

Direct Contact Heat Exchange for Energy Recovery from Hot Temperature Petroleum Refinery Streams

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Abstract Industrial plants are huge consumers of energy, these plants are installing heat exchangers in an effort to reduce energy consumption, and so improve operating efficiencies. Limited numbers of experimental and numerical investigations have dealt with the parameters affecting the heat transfer aspects in single phase direct contact heat exchangers which may be selected for their high thermal efficiency and minimum capital investment. In oil refineries energy from hot temperature oil streams can be recovered by transfer directly to a cheap coolant liquid in liquid-liquid direct contact heat exchangers. The heat recovered from these heat exchangers has different applications including preheating boiler feed water and preheating wash water. Heat recovery from hot temperature refinery products using direct contact heat exchanger throughout a theoretical phenomenological study is central to the theme of this paper. Kerosene-water system has been chosen. The effect of the heating fluid inlet temperature (65-97.50)°C, and mass flow rate (25 to 45) kg/s on direct contact heat exchanger design parameters and heat transfer characteristics were investigated theoretically throughout nine cases. Correlations of heat recovered from the system as well as design and operating characteristics of the heat exchanger were estimated. Increasing kerosene flow rate found to associate directly with increasing the contact surface area, number of plates, number of channels per pass and pressure drop, while when the heat exchanger is designed to operate at high kerosene inlet temperature, big heat exchangers with large areas, high number of plates and channels per pass are needed for efficient heat exchanger performance. Optimization and modeling the effect of kerosene operating variables on heat recovered was conducted using Response Surface Methodology. The results showed that an optimum heat recovery value of 6.8782 megawatt could be achieved for kerosene optimum inlet temperature (91.82°C), and mass flow rate (50.11 kg/s).

Keywords Direct contact heat exchanger, Heat recovery, Hot refinery effluents, Optimization, Modeling

1. Introduction

A heat exchanger is a device used to transfer heat between two or more fluids. The fluids may be separated by a solid wall to prevent mixing or they may be in direct contact. For the heat transfer to occur the two fluids must be at different temperatures and they must come in thermal contact. Heat exchangers are classified to different categories based on the type of transfer process, number of fluids, flow arrangements and heat transfer mechanisms (Shah, 1981; Walker, 1990). Heat exchangers can be classified also based on their construction to recuperative heat exchangers and regenerative heat exchangers. A recuperative heat exchanger has separate flow paths for each fluid and fluids flow simultaneously through the exchanger exchanging heat across the wall separating the flow paths. A regenerative heat exchanger has a single flow

path, which the hot and cold fluids alternately pass through.

There are many types of recuperative exchangers, which can broadly be grouped into indirect contact heat exchangers which keep the fluids exchanging heat separate by the use of tubes or plates etc., and direct contact heat exchangers. Direct contact heat exchanger are classified according to the types of the working fluids to three categories: Immiscible fluid exchangers, Gas-Liquid exchangers and Liquid-Vapor exchangers (Shah, 1994). In immiscible fluid exchangers, two immiscible fluid streams are brought into direct contact. These fluids may be single-phase fluids, or they may involve condensation or vaporization. In Gas-Liquid exchangers, one fluid is a gas and the other a low-pressure liquid and readily separable after the energy exchange (Kang et al., 2002).

Different methods have been used to define the type of direct contact heat exchanger, including layer type, where the hot fluid is stagnant while the cold fluid flows on top, and a spray type, where one of two fluids is injected into the other. Generally, there are two types of spray column, depending on which injection technique is being used: an integrated type and a split type. In the former, the cold fluid

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is dispersed from the bottom of the column into a hot fluid, whereas in the second one, the hot fluid is pumped in counter currently with the flowing cold fluid (Tadrist *et al.*, 1985; Sideman and Gat, 1966).

A direct contact heat exchanger has several advantages over surface heat exchangers such as eliminating metallic heat transfer surface between fluids which are prone to corrosion and fouling, as well as increasing the heat transfer resistance. It can be operated at very low temperature differences or heat transfer driving forces and allows lower mass flow rates of transferring fluids, convenient separation of the fluids, and a high heat transfer coefficient (about 20–100 times than single phase or surface type heat exchanger (Peng *et al.*, 2001; Murshed and Lopes, 2017). Therefore, it can be found in several industrial applications, such as water desalination by freezing, geothermal power energy production, crystallization, waste heat recovery, energy storage systems, solar power energy, and emergency cooling of chemical and nuclear reactors (Sideman, 1966; Dammel and Beer, 2003; Mahmood, 2015; Baqir *et al.*, 2016; Zhu *et al.*, 2014). However, in spite of all the above advantages, many problems still face the direct contact heat exchangers, such as, the stream contamination which depends on the degree of miscibility of the streams, and lack of dependable mathematical design methodology and obscurity in technical duty (Jacobs, 1988). In addition the streams must be at the same pressure in the direct contactor, which could lead to additional cost (Sinnott, 2005).

