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An Improved Film Evaporation Correlation for Saline Water at Sub-atmospheric Pressures

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Abstract. This paper presents an investigation of heat transfer correlation in a falling-film evaporator working with saline water at sub-atmospheric pressures. The experiments are conducted at different salinity levels ranging from 15000 to 90000 ppm, and the pressures were maintained between 0.92 to 2.81 kPa (corresponds to saturation temperatures of 5.9 – 23 ^{0}C) .The effect of salinity, saturation pressures and chilled water temperatures on the heat transfer coefficient are accounted in the modified film evaporation correlations. The results are fitted to the Han & Fletcher's and Chun & Seban's falling-film correlations which are used in desalination industry. We modify the said correlations by adding salinity and saturation temperature corrections with respective indices to give a better agreement to our measured data.

Keywords: Falling film evaporation, Heat transfer coefficient, Desalination, Sub-atmospheric Pressure.
PACS: 44.35.+c

INTRODUCTION

Falling film evaporation processes are common in the chemical, food and desalination industries due to (i) high heat transfer coefficient, (ii) low liquid mass required in the evaporator, (iii) high evaporation rates and (iv) lower temperature differential. In desalination application, the falling film evaporative process reduces the equipment and maintenance costs by mitigating corrosion and scaling. For falling-film evaporator design, steam condenses inside the tubes and saline water is sprayed on the outer surfaces of tubes, casing an evaporation of the solution. The generated vapour separates from the liquid film adhering to the tube surfaces resulting in a higher overall heat transfer coefficient. This process is dependent on three heat transfer resistances: The condensation, the tube material and the evaporative resistances. Many researchers reported that the falling-film coefficient can reach 50% of the condensation heat transfer coefficient and thus, the overall heat transfer coefficient is controlled by the falling film coefficient [1, 2].

Yang and Shen [1] , Ribatski and Jacobi [3] , Aly et al. [4], Bourouni et at.[5] and Liu and Yi [6] investigated the effect of different operating and designing parameters (heat flux, feed flow rate, feed temperature, feed concentration, tube diameter, tube geometry, liquid feeder configuration, vapor flow etc.) on evaporative heat transfer coefficient (EHTC). They found that EHTC increases with increase in operating saturation temperature and heat fluxes. While many theoretical and empirical correlations have been developed at different operating conditions, the Han & Fletcher's [7] correlation for temperatures between 49 - 127 ^{0}C is given in equation 1.

$$h_{evaporation} = 0.0028.\left[\frac{\mu_l^2}{g.\rho_l^2.k_l^3}\right]^{-0.333} \left(\mathrm{Re}_\Gamma\right)^{0.5} \left(\mathrm{Pr}\right)^{0.85} \qquad (1)$$

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This falling film evaporation heat transfer coefficient (FFEHTC) is based on pure water flowing outside the circumferentially grooved electrically heated tubes. Chun & Seban [8] performed the experiments to find out the EHTC for evaporation outside the vertical tubes. Their experiments were based on distilled water flowing outside the vertical tube which was heated by electrical power. Both Han & Fletcher's [7] and Chun & Seban's [8] correlations are extensively used in desalination industry depending on evaporator design horizontal or vertical tubes. Aly et al. [4] investigated the effect of feed water salt concentration for evaporator saturation temperature ranging between 82 - 111^{0}C and found that the overall heat transfer coefficient increases with concentration.

In the literature, there has not been a standard correlation for low saturation temperature ranging from 5.9 - 23 ^{0}C (corresponds to saturation pressure of 0.92 - 2.81 kPa) with varying salinity levels 15000 - 90000ppm which is important for low pressure falling film evaporation process. The objective of this experimental study is to investigate the FFEHTC for horizontal tube evaporator at saturation temperature ranging from 5.9 - 23^{0}C (corresponding saturation pressure is 0.92 - 2.81kpa) and salt concentration from 15000 - 90000ppm. The results are then tabulated and compared with Han & Fletcher's correlation [7]. Based on this comparison, salinity and temperature terms are then incorporated in Fletcher's correlation. The constants/coefficient in the original correlation is also modified to include the effect of sub-atmospheric operation conditions. This ***modified Fletcher's correlation*** is found to be in good agreement with the authors' experimental results. The authors' also compared the results with Chun & Seban's [8] correlation and to accommodate the salinity and low saturation temperature effect the said correlation is also modified. This ***modified Chun & Seban's correlation*** is also found to be in good agreement with the authors' experimental results.

