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A general correlation for heat transfer during evaporation of falling films on single horizontal plain tubes

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ABSTRACT

Falling film evaporators are widely used in many industries including desalination, petrochemical, and refrigeration. Hence ability to correctly predict heat transfer in these evaporators is important. While many prediction methods have been proposed, none has been validated with data from many sources covering a wide range of parameters. Hence there is a need for a well-verified general correlation. This research was done to fulfill this need. A correlation has been developed for heat transfer coefficient of single horizontal tubes with falling film evaporation. It is shown to be in good agreement with data from 22 sources that cover a very wide range of parameters. Included in the data are 11 fluids (water, ammonia, halocarbon refrigerants, hydrocarbons), tube diameters from 12.7 mm to 50.8 mm, heat flux from 1 to 208 kWm^{-2}, and liquid film Reynolds number 19 to 10,734. A total of 1237 data points are predicted with a mean absolute deviation of 17.4%. The new correlation is presented together with details of its verification.

Une corrélation générale pour le transfert de chaleur pendant l'évaporation de films tombant sur des tubes lisses horizontaux simples

Mots-clés: Évaporation en film tombant; Transfert de chaleur; Prévision; Corrélation; Tubes horizontaux

1. Introduction

Falling film evaporators offer high heat transfer at small temperature differences. They are widely used in many industries including desalination, petrochemical, food processing, and refrigeration. They are being used for OTEC (ocean thermal energy conversion systems) and ORC (organic Rankin cycle systems) as low ΔT is essential for their viability. They are increasingly replacing the conventional flooded evaporators as in addition to higher heat transfer coefficient, they contain much less refrigerant and hence reduce adverse environmental impact in case of leakage.

To ensure optimum design of falling film evaporators, accurate well-verified methods for prediction of heat transfer coefficient are needed. While the final objective is to have the ability to design the entire tube bundle, the first step for achieving it is to have reliable methods for predicting heat transfer on a single tube. These can then be developed further to take into account bundle effects. For this reason, many attempts have been made to measure heat transfer on single tubes and many prediction methods, theoretical and empirical, have been proposed. However, none of the prediction methods has been verified with a wide range of data from many sources. Therefore, there is a need for a general correlation validated with a wide range of fluids and operating parameters. This research was done to fulfill this need. This effort has met with considerable success. A correlation has been developed which is shown to be in good agreement with data for single tubes from 22 sources that cover a very wide range. Included in the data are 11 fluids (water, ammonia, halocarbon refrigerants, hydrocarbons), tube diameters from 12.7 to 50.8 mm, heat flux from 1 to 208 kWm^{-2}, and liquid film Reynolds number 19 to 10,734. A total of 1237 data points are predicted with a mean absolute deviation of 17.4%.

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Nomenclature

C_p	specific heat at constant pressure, ($\mathrm{Jkg^{-1}K^{-1}}$)
D	outside diameter of tube, (m)
g	acceleration due to gravity, ($\mathrm{ms^{-2}}$)
H	gap between nozzle/hole outlet and heat transfer tube, or gap between dummy tube and heat transfer tube, (m)
h	heat transfer coefficient, ($\mathrm{Wm^{-2}K^{-1}}$)
h_c	heat transfer coefficient due to convection, ($\mathrm{Wm^{-2}K^{-1}}$)
h_{pb}	heat transfer coefficient due to pool boiling, ($\mathrm{Wm^{-2}K^{-1}}$)
h_{TP}	two-phase heat transfer coefficient, ($\mathrm{Wm^{-2}K^{-1}}$)
k	thermal conductivity, ($\mathrm{Wm^{-1}K^{-1}}$)
M	molecular weight, (-)
p_c	critical pressure, (kPa)
p_r	reduced pressure, (-)
q	Heat flux, ($\mathrm{Wm^{-2}}$)
Re_L	liquid Reynolds number, (-)
R_p	surface roughness, (μm)
Greek	
α	thermal diffusivity, ($\mathrm{m^2s^{-1}}$)
Γ	liquid flow rate per unit length on one side of tube, ($\mathrm{kgm^{-1}s^{-1}}$)
μ	dynamic viscosity, (Pa.s)
ν	kinematic viscosity, ($\mathrm{m^2s^{-1}}$)
ρ	density, ($\mathrm{kgm^{-3}}$)
Subscripts	
lam	Laminar
turb	turbulent

In the following, the new correlation is presented together with details of its development and verification. Previous work in this field is first briefly discussed.

2. Previous work

Numerous experimental studies have been done on falling film evaporation. These have been reviewed among others by Ribatski and Jacobi (2005), Fernández-Seara and Pardiñas (2014), Narváez-Romo and Simões-Moreira (2013), and Thome (1999, 2009, 2017). The studies have included plain and enhanced tubes, single tubes and bundles of tubes, and horizontal and vertical orientations. As the new correlation is for single plain horizontal tubes, only the works on them are discussed here.

Table 1 lists the salient features of 22 studies on heat transfer to saturated liquids falling on single tubes and vertical columns of a single row of horizontal tubes which provide measurements for the top tube of column. All these studies were done with saturated single-component pure fluids without any contaminant such as oil in refrigerant. These include 11 fluids covering a very wide range of tube diameters, flow rates and pressures.

Numerous methods for predicting heat transfer, theoretical and empirical have been proposed. Some of them are based on flow patterns. Mitrovic (1986) identified three falling flow modes or patterns. These are droplet, jet, and sheet. The jet pattern is also known as the column pattern. Hu and Jacobi (1996a) identified two intermediate regimes, namely, jet–sheet and droplet–jet. In the droplet mode, liquid leaves the bottom of tube in the form of drops. In the jet mode, there are continuous columns of liquid falling from the bottom of tubes. In the sheet mode, liquid leaves the tube in the form of a continuous sheet. Hu and Jacobi (1996b) presented a flow pattern-based correlation which was verified only with their own data for water. A recent flow pattern-based model is by Bustamante et al. (2020). It was verified only with their data for a rectangular tube.

Lorenz and Yung (1979) developed a correlation in which contributions of convection and nucleate boiling were combined. The convective effects consisted of those in a thermally developing region and a fully developed region. Their correlation was shown to be in satisfactory agreement with the data of Conti (1978) for ammonia.

Chyu and Bergles (1987) developed two analytical models which were compared only to their own data for water falling on a single tube. Owens et al. (1978) presented an empirical correlation based on data from two sources for ammonia and water.