Considerable attention has been paid to the field of direct contact heat exchangers, particularly when change of phase takes place (Raina *et al.*, 1984, Song *et al.*, 1999). However, most of the efforts have been focused on the evaporation of single drops or condensation of single bubbles (Sideman and Gat, 1966; Peng *et al.*, 2001; Plass *et al.*, 1979; Letan and Kehat, 1968; Letan, 1988). Various numerical models were also developed to study the flow and the heat transfer (Coban and Boehm, 1989; Jacobs and Golafshani, 1989; Brickman and Boehm, 1994; Kang *et al.*, 2002).

On the other hand, in petroleum refineries, the liquid side and some bottom-draw products from atmospheric and vacuum distillation columns are collected at relatively high temperatures, the objectives of the present work is to study the heat recovery from the refinery hot products using water throughout a single phase direct contact heat exchanger for the purpose of saving in energy and reduction of gaseous pollutants associated with energy usage.

Kerosene-water system was selected. The physical, design and heat transfer characteristics of the heat exchanging system were estimated based on heat exchanger design equations and the relevant theoretical information. The effect of kerosene flow rate and temperatures on heat exchanger design parameters and heat transfer characteristics were studied and correlated. Modeling and optimization of the heat exchanger operating variables in order to optimize the heat transfer output using Response Surface Methodology is also included. Typical diagram for

a direct contact heat exchanger of kerosene-water system is shown in Figure 1.

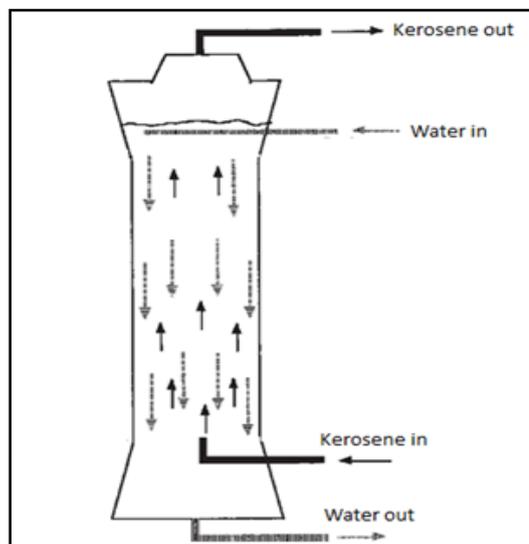


Figure 1. Kerosene-water direct contact heat exchanger

2. Theoretical Analysis

2.1. The Governing Parameters

Heat exchanger theory leads to the heat exchanger design equation that relates the overall heat transfer coefficient, heat transfer surface area, and log mean temperature difference, to the rate of heat transfer. To determine the rate of heat transfer or duty (Q), information about the inlet and outlet of the exchanger are needed, while no information about the internals are included. For the entire exchanger the rate of heat transfer is the total rate of heat transfer of the heating and cooling streams. In the recent work the heat transfer and the design characteristics of single phase direct contact heat exchanger were calculated based on heat exchanger design equations. The calculated parameters and the corresponding mathematical equations used in calculations are shown in appendix 1.

2.2. Heat Recovery from Single Phase (Kerosene-Water) System

The recent study deals with heat recovery from a direct contact heat exchanger used hot petroleum refinery product (Kerosene stream) as the heating fluid and water stream as cooling fluid, proposing that no phase changes in the fluid streams flowing through the exchanger. Rate of heat transfer and the heat exchanger design characteristics calculations were conducted based on data of physical properties of the fluids and the heat exchanger design parameters extracted from literature (Hill, 1950; Marsh, 1987; Kakac and Liu, 2002; Shah and Sekulic, 2003; Sinnott, 2005; Bengtson, 2010). The overall coefficient, light organic-water, is assumed to be $1736 \text{ W m}^{-2}\text{C}^{-1}$ based on the data estimated from (Bengtson, 2010). Table 1 and 2

show the physical properties of the fluids and the heat exchanger design parameters respectively.

Table 1. Physical properties of water and kerosene

Properties	water	Kerosene
Density (kg / m ³)	993	730
Heat capacity (J / (kg.k))	4190	2512
Viscosity (N.s / m ²)	0.8 × 10 ⁻³	0.85 × 10 ⁻³
Thermal Conductivity (w / m.k)	0.62	0.13
Fouling resistance (m ² .k / w)	0.00018	0.00033

Table 2. Heat exchanger design parameters

Parameters	Value
Effective length, m	1.5
Effective plate area, m ²	0.75
Plate spacing, m	0.003
Plate width, m	0.5
Plate thickness, m	0.00075
Material of construction	Titanium plates

2.3. Statistical Analysis Using Statgraphics Plus for Windows Software

The statistical analysis procedure of Statgraphics plus for Windows software (5.1 version) for experimental design and data treatment was used to optimize and model the effect of the operating variables of the heating fluid on rate of heat transfer (heat recovered). Response surface methodology (RSM) in conjunction with central composite rotatable design was performed.

