Application of Threshold Model with Various Tube Wall Temperatures for Crude Oil Preheat Train Fouling

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ABSTRACT: *The Propose of this paper is to introduce a new model for crude oil fouling in preheat trains of crude distillation unit. The experimental results of Australian light crude oil with the tube side surface temperatures between 200-260 ^oC and fluid velocity ranged 0.25 to 0.4m/s were used. The activation energy of chemical reaction depends on the surface temperature has been calculated. The model includes two parts. In the first part it deals with a term for fouling formation and the second part with a term for fouling removal due to chemical and tube wall shear stress respectively. By using the proposed model for Australian crude oil based on Saleh et.al.data the fouling formation rate has been calculated and the threshold curves to identify fouling and no fouling formation zones have been drawn. Finally, a model was developed for various temperatures and shows better results in relation to available models.*

KEY WORDS: *Heat exchanger, Fouling, Modeling, Crude oil, Distillation unit.*

INTRODUCTION

Fouling formation in preheat exchangers of a crude distillation unit (CDU) is identified as a main energy consuming unit in petroleum refineries. Almost half of the overall operational cost of the refineries is due to the energy losses due to fouling formation in the preheat exchangers [1]. As a matter of fact, it is recognized that the main parameter in fouling of CDU is the wall temperature so that for example by increasing the tube wall temperature, chance for asphaltene deposition increases. Furthermore, the presence of some impurities in crude oil such as metals and metal oxides also accelerates the fouling rate [2].

To predict the fouling rate it is necessary to relate the fouling rate to the wall temperature. Therefore, in proposed models the Arrhenius relation is commonly used.

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Crude Oil Fouling Models

A large number of models for crude oil fouling have been presented [3]. However they are not able to predict the fouling formation under changing operating conditions and differing crude types. Some models are only able to predict fouling without considering the effect of fluid velocity on the fouling removal. For example, *Saleh et al.* proposed a model as follow [4]:

$$\frac{dR_f}{dt} = \alpha P^{\beta} u^{\gamma} \exp(\frac{-E}{RT_f}) \tag{1}$$

and in 1995, *Ebert* and *Pancha* [5] proposed threshold model for crude oil fouling formation as follow:

$$\frac{dR_f}{dt} = \alpha \, Re^{\beta} \exp(\frac{-E}{RT_f}) - \gamma\tau_w \tag{2}$$

where:

$\beta = -0.88$

$E = 68kJ / mol$

$\alpha = 8.39m^2K / J$

$\gamma = 4.03\times10^{-11}(m^2 / N)(m^2K / J)$

and;

$$\tau_w = \frac{f}{2}\rho u^2 \tag{3}$$

In equation (2) the first statement shows that the fouling formation depends on chemical reaction and film temperature. The second statement also shows that the fouling removal depends on tube wall shear stress or tube side fluid velocity. This means that as the velocity increases the rate of fouling formation decreases. Typical relationships can be given by the following equations according to flow regimes. For example, for laminar flow regime f can be define [6]:

$$f = \frac{16}{Re} \tag{4}$$

and in turbulent flow[6]:

$$f = 0.0035 + \frac{0.264}{Re^{0.42}} \tag{5}$$

Ebert and *Panchal* threshold model was improved by *Polley et al*. [5]. Their model is required the tube wall temperature in the fouling formation statement as follows:

Table1: Physical properties of Australian light crude oil [4].

Density (g/ml)	0.792
Viscosity (mpa.s)	1.969
Asphaltenes (w%)	<0.01

$$\frac{dR_f}{dt} = \alpha Re^{-0.8} Pr^{-0.33} \exp(\frac{-E}{RT_w}) - \gamma Re^{0.8} \tag{6}$$

where;

$\alpha = 1{,}000{,}000(m^2Kw^{-1}h^{-1})$

$\gamma = 1.5\times10^9 (m^2Kw^{-1}h^{-1})$

$E = 48(KJmol^{-1})$

The model is developed and justified based on *Knudsen's* experimental results [7]. It should be mentioned that to extend the model for the other type of crude oil the constant values have to be re-calculated correspondingly.

The Proposed Model

To propose a new model the experimental results reported by *Saleh et al.* were used [4]. The properties of crude oil that they used are mentioned in table 1.

Table 2 shows the conditions of the experimental tests and also the fouling rate which has been calculated in their report curves [4].