EXPERIMENTS

Adsorption desalination (AD) plant [9-11] in air conditioning laboratory at National University of Singapore is used to perform the experiments as shown in Fig.1. The evaporator of AD plant consists of 48 numbers of stainless steel tubes, arranged in 4-rows, each consist of 12 tubes. For feed (saline water) spray onto the tubes, a spray header with special spray nozzle is fitted inside the evaporator. A vacuum pump is provided to pull the vacuum in case of air ingress into the system and it maintained the saturation pressure inside the evaporator according to chilled water temperature.

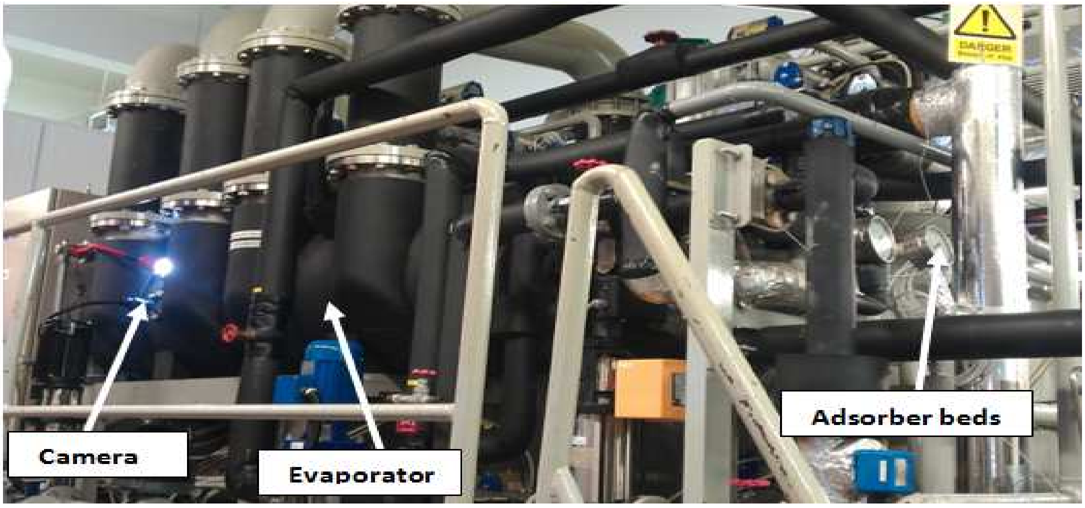

FIGURE 1. A view of AD plant showing the evaporator.

Experimental Procedure

The heat source, chilled water is circulated through the tubes and its temperature is maintained via conditioning facility provided with AD plant. The feed, saline water charged to the evaporator via pre-treatment facility (including de-aeration and filtering). Spray pump then sprayed the saline water onto the tubes. The heat transfer from chilled water to falling film causes its evaporation outside the tube. To control the salt concentration and maintain the falling film evaporation saline water level is regulated inside the evaporator. This also helps to prevent the fouling and corrosion of the evaporating unit. Evaporator shell side saturation pressure is always maintained at lower level than the corresponding saturation temperature of circulating chilled water to ensure evaporation all the time. The evaporator is connected to adsorption/desorption beds via pneumatic controlled butterfly valves to maintain the continuous evaporation. Special high speed camera was installed to view inside the evaporator during experiments. Fig.2 shows spray of saline water and evaporation effect inside the evaporator.