The RSM normally allow identifying the effects of operating parameters (independent variables X_i) on different responses Y_j (dependent variables). A central composite design consisting of 16 experimental runs with two replicates at the center point was established. The mathematical empirical model applies is:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{12} X_1 X_2 \quad (1)$$

Where: Y: is the response or dependent variable; X_1 and X_2 are the independent variable $\beta_0, \beta_1, \beta_2, \beta_{11}, \beta_{22}, \beta_{12}$ are the regression coefficients.

The analyses of variance (ANOVA) were used to determine significant differences between the independent variables ($p < 0.05$). Pareto chart was used to identify the impact of variables on various responses. The vertical line in the Pareto chart determines the effects that are statistically significant at 95% as confidence level (Raymond et al., 2016).

2.3.1. Experimental Design

In order to reduce the experimental trials required to carry out the effects for the main operating parameters (inlet temperature, outlet temperature, and mass flow rate) of kerosene, 3-component rotary central composite design was

used; 16 experiments were designed included 2*3= 6 factorial points, 2*4=8 star point and 2 replicates for the central point. The experiments were performed randomly to minimize the effects of unexpected variability on the observed responses due to unusual responses. The coded and actual levels of independent variables used in experimental design are listed in Table 3.

Table 3. The factorial design matrix with the actual and coded levels of the independent variables

Properties	- α	-1	0	+1	+ α
Kerosene inlet temperature (°C)	58.18	65	75	85	91.8
Kerosene outlet temperature (°C)	26.59	30	35	40	43.4
Kerosene flow rate (kg/s)	24.88	30	37.5	45	50.1

Exp. No.	Inlet temp. (°C)	Outlet Temp (°C)	Flow rate Kg/s
1	65	30	45
2	85	30	30
3	75	35	24.89
4	75	35	37.5
5	58.18	35	37.5
6	75	35	50.11
7	91.82	35	37.5
8	75	26.59	37.5
9	85	40	30
10	65	30	30
11	65	40	30
12	85	40	45
13	75	35	37.5
14	85	30	45
15	75	43.41	37.5
16	65	40	45

α is the (axial distance), k is the number of orthogonal design variables (in this case, k=3).

3. Results and Discussion

3.1. Mathematical Analysis

Improving and optimization of heat exchanger performance is associated with operating the heat exchanger within its designed and specified limits, also the operating parameters that can affect heat exchanger performance should be identified such that they are maintained and controlled at the designed point.

Among the key operating parameters must be monitored are the feed material and heat exchanger operating

temperatures. In the recent work the heat exchanger design parameters and the heat transfer characteristics were calculated. The effect of the heating fluid inlet temperature and its mass flow rate on direct contact heat exchanger design parameters (heat exchange surface area, number of plates, number of channels per pass and pressure drop), and on rate of heat transfer were investigated theoretically throughout nine cases. The spreadsheet results of the nine investigations are summarized in table 4. The cases (from 1 to 5) are investigated at constant average temperature of kerosene (70°C), and different mass flow for kerosene ranging from (25 to 45) kg/s, while, and the cases (1 and from 5 to 9) are estimated at constant mass flow rate of kerosene (25 kg/s) and different kerosene inlet temperature range (65-97.5°C). The investigated operating parameters were correlated with the heat exchanger design parameters and the heat recovered from the heat transfer process.

Table 4. Summary of the spread sheet results of cases (1-9)

Properties	Case 1		Case 2		Case 3	
	W	K	W	K	W	K
Flow rate (kg/s)	65.16	25	78.2	30	91.23	35
Initial temperature (°C)	25	95	25	95	25	95
Final temperature (°C)	35	45	35	45	35	45
Density (kg/m ³)	995	780	995	780	995	780
Heat capacity (J/(kg.K))	4176	2177	4176	2177	4176	2177
Viscosity (N.s/m ²)	0.0008	0.00094	0.0008	0.00094	0.0008	0.00094
Thermal Conductivity (W/(m.K))	0.62	0.137	0.62	0.137	0.62	0.137
Fouling resistance (m ² .K/W)	0.00018	0.00033	0.00018	0.00033	0.00018	0.00033
Heat (W)	2721250		3265500		3809750	
Area (m ²)	50.04		59.78		70.06	
Number of plates	67		79		93	
Number of channels per pass	33		39		46	
Channel velocity (m/s)	1.3	0.64	1.3	0.64	1.3	0.64
Reynolds number	9851	3236	9851	3236	9851	3236
Heat transfer coefficient (W.m ⁻² .°C ⁻¹)	20770	3357	20770	3357	20770	3357
Overall coefficient (W.m ⁻² .°C ⁻¹)	1531		1531		1531	
Pressure drop (bar)	1.12	0.26	1.32	0.3	1.55	0.34