Zhao et al. (2016) developed a correlation which identifies two regimes of heat transfer namely partially dry and fully wet. In the fully wet regime, the entire tube is wetted while in the partially dry regime, part of the tube is dry. Separate equations were given for these two regions and a correlation to identify the transition between the two regimes was provided. They showed fairly good agreement with their own data for R-134a as well as data for halocarbon refrigerants from several sources. Some of the data correlated by them was for tube bundles, for example those of Danilova et al. (1976) and the data of Moeykens (1994) for R-22 and R-123.

Jin et al. (2019) developed a correlation which also has two heat transfer regimes similar to those in Zhao et al. (2016) correlation. They found it to give good agreement with their own data as well as data from two other sources for halocarbon refrigerants and hydrocarbons. They report that the Zhao et al. (2016) correlation gave large deviations with the data for hydrocarbons.

Jige et al. (2019) developed a correlation which was shown to agree with their own data as well as data from three other sources. The fluids were halocarbon refrigerants, water and ammonia.

There are many other correlations which were verified only with the researchers' own data.

From the foregoing discussion, it is clear that none of the hitherto published prediction methods has been verified with wide ranging data from many sources. Therefore, the need for a method which has been verified with a wide range of data is evident.

3. The new correlation

3.1. Development of the new correlation

The new correlation is primarily based on the superposition method of Rohsenow (1952) according to which heat transfer during boiling with forced convection is the sum of that due to forced convection and that due to nucleate pool boiling, expressed by the following equation.

$$h_{TP} = h_c + h_{pb} \tag{1}$$

For the calculation of h_c the method used by Lorenz and Yung (1979) was tried and found satisfactory. They pointed out that a horizontal tube of diameter D can be regarded as a vertical plate of length πD/2 and therefore the correlations for falling films on vertical surfaces can be applied to them. They used the following correlation developed by Chun and Seban (1971) for liquid films on vertical tubes.

For laminar flow,

$$h_{c,lam} = 0.821\left(\frac{\nu^2}{gk^3}\right)^{-1/3} Re_L^{-0.22} \tag{2}$$

For turbulent flow,

$$h_{c,turb} = 0.0038\left(\frac{\nu^2}{gk^3}\right)^{-1/3} Re_L^{0.4}\left(\frac{\nu}{\alpha}\right)^{0.65} \tag{3}$$

Table 1
Rage of data analyzed and results of data analysis.

Source	Geometry	Spray Method	Tube dia, mm	H/D	Tube Material	Fluid	p_r	q, kW/m^2	Re_L	N	New Corr. Deviation,% MAD Avg.
Putilin et al. (1996)	Single tube	Not known	38	Not known	Not known	water	0.0046	10	1139	5	6.4
									5694		4.0
Kim et al. (1998)	Single tube	Note 3	25.4	0.118	Not known	water	0.00141	12	727	90	13.2
								68	5017		4.7
Fletcher et al. (1974)	Single tube	Note 3	50.8	Not known	Copper-nickel	water	0.0006	2	2900	18	21.7
							0.0112	5	10,734		−19.1
			25.4	Not known			0.0006	4	1609	12	44.5
							0.0112	6	5780		−44.5
Parken et al. (1990)	Single tube	Note 3	50.8	Not known	brass	water	0.00051	47	963	18	18.2
							0.01119	79	5450		7.7
			25.4	Not known			0.00460	47	1189	18	29.4
							0.01119	79	6716		22.5
Yang and Shen (2008)	2 tube column	Note 3	14.0	Not known	Al-brass	water	0.00059	14	164	5	21.0
								56			−13.8
Liu and Yi (2001, 2002)	Single tube	Note 3	18.0	0.33	copper	water	0.0046	21	512	32	35.9
								524	5005		35.7
Chyu and Bergles (1987)	Single tube	Note 3	25.4	1	copper	water	0.0046	9	295	18	26.8
								208	2353		3.7
				0.1				10	537	3	6.6
									1598		−6.6
Moeykens and Pate (1994)	Single tube	Note 4	18.9	Not known	copper	R-134a	0.0775	5	200	8	25.9
								41			6.1
	2 tube column		12.7	Not known	copper	R-134a	0.0775	10	538	12	16.6
								25	723		−6.6
Darabi et al. (2000)	Single tube (Note 1)	Note 4	19.0	2.1	Not known	R-134a	0.0190	10	1043	6	7.7
								30			2.8
Chien and Chen (2012)	Column of 3 tubes	Note 4	19.0	0.5	Not known	R-134a	0.1021	4	255	34	12.0
							0.1724	44	750		10.7
Roque (2004)	8 tube column	Note 3	19.05	Not known	copper	R-134a	0.0861	19	261	38	18.6
								56	2839		18.6
Zhao et al. (2016)	Single tube	Note 3	16.0	Not known	copper	R-134a	0.08917	20	572	34	13.8
								60	2309		−3.9
			19.05				0.08917	20	582	140	21.0
							0.1242	80	2096		−14.1
			25.3				0.08917	20	587	30	25.2
								60	2225		−20.0
Zhao et al. (2017)	Single tube	Note 5	19.06	Not known	copper	R-134a	0.0892	20	179	78	20.0
								60	2471		−12.2
						R-123	0.0116	20	137	25	8.9
								60	1178		−0.8
Habert (2009)	8 tube column	Note 3	19.05	Not known	copper	R-134a	0.08614	20	184	34	25.5
								60	2490		−25.2
						R-245fa	0.01813	20	226	19	12.6
								40	1910		−11.2
Fujita and Tsutsui (1998)	column of 5 tubes	Note 3	25.0	1.0	copper	R-11	0.0453	1	19	40	16.5
								10	2000		9.8
Liu and Yi (2001)	Single tube	Note 3	18.0	0.33	copper	R-11	0.0093	4	250	38	18.1
								91	2500		13.0
Chien and Tsai (2011)	column of 3 tubes	Note 4	18.13	Not known	Copper	R-245fa	0.0183	6	187	47	15.1
							0.03361	46	366		5.9
Jige et al. (2019)	Single tube	Note 5	19.0	0.525	copper	R-245fa	0.03361	5	109	29	14.4
								20	772		0.8
						R-1234ze	0.08483	2	136	32	9.0
								20	820		0.7
Tan et al. (1990)	Single tube	Note 4	22.0	Not known	Copper	R-113	0.02481	7	127	12	23.7
								73	756		23.7
Fernandez-Seara	Single tube	Note 4	Not known	Not known	Not known	NH_3	0.05427	2	110	40	14.9
								42	196		5.2
Conti et al. (1978)	Single tube	Note 3	50.0	Not known	Stainless steel	NH_3	0.08062	5	109	18	8.5
									5556		−3.8
Jin et al. (2019)	Single tube	Note 5	19.05	0.315	Copper		0.05329	10	203	113	11.2
						Isobutane	0,06,079	142	4673		−8.3
						Propane	0.13449	10	347	110	22.7
							0.14975	152	2022		−22.7
						R-134a	0.08917	10	233	93	7.8
								112	2139		0.8
Jin et al. (2018)	Single tube	Note 3	19.05	0.315	Copper	R-32	0.14063	20	290	50	8.9
							0.19144	60	2940		−3.6
All sources			12.7	0.1			0.00059	1	19	1237	17.4
			50.8	2.1			0.19144	208	10,734		−5.0

