

Determination of Limiting Heat Flux for The Inception of Nucleate Boiling Regime for Crude Oils

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ABSTRACT

Finding the limiting heat flux above which nucleate boiling starts and below which forced convective heat transfer exists is a crucial task for the accuracy of results from crude oil fouling tests. In this study, crude oils from two sources were tested at bulk temperatures of 100, 120 and 140 °C and different velocities. Heat transfer coefficient increased gradually with bulk temperature indicated lowering of the viscosity at high temperatures which promoted turbulence and enhanced heat transfer. The velocity effects were similar to that of bulk temperatures on maximum heat transfer coefficient while less heat flux was required to achieve the same surface temperature at lower velocities. Deshannavar and Ramasamy's model to predict maximum heat flux was compared with experimental results and a poor estimation was observed for the crude oils tested.

1. Introduction

Heat exchanger train plays an essential role in refineries by increasing the temperature of crude oil to meet the operational needs of refinery. The main problem of heat exchanger operation is the development of fouling layer on the surface of heat transfer, which decreases its thermal efficiency. Fouling has been considered as long-standing problem in refineries, waste water treatment [1] and dairy processing [2] plants and it has a high impact on the operational efficiency, economic growth, and environmental liability. Due to its complex nature, especially in refinery pre-heat trains, the fouling problem is still one of the main concerns in the research society which needs to be solved. Several studies have been done to study the fouling phenomenon on lab apparatus as well as actual heat exchanger trains in refineries. Generally, fouling takes place in forced convective regime in industrial heat exchangers.

Threshold fouling is a state of zero net fouling rate which could be achieved by manipulating the film temperature and bulk velocity. Several researchers developed semi-empirical and empirical models for predicting the threshold fouling conditions [3-8]. In many studies [6, 9-14], different

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experimental setups were employed to determine the fouling behavior of crude oils. As the foulant particles deposition is highly dependent upon fluid velocity [15] and temperature, most of the research studies are carried out at high heat flux and low velocities to induce fast development of the fouling layer in the laboratory apparatus. Sometimes the operational conditions are so escalated that the heat transfer process occurs beyond the forced convective regime. The nucleate boiling condition is described by the formation of small bubbles on heat transfer which leads to fluid mixing near the surface resulting in the increased heat transfer coefficient. This phenomenon can cause a false calculation of the fouling rate [16]. It is of high importance to maintain the fouling experiment in the operating conditions which do not lead to nucleate boiling and to estimate the maximum flux above which boiling starts. Several studies showed the occurrence of boiling during fouling experiments [17, 18]. Ishiyama and Pugh [19] analyzed the impact of boiling condition on the heat exchanger network. They showed that it adversely affected the performance of pump and heat exchangers and forced the pump to reach its hydraulic limits which caused low throughput and increased fouling. Harris [20] found that extra power and pressure were maintained at the boiling condition of light crude oil to achieve the same surface temperature condition when using heavier crude oil without boiling. These results suggested that flashing can reduce the boiling and fouling was achieved at lower wall temperatures. Deshannavar and Ramasamy [21] developed a model to predict the limiting heat flux above which nucleate boiling would be induced for some crude oils. They suggested that the maximum heat flux, q_{\max} , can be calculated by incorporating the temperature from the boiling point curve at 50 vol% cumulative recovery ($T_{bp0.5}$) in the convective heat transfer equation as shown below:

$$q_{\max} = h(T_{bp0.5} - T_b) \quad (1)$$

where T_b and h are bulk temperature of the fluid and heat transfer coefficient, respectively. They found that the Prandtl analogy showed better predictability for heat transfer coefficient with $\pm 12\%$ relative error. The relative percentage error for the maximum flux estimation from the model was $\pm 10\%$.

In this paper, we carried out a study to estimate the minimum heat flux above which nucleate boiling regime persists. Two types of crude oils having different densities at varying bulk temperatures and velocities were tested. The validation of Deshannavar and Ramasamy's model was carried out to show its predictability for the crude oils at varying operating conditions.

2. Methodology

2.1 Experimental Setup

A small-scale recirculation flow equipment with an annular flow was employed to conduct the experiments, as shown in Figure 1. The equipment is installed with a 60 L capacity feed tank fitted with three 5 kW external band heaters to achieve the desired bulk temperature. An internal heating coil is placed to maintain bulk temperature by circulating hot thermal oil. Fouling takes place at an annular test section which consists of fouling probe placed inside a pipe. FIREROD cartridge heaters are installed in the fouling probes. K-type thermocouples are used for the temperature measurement of heaters (T_h). A constant flow is maintained inside the annular section using PID controllers while PI controllers are used to control the heat flux.

