., 1988).

Thus, the model proposed in this work based on Chen's approach provided the best estimate of subcooled flow boiling heat-transfer coefficients in sugar solutions for a range of thermal hydraulic parameters, and may be used for the simulation of heat-transfer performance of sugar mill evaporator under various operating conditions. Although the efforts of modifying the existing flow boiling correlations are by no means exhaustive, they certainly open a perspective to improve the design and operation of the evaporator system of sugar mill with well-established methods.

Conclusions

The boiling heat-transfer characteristics of water and sugar solutions have been examined in an annulus under subcooled flow boiling conditions. The flow boiling data were shown to be in the partial subcooled boiling regime, where forced convection and nucleate boiling occur simultaneously. As a result, the flow boiling heat-transfer coefficient was affected by the thermo-hydraulic conditions of fluid, such as velocity and subcooling, as well as heat flux. Increasing the sugar concentration resulted in a gradual increase in the contribution of nucleate boiling heat transfer, and a decrease in the heat-transfer coefficient. This could be ascribed to a local rise in the saturation temperature of fluid at vapor-liquid interface because of a mixture effect and variations in the fluid properties including viscosity and wettability.

The measured experimental data were successfully correlated to a subcooled flow boiling model developed, based on Chen's approach. This new model incorporated the Rohsenow pool boiling correlation and allowed for the variation of a surface coefficient C_{SF} as a function of sugar concentration. The Dittus-Boelter equation was also revised to yield a better fit to boiling data for water. The new proposed model compared favorably with existing models extracted from the literature under the current experimental conditions, and will assist future design and optimization of sugar mill evaporator units. It was demonstrated that the predictive ability of the proposed model was restricted to water and sugar media but may potentially be improved by explicitly incorporating viscosity, wettability and mixture effects for use in other fluid systems.

Acknowledgment

This work was supported by an ARC-SPIRT research scheme. We thank Sugar Australia P/L., NSW for providing the sugar sample, and, especially, Mr. Gary Blomley for supply arrangement. Financial contribution as well as collaboration by Sugar Research Institute (SRI), Australia is gratefully acknowledged.

Notation

A = heating surface area, m^2
a = gonstant in Eq. A6
Bo = boiling number, ($q/\dot{m}h_{fg}$)
B_M = dimensional constant in Eq. A21
c_p = heat capacity, J/kg °C
C = sugar concentration, % w/w
C_{SF} = surface coefficient
D = diameter, m
$\bar{D}_L$ = log mean diameter ((D_o – D_i)/ln(D_o – D_i)), m
F = enhancement factor for the Chen model in Eq. A1
g = gravitational acceleration, m/s^2
g_o = constant in Eq. A21
h_{fg} = heat of vaporization, J/kg
h = heat transfer coefficient, W/m^2 K
Ja = jacob number, , ($C_p\Delta T_{sc}/h_{fg}$
k = thermoconductivity, W/m K
L = heated length of tube, m
M = molecular weight
$\dot{m}$ = mass flow rate, kg/s
N = constant in Eq. A17
Nu = nusselt number, (hD/k)
P_r = reduced pressure, absolute pressure/critical pressure
ΔP_{sat} = saturated pressure difference corresponding to , ΔT_{sat} in Eq. A4, Pa
Pr = prandtl number, , ($c_p\mu/k$)
q = heat transfer rate, W
q'' = heat flux, W/m^2
r = bubble radius, m
Re = reynolds number, ($\dot{m}D/\mu$)
S = suppression factor in Eq A1
T = temperature, °C
ΔT = temperature difference, K
ΔT_{sat} = superheat (T_w - T_{sat}), K
ΔT_{sc} = subcooling (T_{sat} - T_b), K
U_o = overall heat-transfer coefficient based on outside area, W/m^2 K
ν = kinematic viscosity (μ/ρ), m^2/s
υ_{fg} = vapor-liquid specific volume, m^3/kg
x = quality