Note 1: tube surrounded by a mesh of electrodes. Note 2: For column of tubes, only the data for the top tube was analyzed. Note 3: Gravity flow directly on HT (heat transfer) tube. Note 4: Pressurized spray direct on HT tube. Note 5: Spray on dummy tube above HT tube.

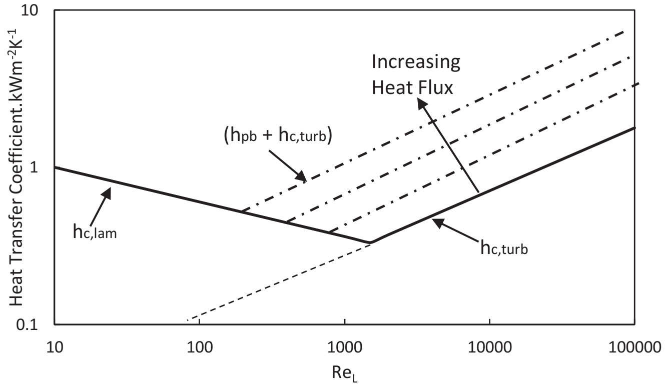

Fig. 1. Schematic representation of the present correlation.

Where α is the thermal diffusivity and ν is the kinematic viscosity of liquid. The liquid film Reynolds number Re_L is defined as:

$$Re_L = \frac{4\Gamma}{\mu} \tag{4}$$

Γ is the liquid mass flow rate per unit length on one side of the tube.

In the absence of bubble nucleation, the transition point between laminar and turbulent flow will occur at the intersection of Eqs. (2) and (3). It is given by the following equation.

$$Re_{l,tran} = 5800\left(\frac{\nu}{\alpha}\right)^{-1.06} \tag{5}$$

When nucleate boiling occurs, it is postulated that the stirring action of the bubbles makes the liquid film turbulent and the transition from laminar to turbulent flow occurs at Reynolds numbers lower than that from Eq. (5). With increasing heat flux, bubble nucleation and its stirring effect will increase, causing lower and lower transition Reynolds numbers. This suggests that $h_{c,turb}$ should be used in the superposition model Eq. (1).

At Re_L lower than that at transition to the turbulent regime, heat transfer coefficient is given by the equation for laminar heat transfer, Eq. (2). The transition between laminar and turbulent regimes is identified by noting that $h_{c,lam}$ will be higher than (h_{pb} + $h_{c,turb}$) at Re_L lower than the transition Re_L. Thus heat transfer coefficient is calculated as the greater of $h_{c,lam}$ and $(h_{pb} + h_{c,turb})$.

The model of the new correlation described above is shown schematically in Fig. 1. At Re_L lower than at the intersection of $(h_{pb} + h_{c,turb})$ lines with the $h_{c,lam}$ line, $h_{TP} = h_{c,lam}$, otherwise $h_{TP} = (h_{pb} + h_{c,turb})$.

The calculation of the pool boiling heat transfer coefficient is now discussed. Numerous correlations have been proposed. Among these, four have been verified with a wide range of data for many fluids. These are the correlations of Mostinski (1963), Cooper (1984). Stephan and Abdulsalam (1980) and Gorenflo et al. (2014). Data for falling film evaporation were analyzed using all of them. Each of them resulted in the best agreement with some data sets and inferior agreement with some other data sets. Considering all data sets, Mostinski correlation resulted in the least deviations with data for hydrocarbons and the Cooper correlation for all other fluids.

The Mostinski correlation is:

$$h_{pb} = 0.00417 q^{0.7} p_c^{0.69}\left(1.8 p_r^{0.17} + 4 p_r^{1.2} + 10 p_r^{10}\right) \tag{6}$$

h_{pb} is in W/m^{2}K, heat flux q in W/m^2, and the critical pressure p_c in kPa.

The Cooper correlation is:

$$h_{pb} = 55 F p_r^{0.12-0.08686 \ln R_p}(-0.4343 \ln p_r)^{-0.55} M^{-0.5} q^{0.67} \tag{7}$$

This correlation is dimensional. Heat flux q is in W/m^2 and h_{pb} in W/m^{2}K. Surface roughness R_p is according to DIN 4762. If the surface roughness is not known, Cooper recommends using $R_p = 1$ μm. $F = 1.7$ for horizontal copper cylinders and $= 1$ for all other heaters of any material or shape. Cooper states that this factor 1.7 is not directly established by test data, is not logical, and may be superseded when more data become available. By substituting $R_p = 1$ μm and $F = 1$ in Eq. (7), the following simplified form of Cooper correlation is obtained.

$$h_{pb} = 55 p_r^{0.12}(-0.4343 \ln p_r)^{-0.55} M^{-0.5} q^{0.67} \tag{8}$$

This is the form which has been widely used and the one that is recommended for use with the correlation presented here.

As discussed in Section 4.2, data from two sources Roques (2004) and Habert (2009) had pool boiling heat transfer coefficient much higher than all the four correlations mentioned above: those of Gorenflo et al., Stephan and Abdelsalam, Mostinski and Cooper. The data of Roques and Habert for falling film evaporation were in satisfactory agreement with the present correlation when their measured pool boiling heat transfer coefficients were used.