Properties	Case 4		Case 5		Case 6	
	W	K	W	K	W	K
Flow rate (kg/s)	104.26	40	417.3	45	51.13	25
Initial temperature (°C)	25	95	25	95	25	85
Final temperature (°C)	35	45	35	45	35	45
Density (kg/m ³)	995	780	995	780	995	790
Heat capacity (J/(kg.K))	4176	2177	4176	2177	4176	2135
Viscosity (N.s/m ²)	0.0008	0.00094	0.0008	0.00094	0.0008	0.001
Thermal Conductivity (W/(m.K))	0.62	0.137	0.62	0.137	0.62	0.138
Fouling resistance (m ² .K/W)	0.00018	0.00033	0.00018	0.00033	0.00018	0.00033
Heat (W)	4354000		4898250		2135000	
Area (m ²)	80.07		90.79		42.74	
Number of plates	107		121		57	
Number of channels per pass	53		60		28	
Channel velocity (m/s)	1.3	0.64	1.3	0.64	1.22	0.75
Reynolds number	9851	3236	9851	3236	9104	3555
Heat transfer coefficient (W.m ⁻² .°C ⁻¹)	20770	3357	20770	3357	19737	3680
Overall coefficient (W.m ⁻² .°C ⁻¹)	1531		1531		1587	
Pressure drop (bar)	1.82	0.39	2.13	0.45	0.86	0.32

Properties	Case 7		Case 8		Case 9	
	W	K	W	K	W	K
Flow rate (kg/s)	78.95	25	128.56	25	78.95	25
Initial temperature (°C)	25	105	25	150	25	200
Final temperature (°C)	35	45	35	45	35	100
Density (kg/m ³)	995	779	995	800	995	730
Heat capacity (J/(kg.K))	4176	2198	4176	2052	4176	2512
Viscosity (N.s/m ²)	0.0008	0.00085	0.0008	0.0015	0.0008	0.00085
Thermal Conductivity (W/(m.K))	0.62	0.136	0.62	0.14	0.62	0.13
Fouling resistance (m ² .K/W)	0.00018	0.00033	0.00018	0.00033	0.00018	0.00033
Heat (W)	3297000		5386500		6280000	
Area (m ²)	55.92		79.08		32.67	
Number of plates	79		105		43	
Number of channels per pass	37		52		21	
Channel velocity (m/s)	1.43	0.58	1.66	0.4	4.79	1.09
Reynolds number	10671.38	3189	12363	1280	35673	5617
Heat transfer coefficient (W.m ⁻² .°C ⁻¹)	21906.67	3218.67	24076.67	2193.33	47994	4680
Overall coefficient (W.m ⁻² .°C ⁻¹)	1506		1236		1845	
Pressure drop (bar)	1.4	0.22	2.76	0.17	8.34	0.48

Where, W is water, and K is kerosene.

3.1.1. Effect of Kerosene Mass Flow Rate

The estimated correlations for the effect of mass flow rate of kerosene at constant kerosene inlet temperature (70°C) are shown in Figures (2-6). An increase in mass flow rate of kerosene resulted in an increase in heat exchanger performance (heat recovered) as shown in Figure 2. The reason behind that is attributed to that high mass flow rate of kerosene will promote turbulence and good thermal contact/transfer. However, with higher values of flow rate, adequate importance should be given to heat exchanger design characteristics to achieving optimum performance. As seen, increasing kerosene flow rate is associated directly with increasing the contact surface area (Figure 3), increasing the number of plates (Figure 4), and number of channels per pass (Figure 5). Moreover, increasing kerosene mass flow rate resulted in increasing the pressure drop (Figure 6). It is well noticed that as a fluid flows through a heat exchanger there will normally be a pressure drop in the direction of the flow. The pressure drop is usually affected by type of flow (laminar or turbulent) and the passage geometry. The reason behind increasing the pressure drop with increasing kerosene mass flow rate may be due to the ununiformed flow rate distribution at high flow rate values. High pressure drop will lead to high velocity at the exit of the heat exchanger that resulted in erosion problems and increase the pumping costs. It is worthy to mention that the effectiveness of heat transfer is gauged by how well getting returns for what spending. Hence, the increased pressure gradient is usually outweighed by a decrease in required passage length so the overall pressure drop remains acceptable (Bassiouny and Martin, 1984).