Greek letters

Γ = constant in Eq. A17/18
δ = wall thickness, m
ρ = density, kg/m^3

σ = surface tension, N/m
μ = dynamic viscosity, N S/m^2
Ψ_o = dimensionless term in Eqn A13–A16 representing value of Ψ at zero subcooling and vapor quality,
$\Psi = q''/\Delta T_{sat}\ h_l$

Subscripts

b = bulk
B = boiling
FC = forced convection
i = inside wall
ib = value at the incipient boiling point
l = liquid
NB = nucleate boiling
o = outside wall
$pool$ = pool boiling
sat = saturation
sc = subcooling
st = steam
$tang$ = point of tangency
T = total of forced convection and nucleate boiling
v = vapor
w = wall

Literature Cited

Bao, Z. Y., D. F. Fletcher, and B. S. Haynes, "Flow Boiling Heat Transfer of Freon R11 and HCFC 123 in Narrow Passages," *Int. J. Heat Mass Transfer*, **43**, 3347 (2000).

Benjamin, R. J., and A. R. Balakrishnan, "Nucleation Site Density in Pool Boiling of Saturated Pure Liquids: Effect of Surface Microroughness and Surface and Liquid Physical Properties," *Exp. Therm. Fluid Sci.*, **15**, 32 (1997).

Bergles, A. E., W. M. Rohsenow, "The Determination of Forced-Convection Surface-Boiling Heat Transfer," *J. of Heat Transfer*, **86**, 365 (1964).

Bjorge, R. W., G. R. Hall, and W.M. Rohsenow, "Correlation of Forced Convection Boiling Heat Transfer Data". *Int. J. Heat Mass Transfer*, **25**, 753 (1982).

Butterworth, D., and R. A. W. Shock: "Flow Boiling," *Proc. 7th Int. Heat Transfer Conf.*, Munich, Germany, 11 (1982).

Campbell, N. A. F., J. G. Hawley, K. Robinson, and M. J. Leathard, "A Review of Predictive Analysis Applied to IC Engine Coolant Heat Transfer,". *J. of the I of Energy*, **73**, 78 (2000).

Celata, G. P., M. Cumo, and T. Setaro, "Forced Convective Boiling in Binary Mixtures". *Int. J. Heat Mass Transfer*, **36**, 3299 (1993).

Chen, J. C., "Correlation for Boiling Heat Transfer to Saturated Fluids in Convective Flow," *I & EC Process Design and Development*, **5**, 322 (1966).

Chen, J. C., and K. Tuzla, "Contribution of Convection and Boiling to Convective Flow Boiling," *Proceedings of Convective Flow Boiling*, J. C. Chen, ed., Taylor & Francis, Alberta, Canada, 181 (1995).

Cooper, M. G.: "Saturation Nucleate Pool Boiling - A Simple Correlation," *Proc. of the First U.K. National Conf. on Heat Transfer*, *Inst. Chem. Eng. Symp*. Ser. No. 86, London, 785 (1984).

Cordiner, J. B., et al., "Heat Transfer Coefficient for Raw Sugar Solutions," *The Sugar J.,* 13 (1969).

Dhir, V. K., "Boiling Heat Transfer," *Annu. Rev. Fluid Mech.*, **30**, 365 (1998)

Doherty, W. O. S., Personal Communications (2000).

Forster, H. K., and N. Zuber, "Dynamics of Vapor Bubbles and Boiling Heat Transfer," *AIChE J.*, **1**, 531 (1955).

Fujita, Y., "The State of the Art - Nucleate Boiling Mechanisms," *Pool and External Flow Boiling, Proc. Eng. Found. Conf.,* 83 (1992).

Garyazha, V. T., and V. R. Kulinchenko, "Investigation of the Mechanism of Boiling Heat Transfer to Water and Sugar Solutions," *Heat Transfer – Sov. Res.*, **7**, 12 (1975).

Guglielmini, G., E. Nannei, and C. Pisoni: "Survey of Heat Transfer Correlations in Forced Convection Boiling., *Multiphase Transport*," T. N. Veziroglu, ed., Hemisphere Publishing Co., 845 (1988).