The new model can be proposed by the following equation:

$$\frac{dR_f}{dt} = \alpha \, Re^{\beta} \exp(\frac{-E}{RT_f}) - \gamma \, Re^{0.4} \tag{7}$$

In this equation E(J/mol) is activation energy. To calculate activation energy, fouling rate in terms of inverse of film temperature should be drawn and the slope of this curve gives the activation energy. The difference between *Polley* and is that the model the proposed model do not show any sever dependency to Pr number and this is due to this fact that the heat capacity and thermal conductivity of crude do not show much differences. However, the amounts of viscosity for various crude are very different and reveal it has a strong impact on the model. The viscosity term is included in Re number. Film temperature is defined by the following equation [2]:

$$T_f = T_b + 0.55(T_s - T_b) \tag{8}$$

Table 2: Experimental condition and the fouling rate of Australian light crude oil [4].

Inlet Bulk Temperature(°C)	Surface Temperature(°C)	Velocity(m/s)	Pressure(kPa)	Fouling Rate(m^2K/kJ) × 10^6	Run No
80	180	0.2500	379	0.2003	1
80	200	0.2500	379	0.2872	2
80	220	0.2500	379	0.3989	3
80	240	0.2500	379	0.4797	4
80	260	0.2500	379	0.4795	5
80	245	0.2500	379	0.4806	6
80	245	0.2500	510	0.4592	7
80	245	0.2500	655	0.5361	8
80	245	0.3500	379	0.2847	9
100	245	0.3500	379	0.2911	10
120	245	0.3500	379	0.5199	11
80	245	0.2500	379	0.5004	12
80	245	0.3000	379	0.3496	13
80	245	0.3500	379	0.2661	14
80	245	0.4000	379	0.2351	15

Table 3: The fouling model constants.

Model	Polley	Ebert	Saleh	Proposed Model
E(J/mol)	22618	22618	22618	22618
α	10^{-13} × 0.1639	6019812	10^{-5} × 1.07	10.98
β	-0.8	-3.48	0.4788	-1.5472
γ	10^{-9} × -0.77620	10^{-6} × -0.338	-0.0228	10^{-10} × 0.96

and by drawing $\ln(dR_f / dt)$ versus $1/T_f$, E(J/mol) is obtained (Fig. 1). For Australian light crude oil the following constants were used in the proposed model:

$$\alpha = 10.98(m^2K/kJ)$$

$$\beta = -1.547$$

$$\gamma = 0.96\times10^{-10}(m^2/N)(m^2K/J)$$

$$E = 22.618(kJ/mol)$$

Evaluation of the Proposed Model

For comparing the proposed models, the constants of models should be calculated based on the experimental results. Therefore, all the constants of the models, except *Polley's* model, is calculated. To calculate the constants in *Polley's* model, the same one has been introduced by ESDU software, can be used. Table 3 shows these constants. Table 4 shows the errors in different models in comparison with the experimental results. In this table summation of square of errors $\sum_{j=1}^{n}\left(\frac{dR_{f,exp}(j)}{dt}-\frac{dR_{f,Th}(j)}{dt}\right)^2$ in *Polley, Ebert, Saleh* models and the proposed model are calculated. As shown in table 4 and 5 the deviation of the proposed model from the experimental results is lower than others. Fig. 2 compares the fouling rate which are calculated from the proposed model based on Australian crude oil fouling data. The proposed model results in a fair agreement with the experimental data.

Polley et al. have compared their model with *Knudsen* [7], *Scarborough* [8], *Shell Wood River* [9] and *Shell Westhollow* [9] Crudes. The specification of crudes can be found in reference [2]. The proposed model is compared to *Polley's et al.* model. It is necessary to obtain model constants for each experimental data.

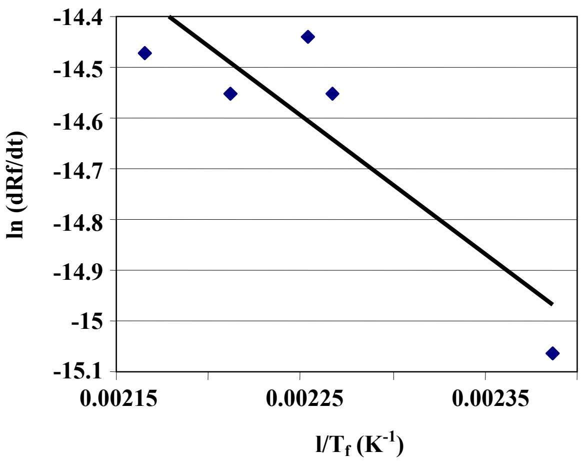

Fig. 1: Calculation of activation energy using the film temperature and the fouling rate.