3.1.2. Effect of Kerosene Inlet Temperature

The estimated correlations for the effect of kerosene inlet temperature at constant kerosene mass flow rate (25 kg/s) are shown in Figures (7-11). At constant mass flow rate of kerosene the heat recovered increases when kerosene temperature increases as shown in Figure 7. Generally, any alterations in the stream temperature will create a variation in the exchanger duty and log mean temperature difference (Dahran, 2017). When the heat exchanger is designed to operates at high kerosene inlet temperature, big heat exchangers with large areas (Figure 8), high number of plates (Figure 9) and channels per pass (Figure 10) are needed for efficient heat exchanger performance.

On another hand as kerosene inlet temperature increases pressure drop decreases owing to decreasing the viscosity of kerosene with increasing kerosene inlet temperature. However, when the operating variables limits are exceeded, the design characteristics will show dramatic changes (Babu, 2004). Hence, reaching a good compromise is relevant to the perfect weighing of the factors against each other.

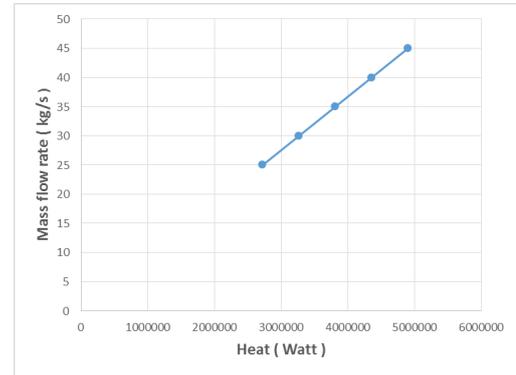


Figure 2. Variation of kerosene mass flow rate with the heat recovered

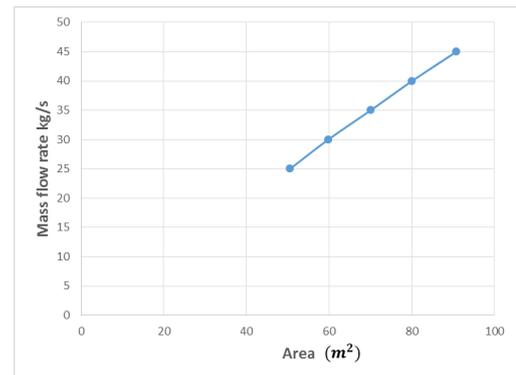


Figure 3. Variation of kerosene mass flow rate with the surface area of the heat exchanger

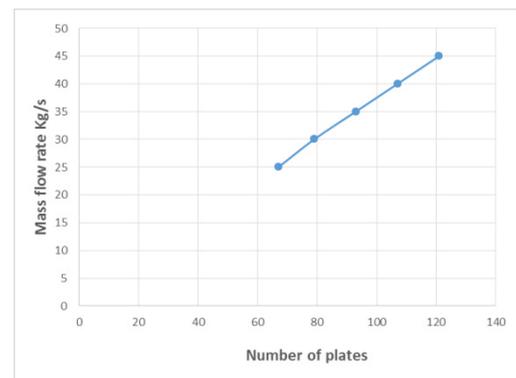


Figure 4. Variation of kerosene mass flow rate with number of plates of the heat exchanger