Gungor, K. E., and R. H. S. Winterton, "A General Correlation for Flow Boiling in Bubes and Annuli". *Int. J. Heat Mass Transfer*, **29**, 351 (1986).

Incropera, F. P., and D. P. DeWitt, *Fundamentals of Heat and Mass Transfer*, Wiley (1996).

Kandlikar, S. G., "An Improved Correlation for Predicting Two-Phase Flow Boiling Heat Transfer Coefficient in Horizontal and Vertical Tubes," *The 21st National Heat Transfer Conf.*, J. B. J. Kitto, ed., *ASME*, Seattle, Wash., 3 (1983).

Kreith, F., *Principles of Heat Transfer*. Intext Press, Inc., New York (1973).

Lavarack, B. P., "Reducing Process Steam Usage? What Will Happen to the Water Balance?" *Proc. Aust. Soc. Sugar Cane Technol.*, **23**, 410 (2001).

Liu, Z., and R. H. S. Winterton, "A General Correlation for Saturated and Subcooled Flow Boiling in Tubes and Annuli, Based on a Nucleate Pool Boiling Equation," *Int. J. Heat Mass Transfer*, **34**, 2759 (1991).

Mayinger, F., and E. Hollborn,"The Effect of Liquid Viscosity on Bubble Formation and Heat Transfer in Boiling," *Heat Transfer in Boiling*, E. Hahne, Grigull, U., ed., Academic Press, 391 (1977).

Moles, F. D., and J. F. G. Shaw, "Boiling Heat Transfer to Subcooled Liquids under Conditions of Forced Convection," *Trans. Inst. Chem. Eng.*, **50**, 76 (1972).

Muller-Steinhagen, H., N. Epstein, and A. P. Watkinson, "Subcooled-Boiling and Convective Heat Transfer for Heptane Flowing Inside an Annulus and Past a Coiled Wire: Part II - Correlation of Data," *J. of Heat Transfer*, **108**, 928 (1986).

Nishikawa, K., andY. Fujita, "On the Nucleation Factor in Nucleate Boiling Heat Transfer" *Memoirs of the Faculty of Engineering,* Kyushu University, **36**, 139 (1976).

Peacock, S. D., and M. Starzak, "Modelling of Climbing Film Evaporators," *Proc. South Afr. Sugar Technol. Association,* **70,** 213 (1996).

Pioro, I. L., "Experimental Evaluation of Constants for the Rohsenow Pool Boiling Correlation," *Int. J. Heat Mass Transfer*, **42**, 2003 (1999).

Prodanovic, V., D. Fraser, and M. Salcudean, "On the Transaction from Partial to Fully Developed Subcooled Flow Boiling,". *Int. J. Heat Mass Transfer*, **45**, 4727 (2002).

Quraishi, M. S., and B. S. Varshney, "Pool Boiling of Aqueous Sugar Solutions," *Indian J. of Technol.*, **13**, 121 (1975).

Rohsenow, W. M., "A Method of Correlating Heat-transfer Data for Surface Boiling of Liquids," *ASME*, **74**, 969 (1951).

Rohsenow, W. M., "Heat Transfer with Evaporation," *Heat Transfer*, University of Michigan Press, Ann Arbor, 101 (1953).

Rohsenow, W. M., "On the Rohsenow Pool-Boiling Correlation," *J. of Heat Transfer,* **94,** 255 (1972).

Shah, M. M., "Generalized Prediction of Heat Transfer during Subcooled Boiling in Annuli," *Heat Transfer Eng.*, **4**, 24 (1983).

Sivagnanam, P., A. R. Balakrishnan, and Y. B. G. Varma, "On the Mechanism of Subcooled Flow Boiling of Binary Mixtures," *Int. J. Heat Mass Transfer*, **37**, 681 (1994).

Sivagnanam, P., and Y. B. G. Varma, "Subcooled Boiling of Binary Mixtures under Conditions of Forced Convection," *Exp. Thermal and Fluid Sci.*, **3**, 515 (1990).