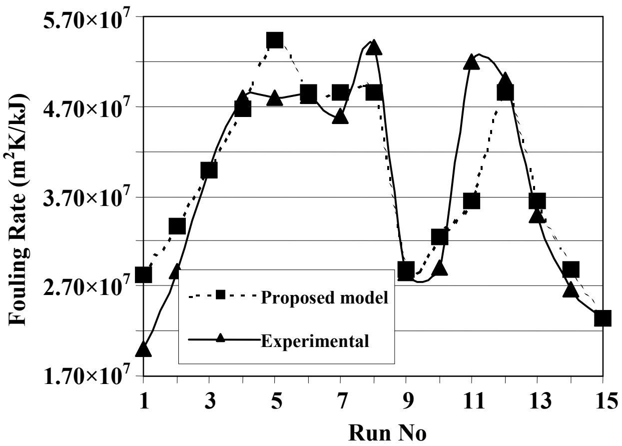

Fig. 2: Comparison of fouling rate of the proposed model and experimental results of Australian crude oil.

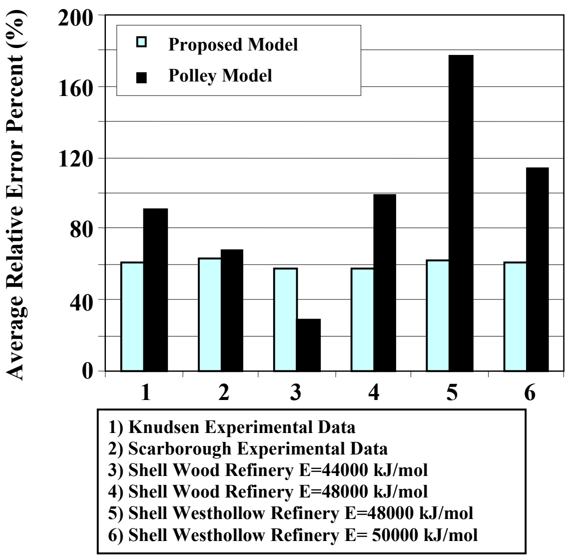

Fig. 3: Comparison of Polley and the proposed models with experimental data.

Tables 6-9 show that the proposed model predicts the fouling rate better than *Polley's et al.* model. The summary of this comparison can be seen in Fig. 3.

Threshold Curves for Prediction of Australian Light Crude Oil Fouling

The proposed model is employed to predict Australian light crude oil. Using the proposed model the fouling threshold curves can be drawn. Threshold curves areplotted versus velocity and tube wall shear stress. To calculate the tube wall shear stress the flow regime has to be identified primarily. Figs. 4, 5 show threshold curves for Australian light crude oil. In these figures there is no fouling phenoena in the areas which are located below the threshold curve, however, there is fouling in the areas above the threshold curves conversely. Threshold curve reveals that by increasing the film temperature, a heat exchanger can be located in fouling zone area or by increasing the fluid velocity the heat exchanger can be expelled from fouling zone and locate in no fouling zone area.

Developing proposed model for different temperature

One of the lack of previous models is that their model was used for long range of temperature. Therefore the error between experimental and theoretical results are very big. In this work the model was developed for different range of temperature. Table 10 shows the model constants for different temperatures. In this table activation energy as the other authors have also mentioned for temperatures above 250^{o}C was assumed to be E=48 kJ/mol [3]. By the constants in table 10 proposed model was compared by polley model for various temperatures. Tables 11-13 show remarkable results and said that proposed model have better results and lower error from experimental data rather than *Polley* model which were mentioned in reference [2]. These results show that this is very useful to divide models for different temperatures. Also these tables show that the proposed model in different temperatures has better performance in relation to *Polley* model. For better comparison the results in tables 11-13 were drawn in Figs. 6-8.

CONCLUSIONS

It is revealed that among the models that predict the fouling formation, one considered that the formation and

Table 4: Summation of square errors of models.