3.2. The new correlation

Based on the discussions in Section 3.1, the new correlation is as below.

h_{TP} is the larger of $h_{c,lam}$ and $(h_{pb} + h_{c,turb})$

$h_{c,lam}$ is calculated with Eq. (2) and $h_{c,turb}$ by Eq. (3)

Recommended correlations for h_{pb} are:

Mostinski correlation, Eq. (6), for hydrocarbons.

The simplified Cooper correlation, Eq. (8), for all other fluids.

Other pool boiling correlations may be used if there is reason to believe that they are better suited, such as those based on tube manufacturer's pool boiling tests on the tubes being used in the heat exchanger. All properties are of saturated liquid.

4. Verification of the new correlation

4.1. Data collection and selection

Efforts were made to collect a wide range of data from many sources. Besides data for single tubes, data for the top tube of single-row column of tubes were also accepted as their behavior will be essentially the same as of a single tube alone. Data for multi-row columns or tube bundles were not considered even when they provided data for top tubes as it was felt that they may be affected by splashing from other tubes and maldistribution of liquid.

Only data for saturated liquids were collected. Data for zeotropic mixtures were not considered as their heat transfer is affected by mass transfer phenomena. Data for refrigerants containing oil were not considered as heat transfer can be significantly affected by oil. For this reason, the data of Zeng and Chyu. (1996) for ammonia were not included as ammonia was circulated by a compressor using oil for lubricantion.

Details of the data collected are given in Table 1. The summary of the range covered by these data is in Table 2.

4.2. Calculation methodology

Pool boiling heat transfer coefficients of hydrocarbons were calculated by the Mostinski correlation and of other fluids by the simplified Cooper correlation except for the data of Roques (2004) and Habert (2009). These researchers performed pool boiling tests on the copper tubes used in their falling film tests. They compared

Table 2
Summary of the range of data analyzed.

Parameter	Range
Fluids	Water, ammonia, R-11, R-32, R-123, R-134a, R-245fa, R-1234ze, propane, isobutane
Tube material	Copper, brass, aluminum-brass, stainless steel, copper-nickel
Tube diameter, mm	12.7 to 50.8
H/D	0.1 to 2.1
Geometry	Single tube, top tube of a column of tubes
Reduced pressure	0.00059 to 0.19144
Γ, $kgm^{-1}s^{-1}$	0.0037 to 0.69
Re_L	19 to 10,734
Heat flux, kWm^{-2}	1 to 208
Number of data sources	22

their measured pool boiling heat transfer coefficients with the predictions of the correlations of Cooper, Gorenflo, and Stephan and Abdelsalam. Their measured heat transfer coefficients were much higher than the predictions of these three correlations, being up to seven times the predicted values. Roques correlated his data for R-134a by the following equation.

$$h_{pb} = 171q^{0.376} \tag{9}$$

Habert (2009) correlated his pool boiling data for R-134a and R-245fa by the following equation.

$$h_{pb} = 35q^{0.67}p_r^{0.42} \tag{10}$$

In Eqs. (9) and (10), h_{pb} is in $Wm^{-2}K^{-1}$ and q is in Wm^{-2}; these equations were used in analyzing the data of Roques and Habert, respectively.

All fluid properties were calculated with REFPROP 9.1, Lemmon et al. (2013).

4.3. Results of data analysis

The deviations of the present correlation with the data analyzed are listed in Table 1. The deviations are defined as:

Mean absolute deviation (MAD):

$$MAD = \frac{1}{N}\sum_{1}^{N} ABS\left\{\left(h_{predicted} - h_{measured}\right)/h_{measured}\right\} \tag{11}$$

Average deviation:

$$Avg.\ Dev. = \frac{1}{N}\sum_{1}^{N}\left\{\left(\mathrm{h_{predicted}} - \mathrm{h_{measured}}\right)/\mathrm{h_{measured}}\right\} \tag{12}$$

As seen in Table 1, the 1237 data points from 22 sources are predicted with MAD of 17.4% and the MAD of most data sets does not exceed 20%. The data are for 11 fluids with very different properties and cover a wide range of flow rates, heat flux, and reduced pressures. Hence this result can be considered very satisfactory.

5. Discussion

The results of data analysis presented in Table 1 are now discussed in the following.

5.1. Applicability to various fluids

As seen in Tables 1 and 2, the present correlation was verified with data for eleven fluids. These include water, ammonia, hydrocarbons, and halogenated hydrocarbon refrigerants. The properties of these fluids cover an extreme range. For example, water has the highest liquid thermal conductivity and halocarbon refrigerants have the lowest thermal conductivity among commonly used fluids. The properties of all other fluids used in heat exchangers are likely to be within the range of the properties of these fluids. Hence this correlation may be expected to be applicable to all pure Newtonian non-metallic fluids used in falling film evaporators. It should also be applicable to azeotropic mixtures as they behave like pure fluids. Application to zeotropic mixtures will, however, require correction for mass transfer effects.

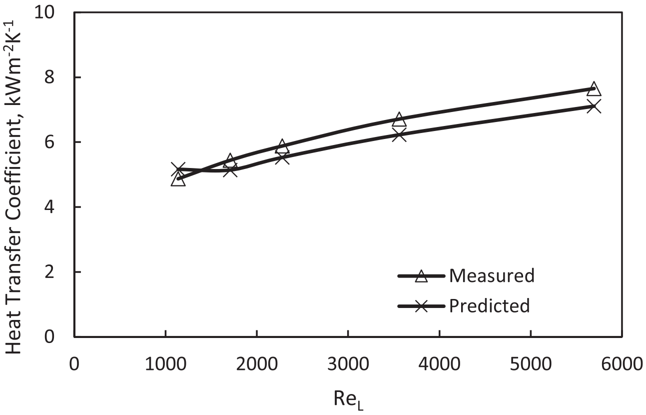

Fig. 2. Comparison of the present correlation with the data of Putilin et al. (1996) for water. Heat flux 10 kWm^{-2}, T_{SAT} 100 °C.

Table 3 lists the deviations of the present correlation and percent of data with MAD less than 30% for different categories of the fluids. For fluids other than water, the MAD is from 13 to 17.4 percent and data with MAD < 30% from 86.3 to 95%. These figures are very good. The MAD for water data is 21.7 and 68.4% of data have MAD less than 30%. The higher deviation with water data probably reflects difficulties in accurate measurement. Heat transfer coefficients for water are very high and hence wall to fluid temperature differences are very small which are difficult to measure accurately. It is especially difficult to accurately determine heat transfer coefficients for water using Wilson plot method as the resistance of the evaporating film is often much smaller than of the heating fluid.