Steiner, D., and J. Taborek, "Flow Boiling Heat Transfer in Vertical Tubes Correlated by an Asymptotic Model," *Heat Transfer Eng.*, **13**, 43 (1992).

Thom, J. R. S., W. M. Walker, T. A. Fallon, and G. F. S. Reising, "Boiling in Subcooled Water during Flow Up Heated Tubes or Annuli," *Proc. Inst. Mech. Engs.*, **180**, 226 (1965).

Vachon, R. I., G. H. Nix, and G. E. Tanger, "Evaluation of Constants for the Rohsenow Pool-Boiling Correlation," *J. of Heat Transfer,* **90,** 239 (1968).

Vadekar, V. V., and P. D. Hills, "Evaporative Heat Transfer to Solutions Containing Dissolved Solids: Effect of Vapour-Liquid Equilibrium and Mass Transfer," *Trans. IChemE.*, **79**, 477 (2001).

Wen, D. S., and B. X. Wang, "Effects of Surface Wettability on Nucleate Pool Boiling Heat Transfer for Surfactant Solutions," *Int. J. Heat Mass Transfer*, **45**, 1739 (2002).

Wenzel, U., B. Hartmuth, and H. Muller-Stainhagen, "Heat Transfer to Mixtures of Acetone, Isopropanol and Water under Subcooled Flow Boiling Conditions - I. Experimental Results," *Int. J. Heat Mass Transfer*, **37**, 175 (1994).

Winterton, R. H. S., "Where Did the Dittus and Boelter Equation Come From?," *Int. J. Heat Mass Transfer*, **41**, 809 (1998).

Yu, H., R. Sheikholeslami, and W. O. S. Doherty, "Composite Fouling Characteristics of Calcium Oxalate Monohydrate and Amorphous Silica by a Novel Approach Simulating Successive Effects of Sugar Mill Evaporator," *Ind. Eng. Chem. Res.*, **41**, 3379 (2002).

Appendix A: Subcooled Flow Boiling Models Used in This Work

Chen model (1966)

$$h_T = h_{FC} + h_{NB} = Fh_l + Sh_{\text{pool}} \tag{A1}$$

For subcooled boiling the temperature driving forces for nucleate boiling and forced convection are different, and the above equation is replaced by

$$q/A = [Sh_{\text{pool}}(T_w - T_s) + Fh_l(T_w - T_b)] \tag{A2}$$

where F=1 for subcooled boiling (as there is no net vapor generation, that is, x=*0* (Gungor and Winterton, 1986).

h_l is calculated with the Dittus-Boelter equation

$$\frac{h_l D}{k} = 0.023\ \text{Re}_l^{0.8}\text{Pr}_l^{0.4} \tag{A3}$$

h_{pool} is calculated by the Forster-Zuber correlation

$$h_{\text{pool}} = \frac{0.00122\Delta T_{sat}^{0.24}\Delta p_{sat}^{0.75}c_{p,l}^{0.45}\rho_l^{0.49}k^{0.79}}{\sigma^{0.5}h_{fg}^{0.24}\mu_l^{0.29}\rho_v^{0.24}} \tag{A4}$$

where

$$S = \frac{1}{1 + 2.53 \times 10^{-6}\text{Re}^{1.17}} \tag{A5}$$

where Re $=$ Re$_l$ $F^{1.25}$ $=$ Re$_l$ (x $=$ 0 and F $=$ 1).

Proposed model based on Chen's approach

The nonboiling coefficient h_l is calculated using the modified Dittus-Boelter equation

$$\frac{h_l D}{k} = a\ \text{Re}_l^{0.8}\text{Pr}_l^{0.4} \tag{A6}$$

where a =0.020 for water and 0.023 for sugar solutions. All fluid properties are determined at the bulk temperature.

The pool boiling coefficient h_{pool} is calculated by the Rohsenow correlation

$$\frac{\Delta T_{sat}c_p}{h_{fg}} = C_{SF}\left[\frac{h_{\text{pool}}\Delta T_{sat}}{\mu h_{fg}}\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}\right]^{0.33}\left[\frac{c_p\mu}{k}\right]^n \tag{A7}$$

where n=1.0 for water and 1.7 for all other fluids. $_{SF}$ values were obtained by data fitting.