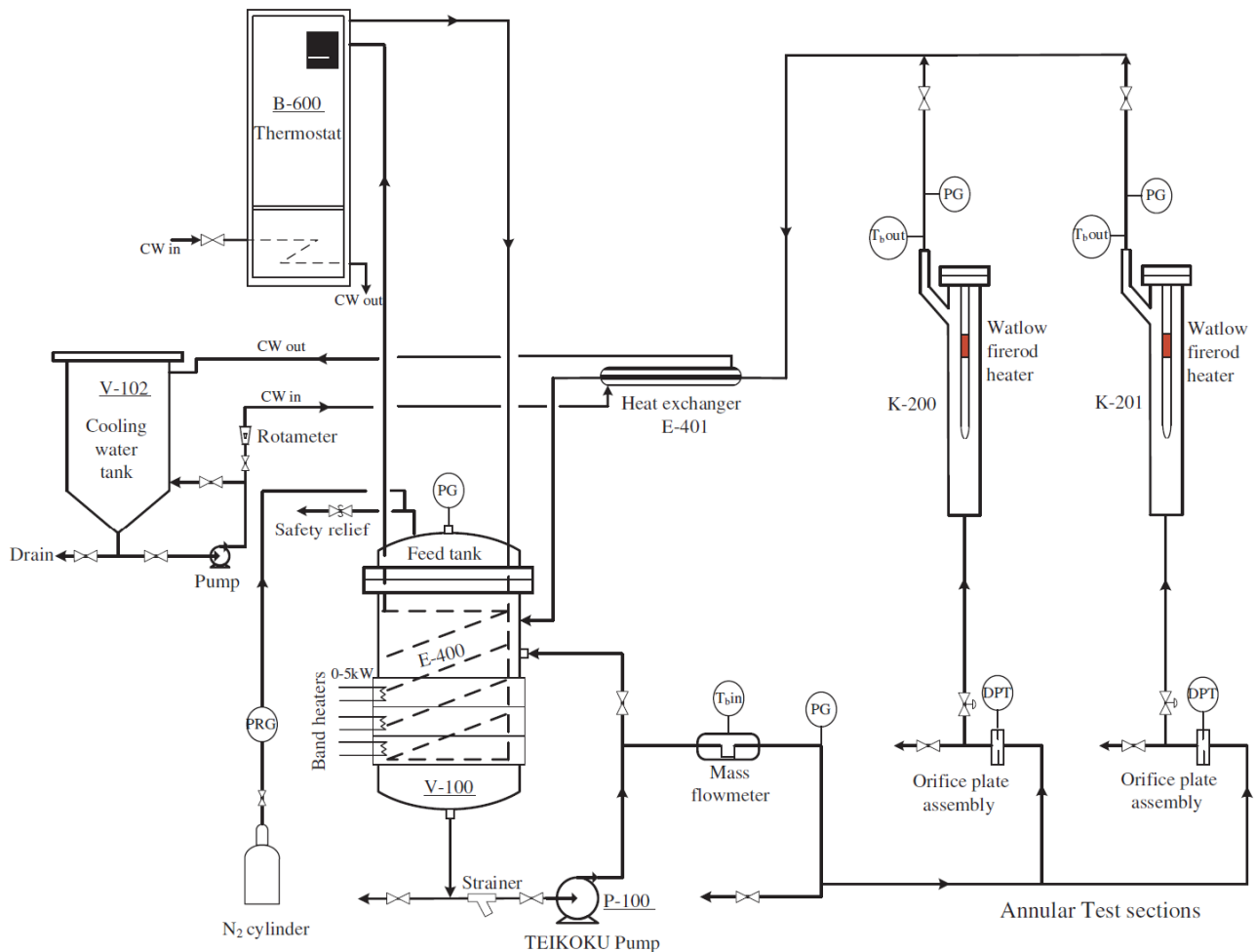


Fig. 1. Schematic of Annular Flow Fouling Research Unit (AFFRU)