Fig. 2 to 10 show the comparison of the present correlation with data for the various types of fluids.

5.2. Effect of reduced pressure

All fluid properties vary with reduced pressure. Further, many correlations have been found to fail at very low or very high reduced pressures. Therefore, it is desirable to look into the effect of reduced pressure on the accuracy of this correlation.

The data analyzed include reduced pressures from 0.00059 to 0.19144. Fig. 11 shows the plot of the mean absolute deviations of all data sets against reduced pressure. There is no indication of any effect of reduced pressure on the accuracy of the present correlation. The deviations at the extreme values of reduced pressure are low. The present correlation adds pool boiling and single-phase heat transfer coefficients. The correlation of Cooper which

Table 3
Deviations of the present correlation with data for various fluids.

Fluid	No. of Data Points	Deviation,% Mean Absolute	Average	% Data with MAD < 30%
Water	219	21.7	5.5	68.4
Halocarbon refrigerants	750	16.7	−5.1	86.3
Hydrocarbons	223	16.9	−15.4	95.0
Ammonia	58	13.0	2.4	91.4
All fluids	1250	17.4	−4.7	84.9

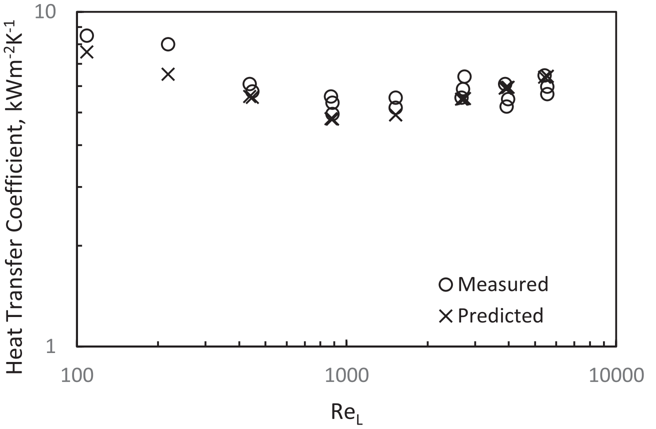

Fig. 3. Comparison of the present correlation with the data of Conti (1978) for ammonia. Heat flux 5 kWm^{-2}, T$_{SAT}$ 22 °C.

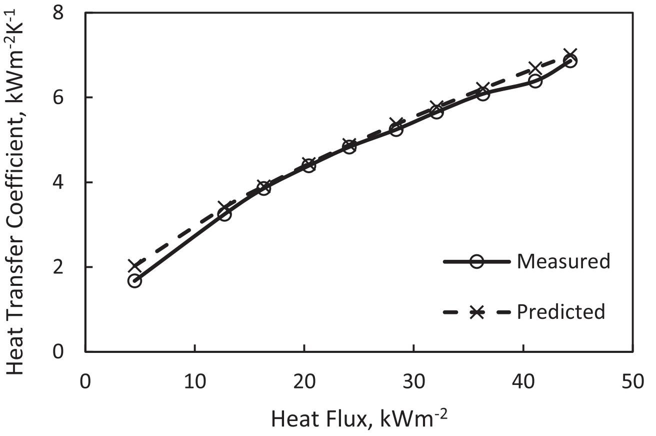

Fig. 4. Comparison of the present correlation with the data of Chien and Chen (2012) for R-134a. T$_{SAT}$ 26.7 °C, Re_L 750.

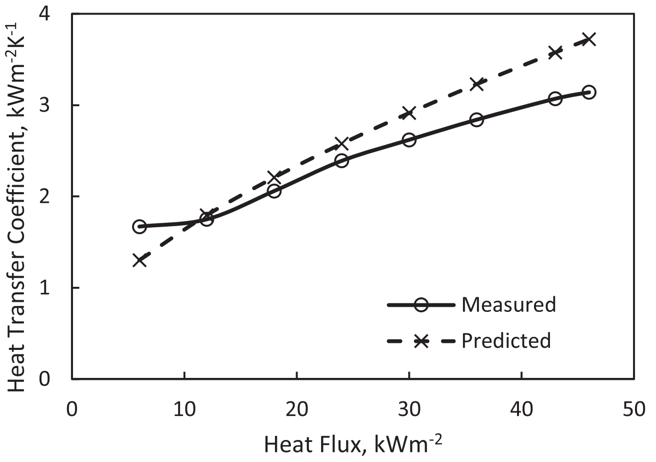

Fig. 5. Comparison of the present correlation with the data of Chien and Tsai (2011) for R-245fa. T$_{SAT}$ 20 °C, Re_L 297.

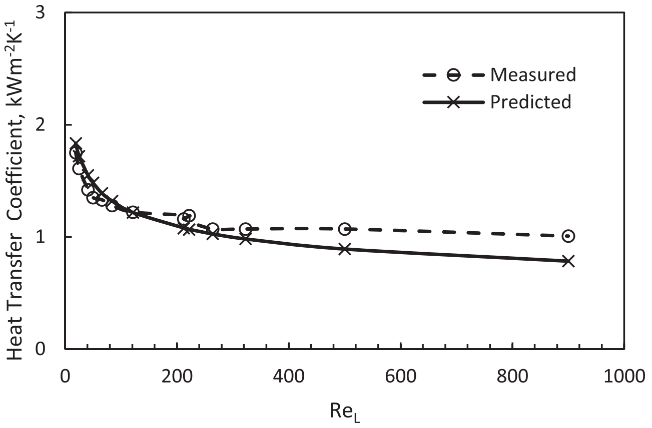

Fig. 6. Comparison of the present correlation with the data of Fujita and Tsutsai for R-11. Heat flux 1 kWm^{-2}, T$_{SAT}$ 44.4 °C.