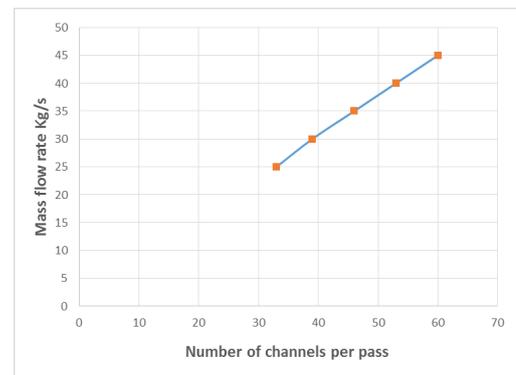


Figure 5. Variation of kerosene mass flow rate with number of channels per pass

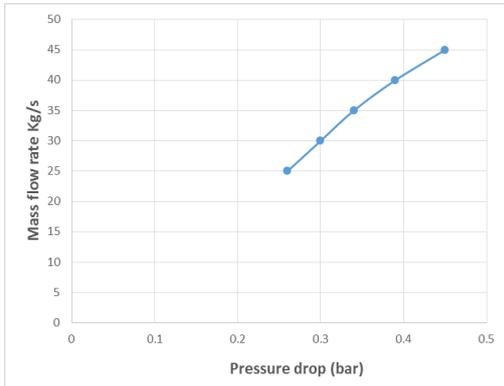


Figure 6. Variation of kerosene mass flow rate with pressure drop

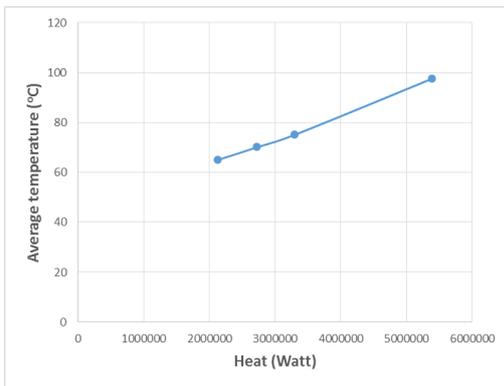


Figure 7. Variation of kerosene temperature with amount of heat recovered

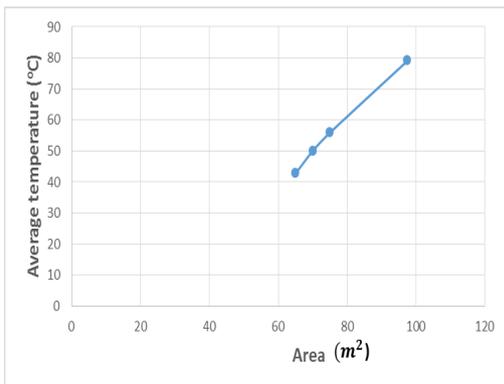


Figure 8. Variation of kerosene temperature with surface area

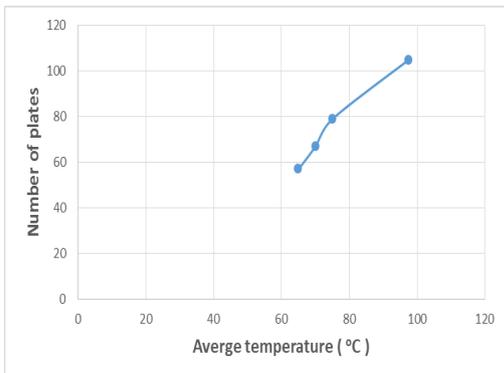


Figure 9. Variation of kerosene temperature with number of plates

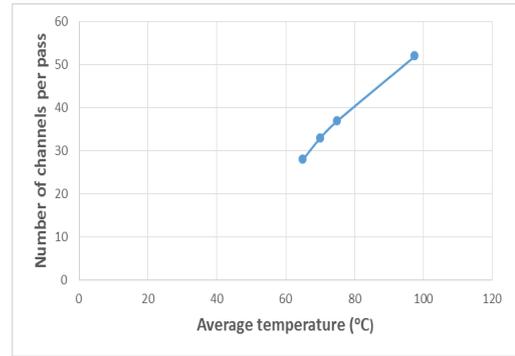


Figure 10. Variation of kerosene temperature with the number of channels per pass

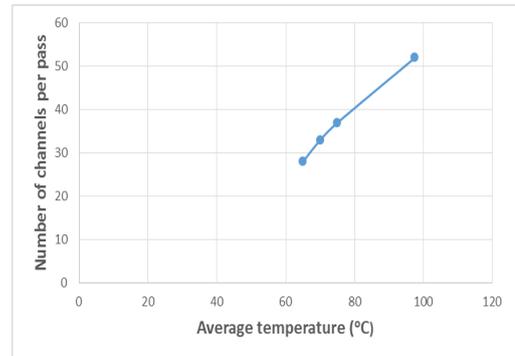


Figure 11. Variation of kerosene temperature with pressure drop

3.2. Response Surface Analysis Results

Response Surface Methodology was applied in order to model and optimize the effect of kerosene operating variables including inlet temperature, outlet temperatures and mass flow rate on the heat could be recovered from the heat transfer process. An experimental design was adopted with 16 experiments to study the effect of kerosene inlet temperature ranged (58.18-91.8)°C, kerosene outlet temperature ranged (26.59-43.4)°C, and kerosene mass flow rate ranged (24.88-50.1) kg/s on rate of heat transfer (heat recovered). The heat recovered corresponding to each experiment was calculated theoretically and applied to the software for analysis. Table 5 listed the levels of independent variables and the response for the 16 runs.

The results of the heat recovered for all the runs were performed and reported in second-order polynomial multiple linear regression models. The response surface analysis is shown in Figure 12 which illustrates the standardized Pareto chart, the main effect plot (general trends), and the estimated response surface.

The vertical line on Pareto chart determines the effects that are statistically significant. The standardized effect is the estimated effect divided by its standard error. Hence a low standardized effect can mean either a low effect of the parameter or a large actual error. Pareto chart of standardized effects was calculated in order to show significant effects of all variables (linear, quadratic and interactions between variables). The vertical line represents the limit between the significant and insignificant effects

regarding the response. The length of each parameter characterizes the absolute importance of the estimated effects. Moreover, the colour of the squares indicates whether the effect is positive or negative. The Pareto chart in Figure 12A showed very strong significant effect of the three variables on the heat recovered. However, the inlet temperature of kerosene seemed of top most significant followed by mass flow rate and outlet temperature.