2.2 Experimental Procedure

Experiments were performed at different bulk temperatures and velocities to develop a boiling curve. At first, the feed tank is filled with crude oil and pressurized up to 50 bar using nitrogen gas. The desired temperature is achieved by circulating the thermal oil in the heating coils and band heaters. After maintaining the velocity and bulk temperatures at a desired value, the test section was heated at constant heat flux using cartridge heaters. The heat flux, q , is gradually increased, and corresponding heater temperatures, T_h , are noted when the values are stable for each power output. To determine the surface temperature the value of thermal wall resistance, R_w , is estimated using the Wilson plot. The Wilson was developed by plotting the inverse value of heat transfer coefficient, h , against $v^{-0.8}$ which led to the formation of straight line. The y-intercept is read from the plot which represents the value of R_w . A linear relationship was found between R_w and T_h which can be expressed as

$$R_w = a + bT_h \quad (2)$$

The values of the constants a and b are shown in Table 1.

Table 1
 Values of constants used in Equation 2

Thermocouples	a	b
1	0.34	0.0014
2	0.29	0.0014

The values of R_w for thermocouples 1 and 2 at $T_h = 250\text{ }^\circ\text{C}$ is $0.685\text{ m}^2\cdot\text{K}/\text{kW}$ and $0.639\text{ m}^2\cdot\text{K}/\text{kW}$, respectively. The surface temperature, T_s , for each corresponding value of T_h was calculated using the following equation

$$T_s = T_h - (R_w \times q) \tag{3}$$

The boiling curves were obtained by plotting the difference of surface and bulk temperatures, $(T_s - T_b)$, vs. heat flux, q and heat transfer coefficient, h . The values of q_{\max} were read from q vs $(T_s - T_b)$ graphs.

2.3 Crude Oil Properties

The properties of crude oils, referred here as crude oil A and B, are presented in Table 2.

Table 2
 Assay of the crude oils

Properties	Units	Crude Oils	
		A	B
Asphaltenes content	%mass	0.0011	1.4313
API gravity	degrees	37.9	32.7
Viscosity @ 40°C	cSt	2.496	4.901
Total sulphur	wt%	0.0621	1.9117
Sodium (Na)	ppm	1.73	0.650
Vanadium (V)	ppm	0.27	15.441
Mercury (Hg)	ppb	9.77	2.52
Nickel (Ni)	ppm	0.32	4.265
Iron (Fe)	ppm	-	1.355
Copper (Cu)	ppm	-	0.112

3. Results

3.1 Crude Oil A

3.1.1 Effect of bulk temperature

Boiling curves were developed for crude oil A to find the minimum heat flux required to induced nucleate boiling at different bulk temperatures. The surface temperatures, T_s , were estimated for corresponding heater temperatures, T_h at different values of heat flux. The heat flux, q , was plotted against the difference between surface and bulk temperatures, $(T_s - T_b)$, at 100, 120 & 140 °C of bulk temperature and 0.4 m/s of velocity as shown in Figure 2. The $T_s - T_b$ value increased linearly with the heat flux, q , up to threshold values of 99.6, 87.6 & 70.57 °C at bulk temperatures of 100, 120 & 140 °C, respectively. After the threshold limit, the $(T_s - T_b)$ value became independent of the heat flux.

The heat transfer coefficient was estimated using the experimental data and a graph was developed by plotting against $(T_s - T_b)$ as depicted in Figure 3. Initially, the heat transfer coefficient increased gradually which indicated lowering of the viscosity at high temperatures which promoted turbulence and enhanced heat transfer. Beyond the threshold limit the slope suddenly became very

steeper which represented the inception of nucleate boiling. the heat flux at threshold points were found to be 75.1, 76.4, and 65.4 kW/m² for bulk temperatures of 100, 120, and 140 °C, respectively.