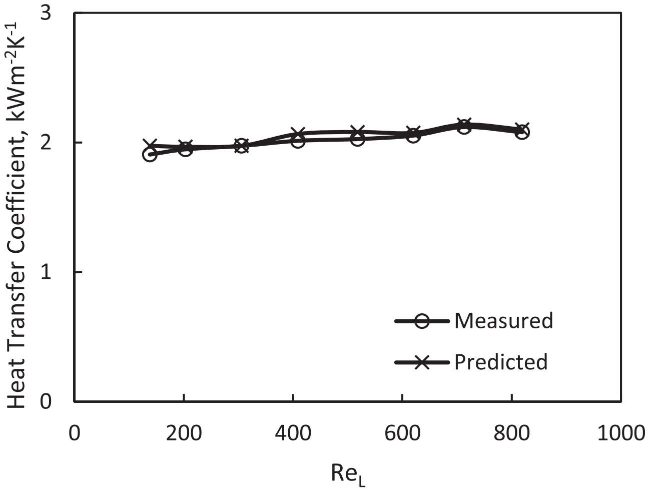

Fig. 7. Comparison of the present correlation with the data of Jige et al. (2019) for R-1234ze. Heat flux 20kWm^{-2}, T$_{SAT}$ 10 °C.

has been recommended for use for most fluids was based on data for reduced pressures up to 0.9. Single phase heat transfer correlations are not known to be affected by pressure. Hence there is no apparent reason for the present correlation to be inapplicable at higher reduced pressures. Still, it will be prudent to be cautious in using it beyond the verified range.

5.3. Effect of tube diameter

The present correlation does not include tube diameter as a parameter while some researchers have indicated that diameter affects heat transfer. This topic therefore needs some discussion.

Fletcher et al. (1974) and Parken et al. (1990) performed tests with water on tubes of diameter 25.4 mm and 50.8 mm. Both reported that the heat transfer coefficient of 25.4 mm tubes was

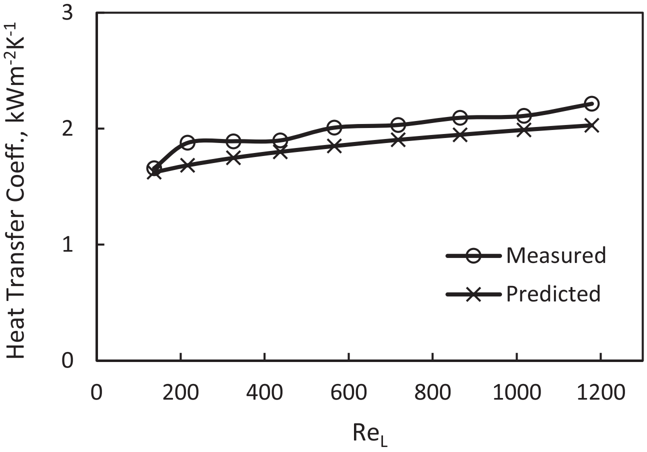

Fig. 8. Comparison of the present correlation with the data of Zhao et al. (2016) for R-123 on a 19.05 diameter tube. T_{SAT} = 6 °C.

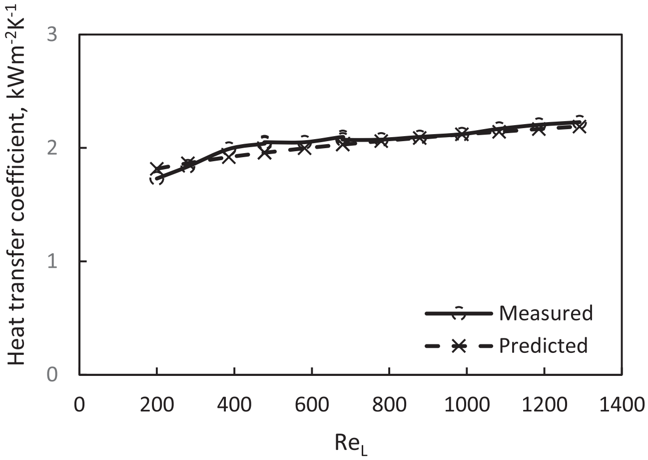

Fig. 9. Comparison of the present correlation with the data of Jin et al. (2019) for isobutane. Heat flux 20 kWm^{-2}, T_{SAT} = 6 °C.

higher than of the 50.8 mm tubes. The 50.8 mm tube data from both sources are in satisfactory agreement with the present correlation. The data of Fletcher et al. (1974) for 25.4 mm diameter tube are considerably underpredicted by the present correlation. The data of Parken et al. (1990) for their 25.4 mm diameter tube are over-predicted by the present correlation. As seen in Table 1, data for tubes of 25.4 mm from many sources are satisfactorily predicted by the present correlation including those of Kim et al. (1998) for water.

Zhao et al. (2016) performed tests on tube diameter 16, 19.05, and 25.4 mm and gave a correlation which involves tube diameter in a complex manner through the use of several dimensionless numbers containing tube diameter such as Nusselt number, Weber number, and a modified boiling number. Jin et al. (2019) gave a similar correlation.

Fig. 12 shows a plot of mean absolute deviations of data sets with the present correlation versus tube diameter. The tube diameters are 12.7 to 50.8 mm. The deviations are seen to be low near the smallest and largest diameters. A very few data sets for tubes of around 19 and 25 mm diameter have large deviations. As there are many data sets at these diameters, some scatter there is not unexpected. Most of the data sets throughout the range of diameters have low to moderate deviations.

Hence it may be concluded that the present correlation is satisfactory in the range of tube diameters (12.7 to 50.8 mm), the range included in the data analyzed.

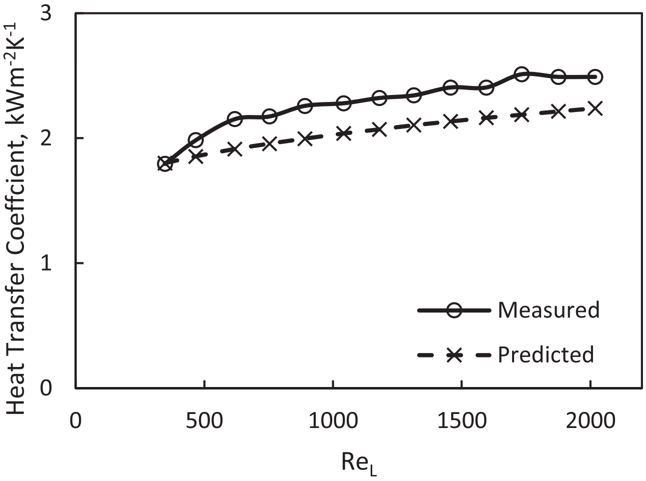

Fig. 10. Comparison of the present correlation with the data of Jin et al. (2019) for propane, heat flux 10 kWm^{-2}, T_{SAT} 6 °C.