Model	Polley	Ebert	Saleh	Proposed Model
Summation of squares of errors	1.0560×10^{-11}	7.5544×10^{-14}	1.2869×10^{-13}	4.2769×10^{-14}

Table 5: Relative errors of the models for Australian experimental data.

Run No	Polley	Ebert	Saleh	Proposed Model
1	3.2256	67.1822	20.3184	41.3818
2	28.0216	30.5786	0.0529	17.5487
3	48.1715	5.3694	15.0292	0.0060
4	56.9046	1.8476	17.2692	2.5745
5	56.8847	9.8957	3.8237	13.3121
6	56.9794	0.7903	14.1942	1.0593
7	54.9754	5.4853	3.5194	5.7669
8	61.4375	9.6543	0.0531	9.4131
9	4.9611	0.3934	44.8234	1.0452
10	7.0380	3.1610	60.0182	11.7267
11	47.9538	39.2356	0.7202	29.6330
12	58.6891	3.2154	17.6044	2.9570
13	31.5859	2.7188	17.9344	4.6156
14	1.6899	7.4192	54.9584	8.1166
15	28.0839	14.5599	75.4035	0.6454

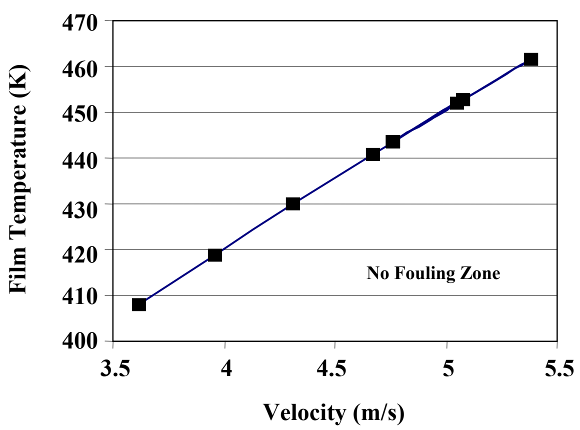

Fig. 4: Threshold curve for Australian light crude oil with respect to tube side fluid velocity.

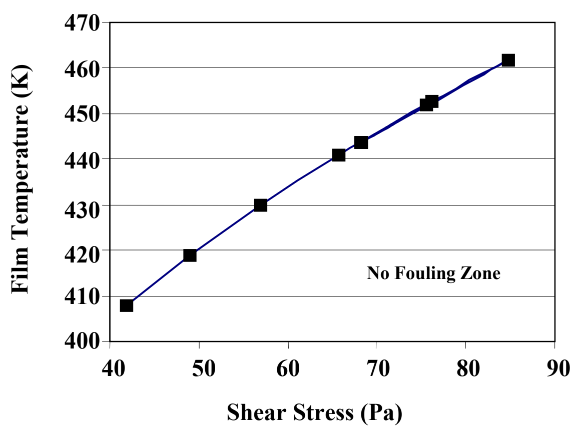

Fig. 5: Threshold curve for Australian light crude oil with respect to tube wall shear stress.

Table 6: Comparison between Polley and the proposed model for Scarborough et al. data[2,8].

Velocity (m/s)	T_S (°C)	T_b (°C)	Measured rate ($m^2KkW^{-1}h^{-1}$) ×10^6	Polley's model ($m^2KkW^{-1}h^{-1}$) ×10^6	The Proposed model ($m^2KkW^{-1}h^{-1}$) ×10^6	Relative error percentage for the proposed model	Relative error percentage for Polley's model
2.48	414	363	3.2	4	1.2930	59.5891	25.0000
1.25	467	371	20.1	37.3	2.2420	88.8468	85.5721
2.48	397	351	2.8	1.6	1.2600	55.0124	42.8571
1.25	432	360	11.4	23.9	1.9380	83.0013	109.6491
1.25	401	353	7.9	14.8	1.7310	78.0922	87.3418
1.29	374	344	5.6	8.4	1.5230	72.8101	50.0000
2.53	404	353	4	2.2	1.2710	68.2209	45.0000
2.53	376	345	1.2	0	1.2310	2.6036	100.0000
					Average relative error percentage	**63.5221**	**68.1775**

Table7: Comparison between Polley and the proposed model for Knudsen et al. data[2,7].