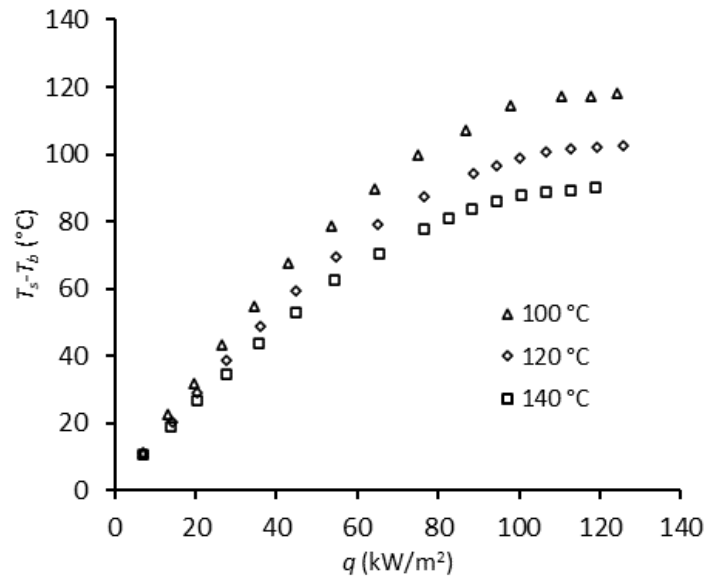


Fig. 2. Boiling curve to determine q_{max} and $(T_s - T_b)_{max}$ at different bulk temperatures for crude oil A at velocity of 0.4 m/s and pressure of 50 bar

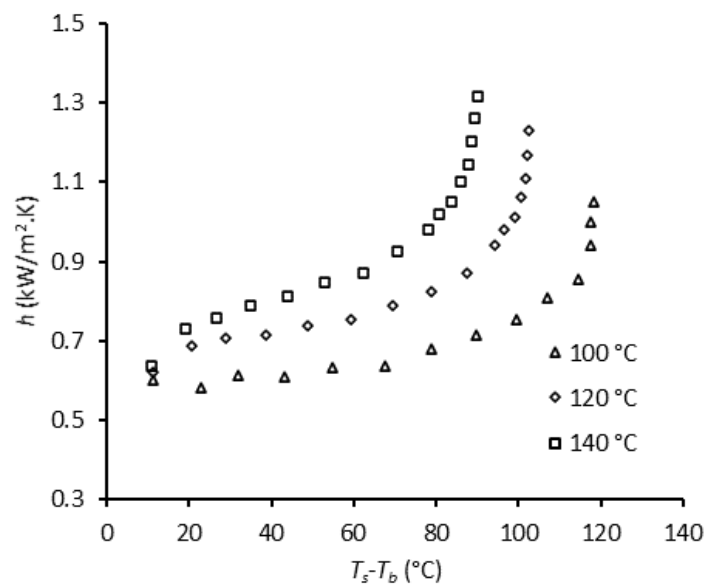


Fig. 3. Boiling curve to determine h_{max} at different bulk temperatures for crude oil A at velocity of 0.4 m/s and pressure of 50 bar

3.1.2 Effect of velocity

To determine the effect of velocity on the threshold values of heat flux, boiling curves were compared at different velocities with same bulk temperature of 100 °C as shown in Figure 4 and 5. The heat transfer coefficient gently increased in the region before the inception of nucleate boiling, as shown in Figure 4, which showed the effect of lowering viscosity and improved heat transfer. The threshold points were determined at graph with values of 99.6, 97.5, 92.7, and 89 °C ($T_s - T_b$) at 0.4,

0.5, 0.6, and 0.7 m/s of velocities, respectively. The point of drastic change in the slope depicted the onset of nucleate boiling. The corresponding values for heat flux were determined in Figure 5. A notable increase in values of h_{\max} and q_{\max} can be seen with increasing velocities [22].

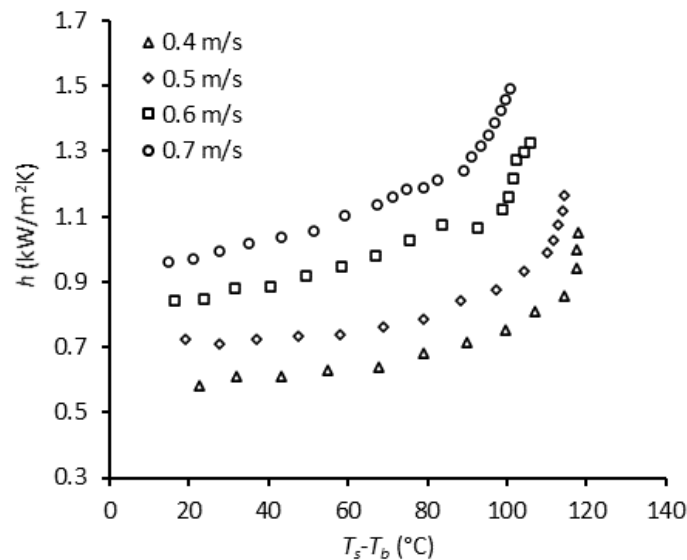


Fig. 4. Velocity effect on h_{\max} for crude oil A at bulk temperature of 100 °C and pressure of 50 bar