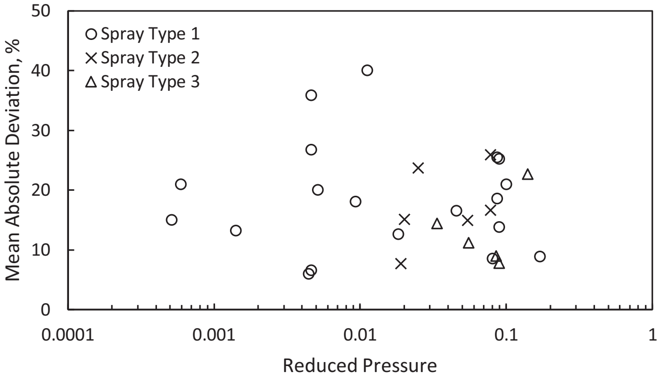

Fig. 11. Mean absolute deviations of all data sets versus reduced pressure. Spray types are: 1. Gravity flow directly on HT tube, 2. Pressurized spray direct on HT tube, 3. Spray on dummy tube above the HT tube.

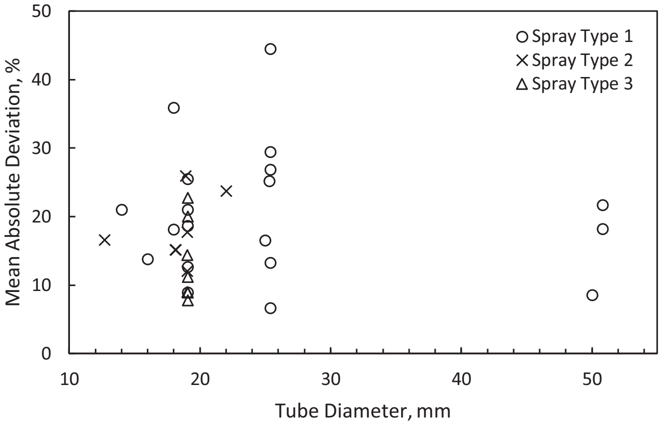

Fig. 12. Mean absolute deviation of the present correlation with all data sets as a function of tube diameter. Spray types are: 1. Gravity flow directly on HT tube, 2. Pressurized spray direct on HT tube, 3. Spray on dummy tube above the HT tube.

5.4. *Effect of method of liquid distribution*

In the experimental data analyzed here, liquid was applied to the heat transfer tube in several ways. These include spray from pressurized manifolds through holes or nozzles, and spray/drip by gravity from a channel with holes located above the tube. In some cases, spray was directly on the heat transfer tube while in some

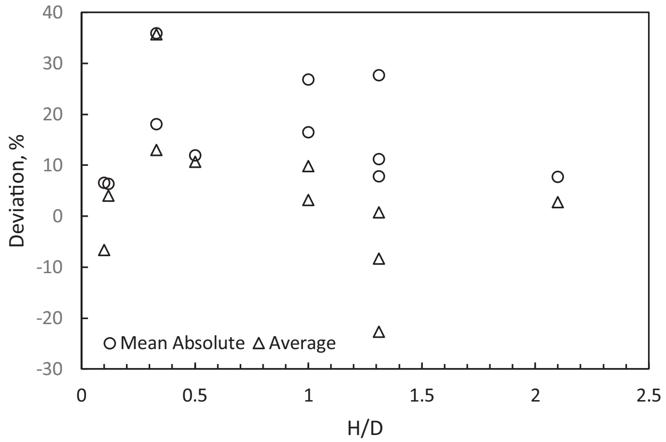

Fig. 13. Effect of H/D on the mean absolute and average deviation of the present correlations with the data sets for which H/D is known.

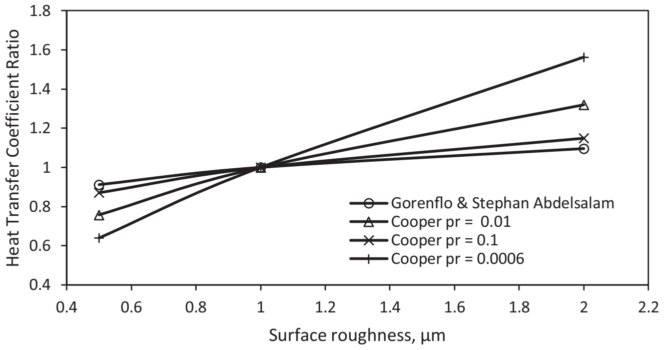

Fig. 14. Effect of tube surface roughness on the heat transfer coefficients predicted by three pool boiling correlations. The ratio shown is h at actual tube roughness to that at roughness of 1 μm.

cases, spray was on a dummy rube directly above the heat transfer tube from which liquid flowed on the heat transfer tube. The method of liquid distribution in each study is listed in Table 1. From the results in this table, the conclusion is that the deviations of the present correlation are not related to the method of liquid distribution. The type of spray is also shown in Figs. 11 and 12. These figures also indicate that the deviations of the present correlation are not related to the type of spray.

Fernandez-Seara et al. (2016) did some of their tests with liquid ammonia directly sprayed on the tube while some of the tests were done with liquid sprayed on a dummy tube from which liquid flowed down on the heat transfer tube. The heat transfer coefficients in the second case were much lower than in the first case. As discussed in the paragraph above, the results of other studies do not indicate any difference between the results with these two types of liquid distribution. It was therefore felt that the data of Fernandez-Sear et al. for indirect liquid application are unusual and were therefore not included in Table 1.

A related topic is the effect of the distance H between the outlet of liquid distributor and the heat transfer tube for the case of direct spray and. When liquid is sprayed on a dummy tube, H is the gap between the dummy tube and the heat transfer tube. Owens (1978) analyzed data from two sources and gave a correlation in which heat transfer coefficient is proportional to $(H/D)^{0.1}$. Chyu and Bergles (1987) performed tests with water using H/D of 0.1 and 1. They found some agreement with the Owens correlation. Their data are in good agreement with the present correlation except the set at the highest heat flux; those did not agree also with the Owens correlation.

The H/D ratios in various studies, where available, are listed in Table 1. It is seen that the majority of sources have not provided this information. This indicates that those researchers did not consider H/D to have effect on heat transfer. The mean absolute and average deviations when known are plotted versus H/D in Fig. 13. The deviations over the entire range of H/D from 0.1 to 2.1 are seen to have low deviations with very few exceptions. The deviations are low at the maximum and minimum values of H/D.