Liu & Winterton model (1991)

$$q/A = \sqrt{[Sh_{\text{pool}}(T_w - T_s)]^2 + [Fh_l(T_w - T_b)]^2} \tag{A8}$$

where

$$S = (1 + 0.055F^{0.1}\text{Re}_l^{0.16})^{-1} \tag{A9}$$

h_l is calculated with the Dittus-Boelter equation and h_{pool} by the Cooper pool boiling correlation

$$h_{\text{pool}} = 55(q'')^{0.67}P_r^{0.12}(-\log_{10}P_r)^{-0.55}M^{-0.5} \tag{A10}$$

where M is the molecular weight of fluid.

Moles & Shaw model (1972)

$$\frac{h_T}{h_l} = 78.5Bo^{0.67}Ja^{-0.5}\text{Pr}^{0.46}\left(\frac{\rho_v}{\rho_l}\right)^{0.7} \tag{A11}$$

where h_l is determined by the Colburn equation

$$\frac{h_l D}{k} = 0.023\ \text{Re}_l^{0.8}\text{Pr}_l^{0.33} \tag{A12}$$

The Prandtl number is calculated at the mean film temperature. All other properties are calculated at the saturation temperature.

Shah model (1983)

$$\text{For } Bo > 0.3 \times 10^{-4}, \quad \Psi_o = 230Bo^{0.5} \tag{A13}$$

$$\text{For } Bo < 0.3 \times 10^{-4}, \quad \Psi_o = 1 + 46Bo^{0.5} \tag{A14}$$

$$\text{If } \frac{\Delta T_{sc}}{\Delta T_{sat}} > 2 \quad \text{or} \quad \frac{\Delta T_{sc}}{\Delta T_{sat}} \geq 6.3 \times 10^4 Bo^{1.25}$$

then

$$q/A = h_l(T_w - T_b) + h_l(\Psi_o - 1)(T_w - T_s) \tag{A15}$$

else

$$q/A = h_l\Psi_o(T_w - T_s) \tag{A16}$$

h_l is calculated by the Dittus-Boelter equation.

Bjorge, Hall and Rohsenow correlation (1982)

The incipient boiling criterion, $\Delta T_{sat,ib}$ under subcooled condition is derived by

For $r_{\text{tang}} > r_{\text{max}}$

$$\Delta T_{sat,ib} = \frac{1}{1 - N}\left(\frac{1}{4\Gamma N} - N\Delta T_{sc}\right) \tag{A17}$$

For $r_{\text{tang}} < r_{\text{max}}$

$$\Delta T_{sat,ib} = \frac{1}{2\Gamma}[1 + (1 + 4\Gamma\Delta T_{sc})^{1/2}] \tag{A18}$$

Table A1. Average Values of Steam-Side Heat-Transfer Coefficient for Water and Sugar Solutions†

Sugar Conc. (%)	Heat-Transfer Rate (W)	h_{st}, Average (W/m^2 K)	SD* (W/m^2 K)	RSD** (%)	Repeatability (W/m^2 K)***
0	9078.7	6421.4	61.5	0.96	196.7
25	7784.0	6636.0	24.4	0.37	76.9
33	6858.3	6877.8	112.1	1.63	353.1
40	6163.4	6967.6	61.9	0.89	195.1
50	5506.4	7128.1	113.1	1.59	361.8

† Heat flux effect data not included.
* Standard deviation = $\sqrt{[(h_{st} - h_{st,avg})^2/n - 1]}$.
** Relative standard deviation = $SD/h_{st,avg} \cdot 100\%$.
***Expected difference between two repeated values ($=t \cdot SD\sqrt{2}$, where t is the student t-value at 95% confidence limit).