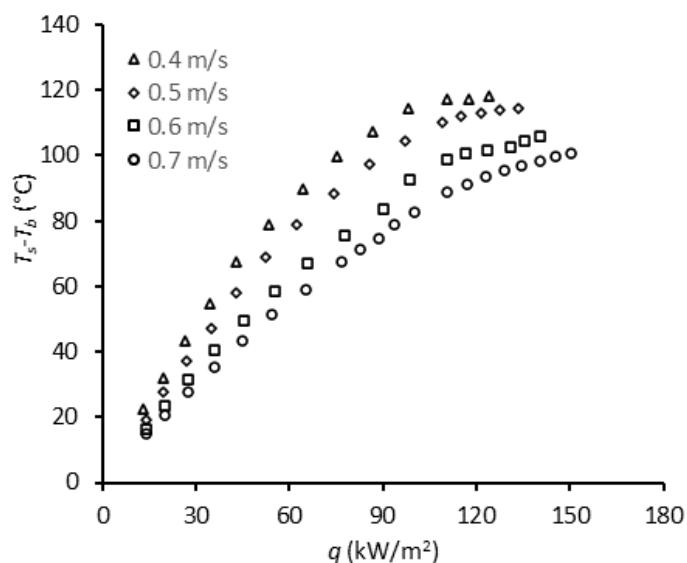


Fig. 5. Velocity effect on q_{\max} and $(T_s - T_b)_{\max}$ for crude oil A at bulk temperature of 100 °C and pressure of 50 bar

3.2 Crude oil B

3.2.1 Effect of bulk temperatures

Figure 6 and 7 show the boiling curves of crude oil B at 0.6 m/s of velocity and 100, 120 and 140 °C of bulk temperatures. The slope is suddenly increased after the inception of nucleate boiling. The forced convective regime was ceased to exist beyond the limiting values of $(T_s - T_b)$ which were found to be 117.4, 107.6, and 80.3 °C at bulk temperatures of 100, 120, and 140 °C, respectively. The corresponding values of maximum heat flux are shown in Table 3.

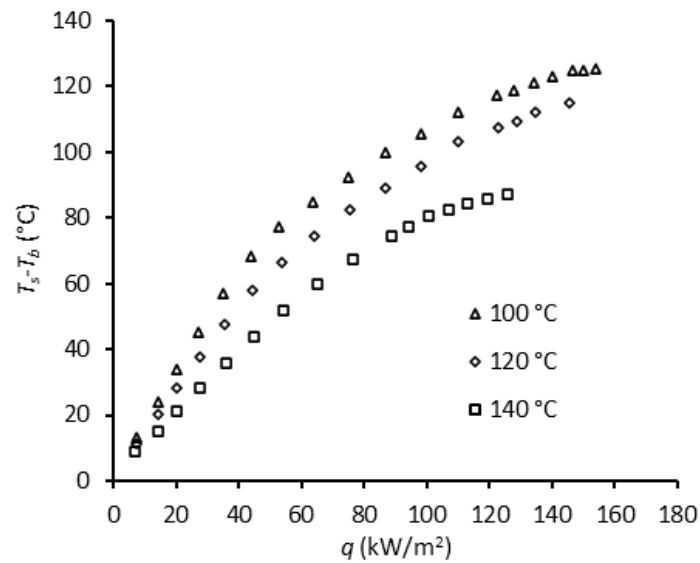


Fig. 6. Boiling curve to determine q_{max} and $(T_s-T_b)_{max}$ at different bulk temperatures for crude oil B at velocity of 0.6 m/s and pressure of 50 bar

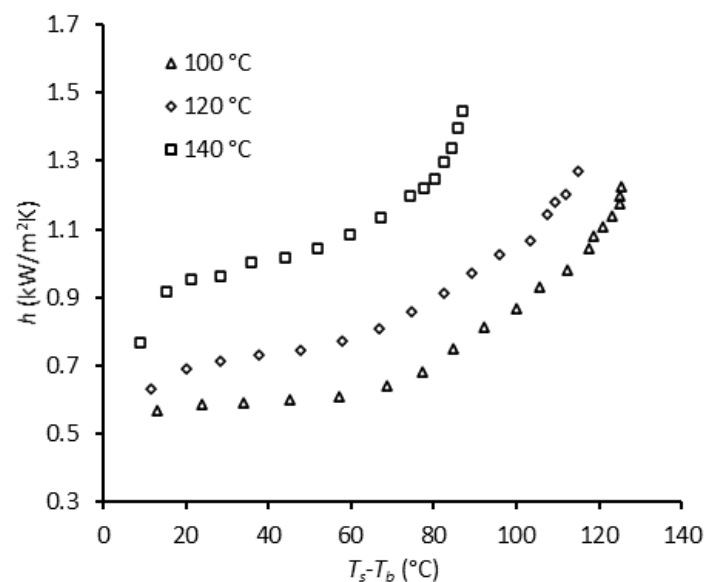


Fig. 7. Boiling curve to determine h_{max} at different bulk temperatures for crude oil B at velocity of 0.6 m/s and pressure of 50 bar