Velocity (m/s)	T_S (°C)	Measured rate ($m^2KkW^{-1}h^{-1}$) ×10^6	Polley model ($m^2KkW^{-1}h^{-1}$) ×10^6	Proposed model ($m^2KkW^{-1}h^{-1}$) ×10^6	Relative error percent for proposed model	Relative error percent for Polley model
0.91	232	7	0.9	1.8530	73.5247	87.1429
0.91	246	25	2	1.9270	92.2919	92.0000
0.91	260	5	3.4	2.0110	59.7894	32.0000
0.91	261	2	3.5	2.0170	0.8437	75.0000
0.91	288	2	7.4	2.2080	10.3842	270.0000
0.91	316	6	13.5	2.4480	59.2042	125.0000
0.91	343	9	21.9	2.7240	69.7294	143.3333
0.91	371	37	34	3.0640	91.7187	8.1081
1.68	260	0	0	0.9850	-	-
1.68	288	21	2.3	1.0470	95.0151	89.0476
1.68	302	3	4	1.0810	63.9823	33.3333
1.68	316	1.1	6	1.1160	1.4651	445.4545
1.68	343	7	11.2	1.1910	82.9899	60.0000
1.68	371	26	18.6	1.2780	95.0860	28.4615
2.44	315	1.5	2.2	0.9810	34.5992	46.6667
2.44	316	2.7	2.3	0.9830	63.6080	14.8148
2.44	316	1.2	2.3	0.9830	18.1181	91.6667
2.44	316	5	2.3	0.9830	80.3483	54.0000
2.44	343	5	6.2	1.0260	79.4847	24.0000
2.44	371	72.5	11.7	1.0730	98.5205	83.8621
3.05	316	0.5	0.23	0.9910	98.1659	54.0000
3.05	329	1	1.6	1.0080	0.8039	60.0000
				Average relative error percentage	60.4606	91.3282

Table 8: Comparison between Polley and the proposed model for Shell Wood River refinery data[2,9].

Velocity (m/s)	T_S (°C)	T_b (°C)	Measured fouling rate $\times 10^6$	Polley model fouling rate $\times 10^6$ E=44000	Polley model fouling rate $\times 10^6$ E=48000	Proposed model fouling rate $\times 10^6$ E=44000	Proposed model fouling rate $\times 10^6$ E=48000	Relative error percent for proposed model E=44000	Relative error percent for proposed model E=48000	Relative error percent for Polley model E=44000	Relative error percent for Polley model E=48000
1.15	260	230	0	0	0.03	0.9340	0.9270	-	-	-	-
0.95	255	230	0	0	0	0.9550	0.9460	-	-	-	-
1.16	260	220	0.5	0	0.3	0.9220	0.9150	84.3466	40.0000	40.0000	100
0.98	255	220	1.1	0	1.2	0.9340	0.9240	15.0811	9.0909	9.0909	100
1.16	270	227	0.8	0	1.2	0.9450	0.9390	18.0742	50.0000	50.0000	100
1.16	288	223	5.6	0	3.8	0.9660	0.9610	82.7487	32.1429	32.1429	100
0.98	295	223	8.1	0.35	7.1	1.0050	1.0000	87.5945	12.3457	12.3457	95.6790
							Average relative error percent	57.5690	57.3449	28.7159	99.1358

Table 9: Comparison between Polley and the proposed model for Shell Westhollow refinery data[2].

Velocity (m/s)	T_S (°C)	T_b (°C)	Measured fouling rate $\times 10^6$	Polley model fouling rate $\times 10^6$ E=48000	Polley model fouling rate $\times 10^6$ E=50000	Proposed model fouling rate $\times 10^6$ E=48000	Proposed model fouling rate $\times 10^6$ E=50000	Relative error percent for proposed model E=48000	Relative error percent for proposed model E=50000	Relative error percent for Polley model E=48000	Relative error percent for Polley model E=50000
1.77	344	288	2.6	14.4	8.8	3.2220	3.3590	23.9230	29.1810	453.8462	238.4615
1.77	393	288	7.9	31.6	21.1	4.0270	4.2590	49.0307	46.0929	300.0000	167.0886
2.13	349	284	3.5	12.8	7.6	2.3170	2.3930	33.8033	31.6166	265.7143	117.1429
2.13	396	283	37.5	27.8	18.4	2.8010	2.9310	92.5301	92.1848	25.8667	50.9333
3.17	331	275	5.4	4.5	1.5	1.2970	1.3120	75.9738	75.7119	16.6667	72.2222
3.17	419	275	25.7	26.2	17.1	1.6580	1.7030	93.5497	93.3737	1.9455	33.4630
							Average relative error percent	61.6484	61.3601	177.339	113.2186

Table 10: constants for developed proposed model.