where

$$\Gamma = \frac{k_l h_{fg}}{8\sigma T_{sat} \upsilon_{fg} h_{FC}}, \quad N = \frac{h_{FC} r_{\max}}{k_l}$$

$$r_{\tan g} = \frac{4\sigma T_{sat} \upsilon_{fg}}{h_{fg} \Delta T_{sat,ib}}$$

$$r_{\max} = 10^{-6} \text{ (m)}$$

if $\Delta T_{sat} < \Delta T_{sat,ib}$,

$$q/A = q_{FC} = h_l(\Delta T_{sat} + \Delta T_{sc}) \tag{A19}$$

else

$$q/A = \sqrt{q_{FC}^2 + q_{NB}^2 \left[1 - \left(\frac{\Delta T_{sat,ib}}{\Delta T_{sat}}\right)^3\right]^2} \tag{A20}$$

h_l is obtained by the Colburn correlation and q_{NB} is determined by the Mikic-Rohsenow pool boiling correlation

$$\frac{q_{NB}}{\mu_l h_{fg}} \left(\frac{g_o \sigma}{g(\rho_l - \rho_v)}\right)^{1/2} = B_M \frac{k_l^{1/2} \rho_l^{17/8} c_{p,l}^{19/8} \rho_v^{1/8}}{\mu_l h_{fg}^{7/8} (\rho_l - \rho_v)^{9/8} \sigma^{5/8} T_{sat}^{1/8}} \Delta T_{sat}^3 \tag{A21}$$

where B_M is a dimensional constant depending on cavity size distribution and fluid properties. For comparison with the model proposed in this work, a single value of 1.89×10^{-14} (for water) was used for all fluids tested.

Appendix B: Steam-Side Heat-Transfer Coefficient (h_{st})

The steam-side heat-transfer coefficient was calculated assuming laminar film condensation (30 > Re) on a vertical plate (Kreith, 1973; Incropera & DeWitt 1996)

$$h_{st} = 0.943 \left[\frac{g\rho_l(\rho_l - \rho_{st}) k_l^3 h'_{fg}}{\mu_l (T_{sat,st} - T_i) L}\right]^{1/4} \tag{A22}$$

where ρ_l, k_l and μ_l are density, thermal conductivity and viscosity of saturated liquid at film temperature, respectively. $T_{sat,st}$ is the condensation temperature of saturated steam at prevailing pressure, T_i is the temperature of inside surface of tube wall and h'_{fg} is a modified latent heat of vaporization.

$$h'_{fg} = h_{fg} + 0.68 c_{p,l}(T_{sat,st} - T_i) \tag{A23}$$

where $c_{p,l}$ is specific heat of saturated liquid at film temperature. The condensation rate (condensate mass-flow rate) is obtained by

$$\dot{m} = \frac{q}{h'_{fg}} \tag{A24}$$

The assumption of laminar film condensation may be checked by calculating Re

$$\text{Re} = \frac{4\dot{m}}{\mu_l b} \tag{A25}$$

where b is the tube perimeter (inside).

It is found that most of the data were in the wavy-laminar region ($30 \leq \text{Re} \leq 1800$), for which Re and h_{st} are recalculated by

$$\frac{\mu_l h'_{fg}}{4L(T_{sat,st} - T_i)} = \frac{k_l}{(1.08 \text{ Re}^{1.22} - 5.2)(\nu_l^2/g)^{1/3}} \tag{A26}$$

$$h_{st} = \frac{\text{Re}}{(1.08 \text{ Re}^{1.22} - 5.2)} \frac{k_l}{(\nu_l^2/g)^{1/3}} \tag{A27}$$

where ν_l is kinematic viscosity of saturated liquid at film temperature.

The average steam-side heat-transfer coefficients for all working fluids are given in Table A1. The small variations in h_{st} observed for each fluid are because of nonuniform steam-side conditions in the experimental run (that is, variation in the steam pressure because of inherent fluctuations in the steam supply conditions). The resistances to heat transfer on condensing steam-side are much smaller in comparison to those on the fluid-side (see Figure 8) and, as a result, the overall heat-transfer coefficients will be mainly controlled by the boiling heat-transfer coefficients in the annulus.

Manuscript received Feb. 11, 2003, and revision received Sept. 4, 2003.