3.2.2 Effect of velocity

The effect of velocity on the inception point of nucleate boiling for crude oil B was determined through boiling curves which were developed at different velocities such as 0.4, 0.5, 0.6, and 0.7 m/s and bulk temperature of 120 °C as shown in Figure 8 and 9. The limiting values of (T_s-T_b) were found to be 130.3, 131.3, 107.6, and 100.3 °C at 0.4, 0.5, 0.6, and 0.7 m/s of bulk velocities, respectively. The corresponding threshold values of heat flux were also determined from Figure 9.

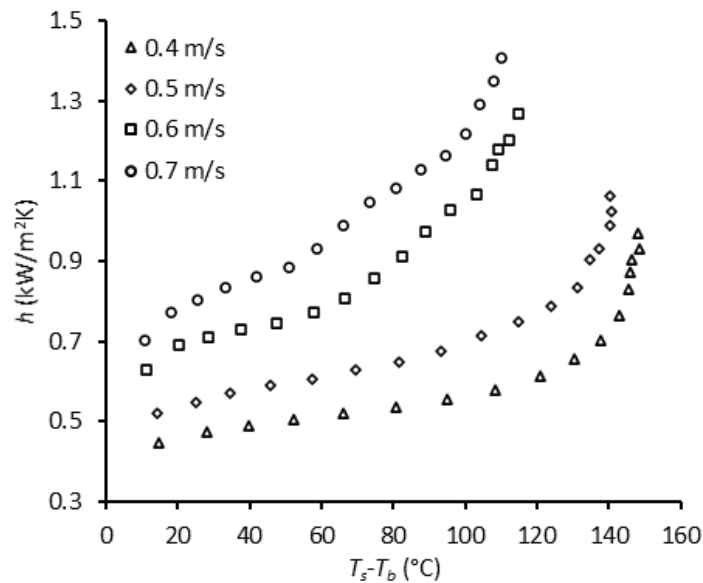


Fig. 8. Velocity effect on h_{max} for crude oil B at bulk temperature of 120 °C and pressure of 50 bar

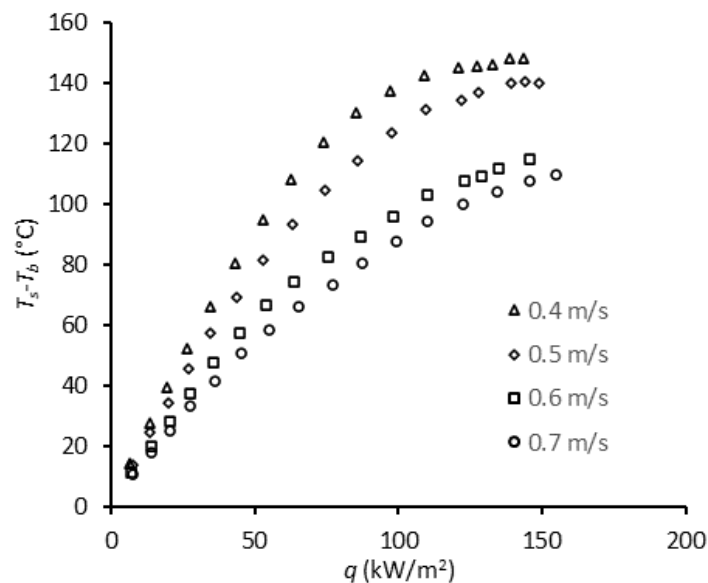


Fig. 9. Velocity effect on q_{max} and $(T_s - T_b)_{max}$ for crude oil B at $T_b = 120$ °C and $P = 50$ bar

4. Discussion on Boiling Curves

The boiling curves developed consist of two distinct regions i.e., forced convective and nucleate boiling regimes. In the first phase of forced convective heat transfer, the graphs of boiling curves showed a linear rise in $(T_s - T_b)$ with the heat flux. Similarly, the heat transfer coefficient was slightly increased with the heat flux which indicated the viscosity decline and increased turbulence resulted in improved heat transfer. The same phenomenon was elucidated by the rise in heat transfer coefficient with bulk temperatures. After the onset of nucleate boiling, the energy transferred did not contributed in the temperature rise which was depicted by the straight line in q vs. $(T_s - T_b)$ graph.