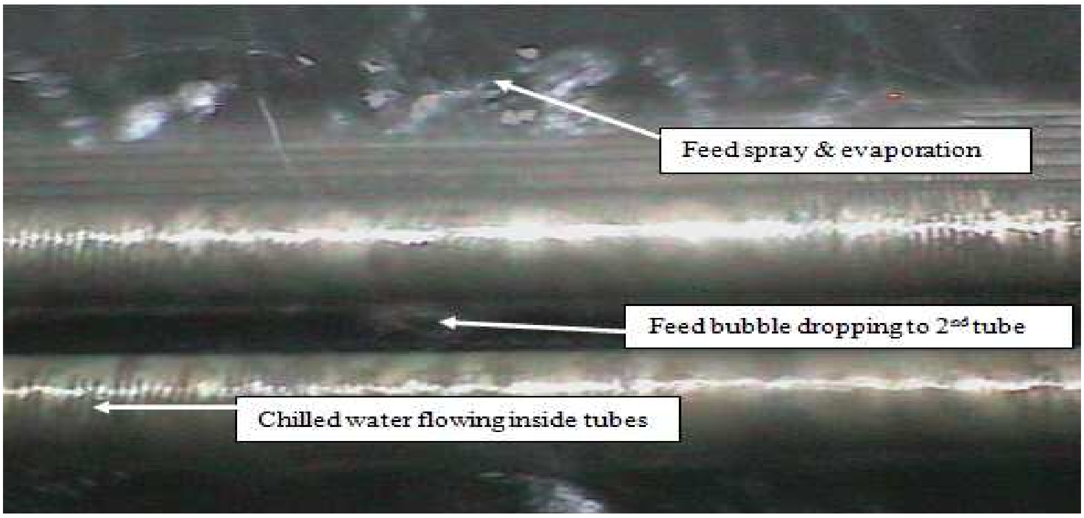

FIGURE 2. An inside view of evaporator.

Instrumentation

To measure all the temperature including feed and vapor, 5kΩ type thermister (±0.1^{0}C) are installed on evaporator at various point. For pressure reading, Yokogawa M&C corporation pressure transmitters (0-50kpa abs) are provided at different locations. Similarly flow rate is controlled by diaphragm valve and flow meters. All temperature, Pressure and flow readings are continuously monitored by a data logger. The total heat supplied by the chilled water to the saline water is calculated by:

$$Q_{\sup plied} = \dot{m}_{chilled}.Cp_{Tchilled}.\left(T_{chilled,in} - T_{chilled,out}\right) \quad (2)$$

where, $\dot{m}_{chilled}$ is chilled water flow rate and $T_{chilled,in}$ & $T_{chilled,out}$ are chilled water inlet and outlet temperatures respectively. The overall heat transfer coefficient is than calculated by:

$$Q_{\sup plied} = U.A_{evaporator}.LMTD \quad (3)$$

where, U is overall heat transfer coefficient, $A_{evaporator}$ is evaporator heat transfer area and LMTD is log mean temperature difference. The tube side heat transfer coefficient is calculated by Dittus-Boelter correlation:

$$Nu = \frac{h_{tube,side}.d_{i,tube}}{k} = 0.023.\mathrm{Re}^{\frac{4}{5}}.\mathrm{Pr}^{n} \quad (4)$$

where, $h_{tube,side}$ is tube side heat transfer coefficient, $d_{i,tube}$ is tube inside diameter, k is thermal conductivity of the liquid at specific temperature, Re is the Reynolds number and Pr is the Prandtl number. Falling film evaporation heat transfer coefficient is than calculated by overall heat transfer coefficient correlation as given below:

$$\frac{1}{UA} = \frac{1}{h_{tube,side}A_i} + R_{wall} + \frac{1}{h_{out,side}A_o} \quad (5)$$

where, A_i is inside heat transfer area, R_{wall} is tube wall material resistance, A_o is outside heat transfer area and $h_{out,side}$ is outside (falling film evaporation) heat transfer coefficient. The evaporator design and operational parameters are provided in Table-1 below.

TABLE (1. Operational and Design Parameters of Evaporator.

Parameters	Values	Units
Operational Parameters		
Chilled Water Flow Rate	48	LPM
Chilled Water Temperature	10 - 30	^{0}C
Saturation Temperature	5.9 - 23	^{0}C
Saturation Pressure	0.92 - 2.81	^{0}C
Feed Salinity	15,000 – 90,000	ppm
Design Parameters		
Number of Tubes	48	
Length of Each Tube	1.99	m
Tube Outer Diameter	16	mm
Tube Thickness	0.7	mm

RESULTS AND DISCUSSION

Table-2 lists the measured experiments in an evaporator that operates in sub-atmospheric pressures where the saturation temperatures ranges from 5.9 - 23^{o}C and the salt concentration changes from 15000 - 90000 ppm.

TABLE (2). Experimental values of LMTD, dT & Q at different chilled water temperature and feed water salinity.