Temperature (°C)	180-250	250-300	300-350	Above 350
E(J/mol)	22618	48000	48000	48000
$\alpha\,(m2K/kJ)$	10.98	0.10974	0.2×10^{-29}	11965.97
β	-1.5472	-36.8289	5.114	-1.9226
$\gamma\,(m^2K/kJ)$	$10^{-10}\times0.96$	-0.6188×10^{-11}	-7889×10^{-11}	-0.15386×10^{-11}

Table 11: Comparison between Polley and the developed proposed model in temperature about 250-300 ^oC.

Item	Velocity (m/s)	T_S (^oC)	Measured rate ($m^2KkW^{-1}h^{-1}$) $\times 10^6$	Polley model ($m^2KkW^{-1}h^{-1}$) $\times 10^6$	Proposed model ($m^2KkW^{-1}h^{-1}$) $\times 10^6$	Relative error percent for proposed model	Relative error percent for Polley model
1	0.9100	246	25.0000	2.0000	25.0207	0.0827	92.0000
2	0.9100	260	5.0000	3.4000	5.5376	10.7528	32.0000
3	0.9100	261	2.0000	3.5000	5.0481	152.4035	75.0000
4	0.9100	288	2.0000	7.4000	1.2290	38.5479	270.0000
5	0.9100	316	6.0000	13.5000	1.0335	82.7744	125.0000
6	1.6800	288	21.0000	2.3000	1.2557	94.0207	89.0476
7	1.6800	302	3.0000	4.0000	1.2756	57.4807	33.3333
8	1.6800	316	1.1000	6.0000	1.2943	17.6655	445.4545
9	2.4400	315	1.5000	2.2000	1.5012	0.0797	46.6667
					Average relative error percentage	50.4231	134.2780

Table 12: Comparison between Polley and th edeveloped proposed model in temperature about 300-350 ^oC.

Item	Velocity (m/s)	T_S (^oC)	Measured rate ($m^2KkW^{-1}h^{-1}$) $\times 10^6$	Polley model ($m^2KkW^{-1}h^{-1}$) $\times 10^6$	Proposed model ($m^2KkW^{-1}h^{-1}$) $\times 10^6$	Relative error percent for proposed model	Relative error percent for Polley model
1	1.7700	344	2.6000	14.4000	2.5920	0.3073	453.8462
2	1.7700	393	7.9000	31.6000	3.1459	60.1791	300.0000
3	2.1300	349	3.5000	12.8000	3.4920	0.2297	265.7143
4	2.1300	396	37.5000	27.8000	4.7617	87.3021	25.8667
5	3.1700	331	5.4000	4.5000	8.4550	56.5743	16.6667
6	3.1700	419	25.7000	26.2000	25.7046	0.0179	1.9455
					Average relative error percentage	34.1017	177.3399

Table 13: Comparison between Polley and th edeveloped proposed model in temperature above 350 ^oC.

Item	Velocity (m/s)	T_S (^oC)	Measured rate ($m^2KkW^{-1}h^{-1}$) $\times 10^6$	Polley model ($m^2KkW^{-1}h^{-1}$) $\times 10^6$	Proposed model ($m^2KkW^{-1}h^{-1}$) $\times 10^6$	Relative error percent for proposed model	Relative error percent for Polley model
1	2.4800	414	3.2000	4.0000	3.2004	0.0122	25.0000
2	1.2500	467	20.1000	37.3000	14.5908	27.4090	85.5721
3	2.4800	397	2.8000	1.6000	2.8008	0.0293	42.8571
4	1.2500	432	11.4000	23.9000	11.4010	0.0088	109.6491
5	1.2500	401	7.9000	14.8000	9.2541	17.1408	87.3418
6	1.2900	374	5.6000	8.4000	7.1794	28.2040	50.0000
7	2.5300	404	4.0000	2.2000	2.8363	29.0929	45.0000
8	2.5300	376	1.2000	0	2.3955	99.6289	100.0000
					Average relative error percentage	25.1907	68.1775