The inception of nucleate boiling can also be related with the exponential increase of the heat transfer coefficient. The values of $(T_s - T_b)_{max}$, q_{max} , and h_{max} for all the runs below which forced convective heat transfer persisted for both crude oil A and B are presented in Table 3.

Table 3
 Maximum heat flux, heat transfer coefficients under forced convective heat transfer

Run no.	Crude Oils	T_b (°C)	v (m/s)	q_{max} (kW/m ²)	h_{max} (kW/m ² .K)	$(T_s-T_b)_{max}$ (°C)	$T_{s,max}$ (°C)
1	A	100	0.4	75.1	0.754	99.6	199.6
2		100	0.5	85.4	0.8757	97.5	197.5
3		100	0.6	98.7	1.12	92.7	192.7
4		100	0.7	110.3	1.24	89	189
5		120	0.4	76.4	0.872	87.6	207.6
6		120	0.5	76.8	0.996	77	197
7		120	0.6	76.4	1.13	67.3	187.3
8		120	0.7	106	1.32	80.4	200.4
9		140	0.4	65.4	0.926	70.6	210.6
10		140	0.5	76.8	0.996	77	217
11		140	0.6	76.4	1.13	67.3	207.3
12		140	0.7	106	1.32	80.4	220.4
13	B	100	0.4	99.2	0.66	150.3	250.3
14		100	0.5	110	0.8	137.6	237.6
15		100	0.6	122.3	1.04	117.4	217.4
16		100	0.7	133.6	1.2	110	210
17		120	0.4	85.5	0.656	130	250
18		120	0.5	109.4	0.833	131.3	251.3
19		120	0.6	122.8	1.14	107.6	227.6
20		120	0.7	122.3	1.22	100.3	220.3
21		140	0.4	76.4	0.98	78	218
22		140	0.5	88.8	1.06	83.8	223.8
23		140	0.6	100.4	1.25	80.3	220.3
24		140	0.7	111.4	1.345	82.8	222.8

5. Prediction of Maximum Heat Flux

The temperature values at 50 cumulative percentage of volume recovered were determined from the true boiling point distillation curves are 260 °C for crude oil A and 320 °C for crude oil B. Heat transfer coefficients were determined using various equations such as Prandtl analogy (h_{PA}), Dittus-Boelter (h_{DB}), Sieder and Tate (h_{ST}), Wiegand (h_{WE}), and Gnielinski (h_{GE}) correlations. The correlations are presented as follows

Prandtl analogy

$$St = \frac{\frac{f}{2}}{1 + 5\sqrt{\frac{f}{2}}(Pr - 1)} \tag{4}$$

Dittus-Boelter equation

$$Nu = 0.023Re^{0.8}Pr^{0.4} \tag{5}$$

Sieder and Tate equation

$$Nu = 0.027Re^{0.8}Pr^{\frac{1}{3}}\left(\frac{\mu}{\mu_w}\right)^{0.14} \quad (6)$$

Wiegand correlation

$$Nu = 0.023a^{0.45}Re^{0.8}Pr^{\frac{1}{3}}\left(\frac{\mu}{\mu_w}\right)^{0.14} \quad (7)$$

Gnielinski correlation

$$Nu = \frac{\left(\frac{f}{8}\right)(Re1000)Pr}{1 + 12.7\left(\frac{f}{8}\right)^{\frac{1}{2}}\left(Pr^{\frac{2}{3}} - 1\right)} \quad (8)$$

where St , Nu , Pr , and Re represent Stanton, Nusselt, Prandtl, and Reynolds numbers, respectively. Additionally, a represents the annular diameter ratio and the friction factor (f) was estimated using the following equation as

$$f = \frac{0.25}{\left[\log\left(\frac{1}{3.7\left(\frac{De}{\epsilon}\right)} + \frac{5.74}{Re^{0.9}}\right)\right]^2} \quad (9)$$

where De and ϵ are effective diameter and pip roughness.