Salinity (ppm)	**LMTD**			**dT ($T_{chilled\ water\ out} - T_{evaporator}$)**			**$Q_{supplied}$ (kw)**		
$T_{chilled,in}$	**30^{0}C**	**20^{0}C**	**10^{0}C**	**30^{0}C**	**20^{0}C**	**10^{0}C**	**30^{0}C**	**20^{0}C**	**10^{0}C**
15000	4.1056	3.6117	3.1217	5.4928	3.5868	1.7134	17.6753	12.9803	8.5847
30000	4.1641	3.5947	3.0583	3.4338	2.7786	1.4839	18.772	12.7345	7.9723
60000	4.2872	3.6268	3.1060	4.8566	3.9046	2.2999	19.4110	13.0753	8.4527
75000	4.1371	3.5668	3.0498	5.1555	3.7878	2.0451	18.4096	12.8382	8.1511
90000	4.1732	3.6474	3.1267	4.8793	3.3792	2.0474	18.8720	13.7007	8.8761

The results show a linear increase in the overall heat transfer coefficient with increasing saturation temperatures, and this is attributed to the drop in the specific volume of vapours. The effect of salinity is marginal about 5% at most. These distributions can be seen in Fig.3.

As there is no available correlation for falling film evaporative heat transfer at sub-atmospheric pressures, the existing Han & Fletcher (for horizontal tubes) and the Chun & Seban (for vertical tubes) are unable to capture the trend of our experiments, as shown in Fig.3.

We incorporated two additional parameters, namely the salinity and saturation temperature terms, as shown equations in Table-3, and a further regression with these parameters give a good agreement with our experiments and the uncertainty is found to be less than 4.5%. The results are shown below in Fig.4.

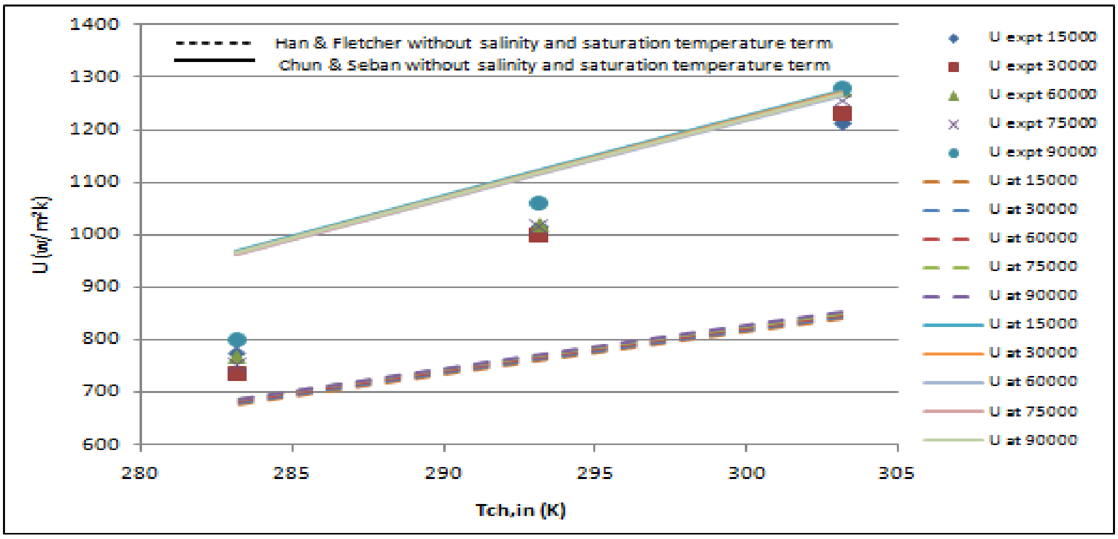

FIGURE 3. U experimental and calculated by Han & Fletcher's and Chun & Seban correlations without salinity and saturation temperature terms.