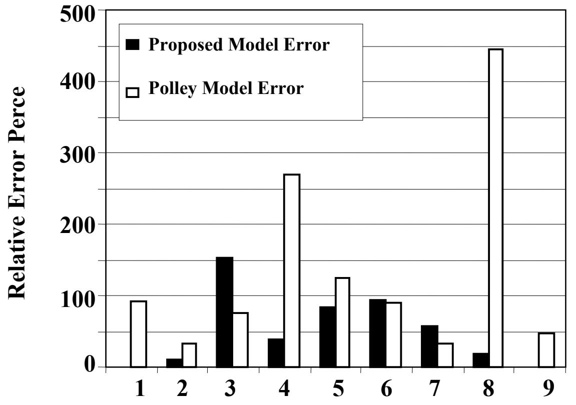

Fig. 6: Comparison between Polley and the developed proposed model in temperature about 250-300 ^oC(table 11).

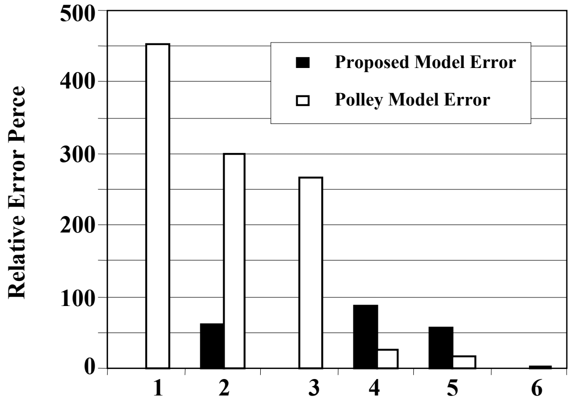

Fig. 7: Comparison between Polley and the developed proposed model in temperature about 300-350 ^oC(table 12).

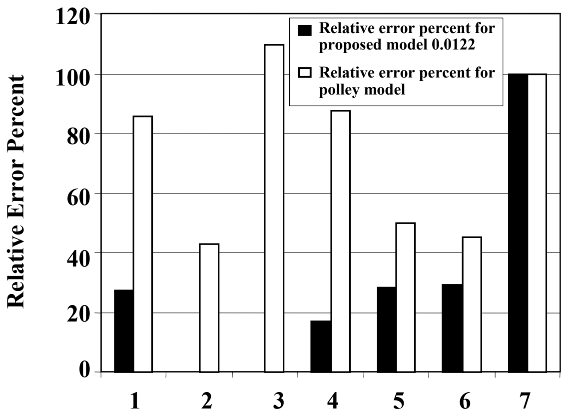

Fig. 8: Comparison between Polley and the developed proposed model in temperature above 350 ^oC (table 13).

removal of fouling layer has a great importance. Fortunately the proposed model takes this advantage. As shown the model can predict fouling rate for various crudes and in different conditions better than other models especially *Polley* model. The difference between *Polley* and the proposed model is that the model does not show any sever dependency to Pr number and this is due to this fact that the heat capacity and thermal conductivity of crude do not show much differences. By proposing is able to identify easily whether a heat exchanger is located in fouling zone or not. In addition, this curve distinguishes if a heat exchanger is located in fouling zone and how it can be expelled from this zone. For instance, in Fig. 4 a heat exchanger with tube side velocity, u=4.25(m/s) and T_f =420K, is located below the threshold curve (means no fouling zone). By increasing the film temperature to T_f =440K the exchanger moves to above the threshold curve (means fouling zone). Now, the velocity should be increased to exit from fouling zone. Finally the proposed model was developed for various surface temperatures and show remarkable results. By Comparing the proposed model with *Polley* model it can be seen that the proposed model has very low deviation from experimental results in relation to *Polley* model.

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Nomenclatures

E	Activation energy
f	Friction factor
P	Pressure
R	Gas constant
Re	Dimensionless Reynolds number
R_f	Fouling Formation
t	Time
T_b	Bulk temperature
T_f	Film temperature
T_s, T_w	Wall temperature
u	Velocity
ρ	Density
τ	Shear stress
$\frac{d(R_{f,exp})}{dt}$	Fouling rate due to experimental results
$\frac{d(R_{f,Th})}{dt}$	Fouling rate due to model results

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