The maximum heat transfer coefficients were estimated using the above correlations. The sum of squares errors (SSE) for h_{DB} , h_{ST} , h_{GE} , and h_{WE} were found to be 0.38, 0.23, 0.18, and 0.29, respectively. The best predictions were made by Gnielinski correlation as can be seen in Figure 10. Although Deshannavar and Ramasamy [21] suggested the Prandtl analogy to be more accurate to predict the heat transfer coefficient, it showed highest errors in present study.

The theoretical maximum flux was estimated using heat transfer coefficients predicted by Gnielinski correlation as shown below

$$q_{max} = h_{GE}(T_{bp0.5} - T_b) \quad (10)$$

The estimated theoretical and experimental q_{max} are compared in Figure 11. The relative error values range from 31 to 115 %. Hence, the model needs to be updated to predict the maximum heat flux.

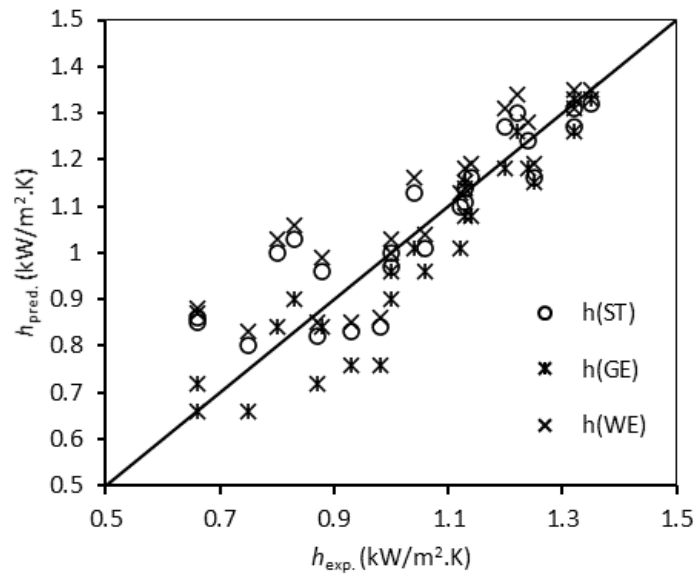


Fig. 10. Comparison of theoretical and experimental heat transfer coefficients, $\text{kW/m}^2\cdot\text{K}$

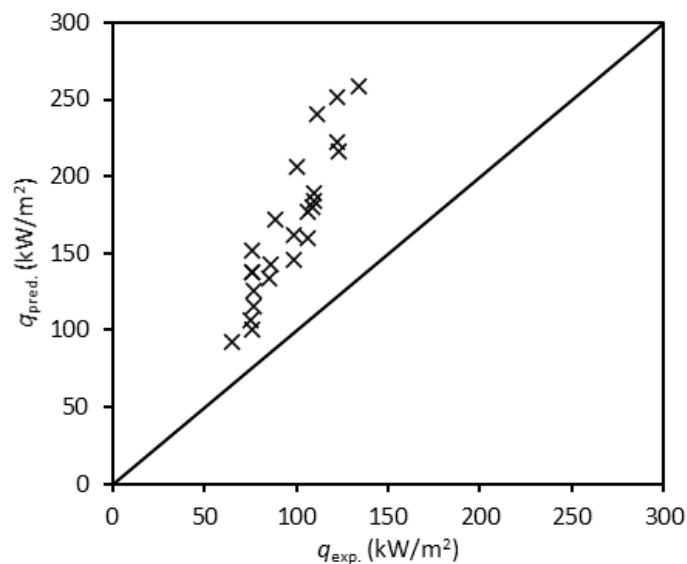


Fig. 11. Comparison of theoretical and experimental maximum heat flux (q_{max}), kW/m^2

6. Conclusions

The accuracy of fouling experimental results highly depends on the heat transfer regime. Boiling can contribute to significant errors in the estimation fouling rate. In order to carry out the fouling experiments, it is highly recommended to predetermine the maximum heat flux below which forced convective regime exists. In this study, two crude oils were tested for maximum heat flux in forced convective regimes at different operating conditions. The results suggest that the maximum heat transfer coefficient increased with increasing bulk temperature which indicate a decrease in crude oil viscosity as temperature rises and an increase in turbulence which promoted heat transfer. The velocity effects were similar to bulk temperature effects as increasing both led to the increased requirement of heat flux for similar surface temperatures. The model was found to be inadequate to

predict maximum heat flux specially for the crude oils studied. It is concluded that the study to find the maximum heat flux should essentially be carried out through experiments.

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