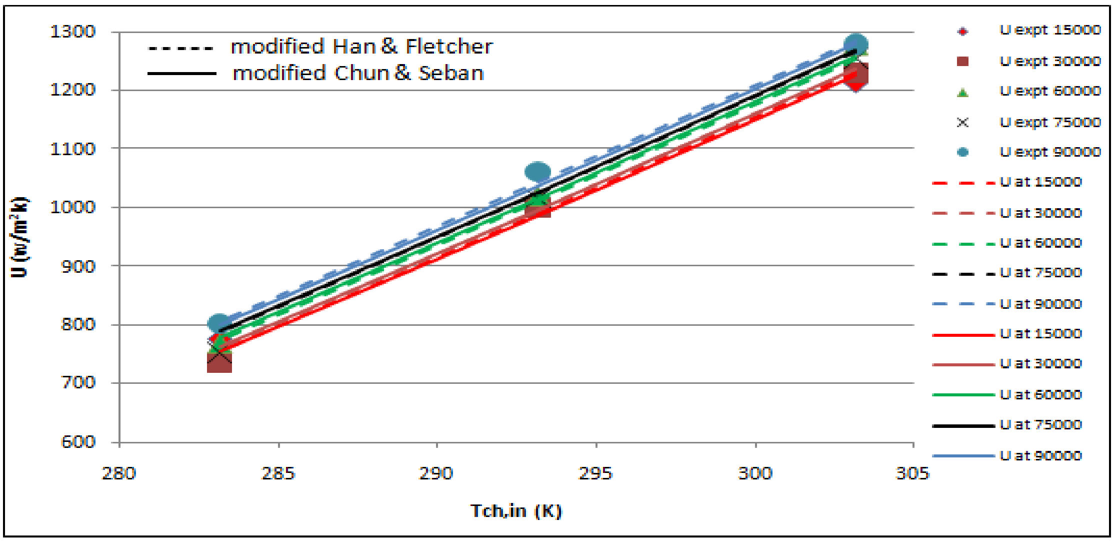

FIGURE 4. U experimental and calculated by modified Han & Fletcher's and Chun & Seban's correlations.

TABLE (3). Comparison of Correlations.

Han & Fletcher correlation (Horizontal tubes)	
Original	$h_{evaporation} = 0.0028.\left[\frac{\mu_l^2}{g.\rho_l^2.k_l^3}\right]^{-0.333} (\mathrm{Re}_\Gamma)^{0.5} (\mathrm{Pr})^{0.85}$
Modified	$h_{evaporation} = 0.0017.\left[\frac{\mu_l^2}{g.\rho_l^2.k_l^3}\right]^{-0.61} (\mathrm{Re}_\Gamma)^{-0.33} (\mathrm{Pr})^{-0.75} \left[2.\exp\left(\frac{S}{S_o}\right)-1\right]^{0.07} \left(\frac{T_{sat}}{T_{ref}}\right)^{-0.73}$
Chun & Seban correlation (vertical tubes)	
Original	$h_{evaporation} = 0.821.\left[\frac{\mu_l^2}{g.\rho_l^2.k_l^3}\right]^{-0.333} (\mathrm{Re}_\Gamma)^{-0.22}$
Modified	$h_{evaporation} = 0.20.\left[\frac{\mu_l^2}{g.\rho_l^2.k_l^3}\right]^{-0.10} (\mathrm{Re}_\Gamma)^{1.66} \left[2.\exp\left(\frac{S}{S_o}\right)-1\right]^{0.006} \left(\frac{T_{sat}}{T_{ref}}\right)^{-1.01}$

CONCLUSIONS

The falling film evaporation heat transfer coefficient has been measured experimentally and correlated with modified known correlations for sub-atmospheric operating conditions. The overall heat transfer coefficient is found to increase with increasing chilled water temperatures due to a drop in the specific volume of vapor. The saline water concentration has marginal effect about 5% at most on overall heat transfer at all operating conditions. The Han & Fletcher's and Chun & Seban's correlations are unable to capture the correct trend of heat transfer coefficients, with the latter over predicting and the former tend to under predict, and they are un-suitable for vacuum pressures and low temperature application. We incorporated correction terms to account for both the salinity and temperature effects. With these improved parameters, the said correlations are found to have good agreement with experimental results with an experimental uncertainty of 4.5%. The improved correlations can be used for chilled water temperature ranging 10 - 30^{0}C (corresponding evaporator saturation temperature 5.9 – 23^{0}C and saturation pressure ranging 0.92 – 2.81kpa) and for saline concentration as high as 90000ppm.

NOMENCLATURE

μ_l = Liquid viscosity (kg/m-sec)

ρ_l = Liquid density (kg/m^3)

k_l = Liquid conductivity (w/m-k)

Re_Γ = Film Reynolds number

Pr = Prandtl number

S = Feed water salinity (ppm)

S_o = Reference sea water salinity (30000ppm)

T_{sat} = Evaporator saturation temperature (k)

T_{ref} = Reference saturation temperature (k) ($T_{ref,Han\&Fletcher}$ = 49^{0}C , $T_{ref,Chun\&Seban}$ = 46^{0}C)

$T_{ch,in}$ = Chilled water inlet temperature (k)

ABBRIVEATIONS

EHTC = Evaporation heat transfer coefficient
FFEHTC = Falling film evaporation heat transfer coefficient
AD = Adsorption desalination

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