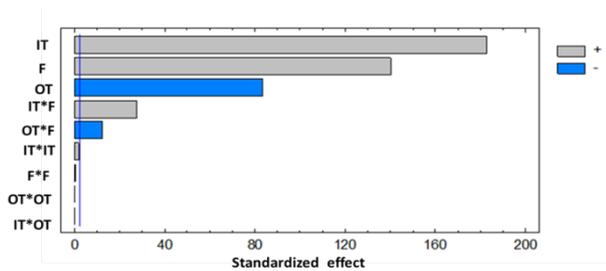
Table 5. Levels of independent variables and the responses

Experiment No.	Inlet temp. °C	Outlet Temp. °C	Flow rate kg/s	Specific heat J/kg.K	Heat Recovered (megawatt)
1	65	30	45	2051.53	3.23
2	85	30	30	2101.77	3.47
3	75	35	24.88	2093.40	2.08
*2	75	35	37.5	2093.34	3.14
6	58.18	35	37.5	2072.47	1.80
7	75	35	50.11	2093.40	4.20
8	91.82	35	37.5	2135.27	4.55
9	75	26.59	37.5	2089.21	3.79
10	85	40	30	2135.27	2.88
11	65	30	30	2051.53	2.15
12	65	40	30	2085.03	1.56
13	85	40	45	2135.27	4.32
14	85	30	45	2101.77	5.20
15	75	43.41	37.5	2114.33	2.50
16	65	40	45	2085.03	2.35

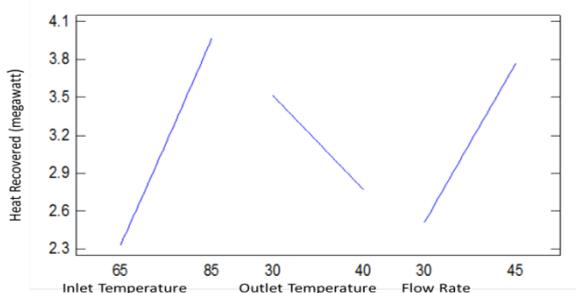
*2: Two central points

The main effects plot (Figure 12B) shows that the amount of heat recovered increases with increasing kerosene inlet temperature and flow rate and decreases with the increasing the out let temperature.

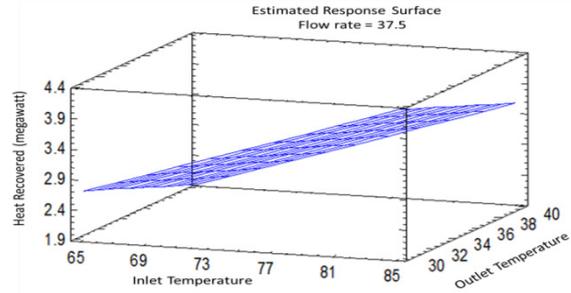
Figure 12C shows the estimated response surface at constant kerosene flow rate (37.5) kg/s.



A. Pareto chart for heat recovered



B. General trends



C. Response surface

Figure 12. Pareto chart (A), general trends (B), response surface (C) for the effect of kerosene inlet temperature, outlet temperature and flow rate on the heat recovered

The polynomial empirical model, regression coefficients R^2 (adjusted to d.f.), and the optimized values of the heat recovered were estimated from response surface analysis (RSA). The mathematical model correlates the heat recovered with kerosene operating variables is expressed in equation 2.

$$\text{Heat Recovered (megawatt)} = 0.559097 - 0.01395*IT - 0.00536*OT - 0.0074*F + 0.000098*IT^2 + 0.0*IT*OT + 0.0022*IT*F + 0.0000398*OT^2 - 0.00193*OT*F - 0.000045*F^2 \quad (2)$$

Where, IT is the kerosene inlet temperature, OT is the outlet kerosene temperature and F is the kerosene mass flow rate.

Very high regression coefficient was estimated (R -squared = 99.98) which confirms that the model is of high accuracy and capable to perfectly generalize between input and output parameters with reasonable good predictions. An optimum value of heat (6.8782 megawatt) could be estimated from the model for an optimum operating parameters of the heat exchanger at kerosene inlet temperature 91.8°C, kerosene outlet temperature 26.81°C, and kerosene mass flow rate 50.1 kg/s as estimated from RSA. The optimized parameters for kerosene are listed in table 6.

Table 6. Optimum parameters for heat recovery from RSA

Optimum heat recovery = 6.87823 (megawatt) = 6878230 Joule/sec	
Kerosene operating variables	Optimum value
Inlet Temperature	91.82 (°C)
Outlet Temperature	26.81 (°C)
Mass Flow Rate	50.11 (kg/s)

4. Conclusions

Studies related to the applications of recoverable heat to produce additional power using direct contact heat exchangers are very important from economic and environmental point of view. In oil industry, direct contact heat exchangers are important heat source for providing additional power. Waste heat recovery could take place

through a thermal approach that uses the hot temperature oil streams to heat up water and partially fulfill heating or hot water needs of the industrial site. To recover heat from these heat exchangers efficiently, the heat exchangers are needed to be designed in such a way that it can handle the heat load with reasonable size, weight and pressure drop. Upon investigating how physical, design and heat transfer characteristics of single phase kerosene-water direct contact

heat exchange system influenced the heat exchangers effectiveness, the design parameters were of significant impact. Also, Statgraphics plus software seemed very applicable to optimize and model the amount of heat recovered as well as kerosene operating variables. With an optimum design of the heat exchanger an optimum heat value (6.88 megawatt) could be recovered when kerosene enters the heat at 91.18°C and flow rate of 50.1 kg/s.