The conclusion from the above discussion is that H/D does not have significant effect on heat transfer.

5.5. Effect of tube material

The present correlation calculates two-phase heat transfer coefficient as the sum of convective and pool boiling heat transfer coefficients. While the correlations recommended for use with the present correlation do not include effect of tube material, some others do. The Gorenflo et al. (2014) correlation includes $(k\rho C_p)$ of the tube material as a parameter. Cooper (1984) had tentatively included a multiplier of 1.7 for horizontal copper cylinders. Hence some discussion on this topic is needed.

The tube materials for all data are listed in Table 1. These include copper, stainless steel, brass, aluminum-brass, and copper-nickel. Their properties vary greatly. The $(k\rho C_p)$ of copper is about 25 times that of stainless steel. On this basis the Gorenflo correlation predicts the heat transfer coefficient on stainless steel to be about 0.43 times that on copper. The pool boiling correlations used in the present data analysis, the Mostinski and simplified Cooper correlations, do not have any factor for tube material. Yet the data of Conti (1978) for a stainless steel tube as well as many data sets for copper are equally well predicted.

Many other studies also show that tube material does not affect nucleate boiling and hence $F = 1$ should be used in the Cooper correlation, Eq. (7). For example, Shah (2007) compared pool boiling data for copper tubes from seven sources with the Cooper correlation. Six of these indicated $F \approx 1$, only one indicating high F. Gungor and Winterton (1986, 1987) and Liu and Winterton (1991) gave successful correlations for saturated boiling in tubes which were verified with extensive data that included data for copper tubes as well as many other tubes of other materials. They used the Cooper correlation with $F = 1$ for the nucleate boiling contribution for tubes of all materials. Thome (2009) also recommends use of $F = 1$. Hence while there are a very few cases in which $F > 1$ is needed, $F = 1$ is appropriate in most cases.

The conclusion is that the present correlation is applicable to tubes made of all common materials without any correction factors. Where Cooper correlation is used in the present correlation, it is in its simplified form, Eq. (8), for all tube materials.

5.6. Effect of tube roughness

It is interesting to look into the effect of roughness predicted by various correlations. Gorenflo et al. (2014) as well as Stephan and Abdelsalam (1980) state that roughness of most commercially manufactured tubes is around 1 μm. Hence roughness of tubes used in heat exchangers is unlikely to be outside the range of at most 0.5 to 2 μm. According to these two correlations, $h \, \alpha \, R_p{}^{0.133}$. Hence reducing R_p from 1 to 0.5 μm reduces h by about 9%. Increasing R_p from 1 to 2 μm increases h by about 11%. This much variation is within the usual margin of error in the measurement of heat transfer coefficients. In the Cooper correlation, effect of roughness on h also depends on reduced pressure. The predictions of the Cooper correlation at reduced pressures from 0.0006 to 0.1 are shown in Fig. 14 together with the predictions of Gorenflo et al. and Stephan-Abdelsalam correlations. At $p_r = 0.1$, the predictions of the Cooper correlation are close to those of the other two correlations. At $p_r = 0.0006$, it shows changes of −36 and +56% at roughness of 0.5 and 2 μm respectively from the heat transfer coefficient at roughness of 1 μm. The reduced pressures in the test data analyzed in the present study ranged from 0.00059 to 0.191. The actual roughness used in various studies is not known but they must have varied to some extent. As shown in Fig. 11 and discussed in Section 5.2, the deviations of the present correlation are not related to pressure. If there was as much effect of roughness as in the Cooper correlation, some effect of reduced pressure would have been noticeable in the results. It therefore appears that the large effect of roughness at low pressures in the Cooper correlation is not correct.

That the effect of surface roughness of commercial tubes is negligible is also shown by the fact that several well-verified correlations for saturated boiling in tubes have used the Cooper correlation assuming roughness is 1 μm. Among them are Gungor and Winterton (1986, 1987) and Liu and Winterton (1991). These correlations were verified with data from many sources that included tubes of many materials. Shah (2017) correlation for boiling in tube bundles also uses the Cooper correlation with $R_p = 1$ μm and gives good agreement with data for tubes of a variety of materials.

5.7. *Effect of oil in refrigeration systems*

Most refrigeration systems used compressors lubricated by oil. In such systems, oil is carried along with the refrigerant into the evaporator where it usually has significant effect on heat transfer. This topic is therefore briefly discussed.

Most halocarbon refrigerants are miscible with oil. In such evaporators, small amounts of oil usually increase heat transfer coefficient while large quantities cause deterioration. Moeykens et al. (1995) performed falling film evaporation tests on single tubes with R-134a containing 0 to 3% oil. Heat transfer coefficients with oil were up to three times those without oil. In a recent study by Li et al. (2021) on a bundle of plain tubes with falling films using R-134a, 5% oil caused up to 100% increase in heat transfer under some conditions compared to 0.5% oil content while in other conditions it was in the 20% range.

Oils used with ammonia can be miscible or immiscible. Zheng et al. (2001) studied effect of miscible oil during pool boiling of ammonia on a plain tube. Up to 30% decrease in heat transfer coefficient occurred by the addition of 1% oil. Tests on ammonia with immiscible oil boiling inside tubes have been reported by Shah (1975), Chaddock and Buzzard (1986) and Boyman et al. (2004). All reported very large decrease in heat transfer coefficients due to the presence of oil. Boyman et al. reported 50% decrease with only 0.2% oil content.

From the above discussion, the conclusion is that presence of oil in halocarbon refrigerants is likely to increase heat transfer. In ammonia systems, both miscible and immiscible oils reduce heat transfer and its effect must be considered in sizing ammonia evaporators. Effect of oil in refrigeration systems has recently been reviewed in Shah (2021).

6. Conclusions

(1) A new simple correlation has been presented for heat transfer to saturated pure fluids falling on single horizontal tubes.
(2) The new correlation was compared to data for 11 diverse fluids (water, ammonia, halocarbon refrigerants, hydrocarbons) from 22 sources. The data included tubes of diameter 12.7 to 50.8 mm made of a variety of materials, liquid Reynolds numbers 19 to 10,734, heat flux from 1 to 208 kWm^{-2}, and reduced pressures from 0.00059 to 0.19. The 1273 data points were predicted with mean absolute deviation of 17.4%,
(3) This new thoroughly verified correlation is likely to be useful in the design and analysis of falling film evaporators as other correlations have had very limited verification.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

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