Appendix 1. Governing parameters and mathematical equations

	Parameter	Mathematical Equation	Equation Number
1	Rate of heat transfer or duty (Q): The basic design equation used for analyzed Q is shown in equation 1	$Q = mC_p(T_i - T_o)$	(1)
2	The equivalent (hydraulic) diameter d_e , taken as twice the gap between the plates (m)	$d_e = \frac{2pw}{p+w}$	(2)
3	Log mean temperature difference, ΔT_{lm}	$\Delta T_{lm} = \frac{(T_{h,i} - t_{c,o}) - (T_{h,o} - t_{c,i})}{\ln \frac{(T_{h,i} - t_{c,o})}{(T_{h,o} - t_{c,i})}}$	(3)
4	Number of transfer units (NTU) Typically, the NTU range is from 0.5 to 4.0, and for most applications will lie between 2.0 to 3.0	$NTU = \frac{T_{h,i} - T_{h,o}}{\Delta T_{lm}}$	(4)
5	Heat exchanger surface area (A)	$A = \frac{Q}{u_{ass} \Delta T_{lm} F_T}$	(5)
6	Number of plates, channel per pass and channel velocity	Number of plates = total heat transfer area / effective area of one plate Channel cross-sectional area = plate spacing \times plate width Channel velocity = (mass flow rate) / (density \times number of channel per pass \times channel cross-sectional area)	(6) (7) (8)
7	Heat transfer coefficient for the two fluids (h_i)	$h_i = \frac{Nu \times k_f}{d_e}$ $Nu = 0.26(Re)^{0.65}(Pr)^{0.4}$ $Re = \frac{\rho \times u \times d_e}{\mu}$ $Pr = \frac{c_p \times \mu}{k_f}$	(9) (10) (11) (12)
8	Overall heat transfer Coefficient	$\frac{1}{u_{cal}} = \frac{1}{h} + \frac{1}{R_d} + \frac{\text{plate thickness}}{\text{Thermal conductivity of titanium}} + \frac{1}{h} + \frac{1}{R_d}$	(13)
9	Pressure drop	As a fluid flows through a heat exchanger there will normally be a pressure drop in the direction of the flow. The Pressure drop in a plate heat exchanger can be calculated from equation 14 $\Delta P_p = 8j_f \left(\frac{L_p}{d_e}\right) \frac{\rho u^2}{2}$ $j_f = 0.6 (Re)^{-0.3}$ The Pressure loss through the ports in a plate heat exchanger can be calculated from equation 16. $\Delta P_{pt} = 1.3 \frac{\rho u_{pt}^2}{2} N_p$ Total pressure drop = $\Delta P_p + \Delta P_{pt}$	(14) (15) (16) (17)

Symbols and Definitions

SYMBOL	DEFINITION (Units)
A	Heat transfer area (m^2)
d_e	E valuation diameter (m)
m	Flow rate (m/s)
C_p	Heat capacity (J / (kg.K)
T_i	Inlet Temperature ($^{\circ}C$)
T_o	Outlet Temperature outlet ($^{\circ}C$)
ΔT_{lm}	Log mean temperature difference ($^{\circ}C$)
$T_{h,i}$	Hot temperature inlet ($^{\circ}C$)
$T_{o,i}$	Cold temperature inlet ($^{\circ}C$)
$T_{h,o}$	Hot temperature outlet ($^{\circ}C$)
$T_{c,o}$	Cold temperature outlet ($^{\circ}C$)
U_{ass}	Overall heat transfer assuming ($W.m^{-2}.^{\circ}C^{-1}$)
U_{cal}	Overall heat transfer calculation ($W.m^{-2}.^{\circ}C^{-1}$)
F_T	Correction factor ($m^2.k / W$)
P	Plate spacing (m)
w	Plate width (m)
Re	Reynolds number (dimensionless)
ρ	Density (kg / m^3)
u	Velocity (m/s)
μ	Viscosity ($N.s / m^2$)
Pr	Prandtl number (dimensionless)
k_f	Thermal conductivity ($W / (m.K)$)
Nu	Nusselt number (dimensionless)
h_p	Heat transfer coefficient ($W.m^{-2}.^{\circ}C^{-1}$)
j_f	Friction factor (dimensionless)

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