International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 7, Issue 5 [Jun 2018] PP: 44-62

Heat Transfer Studies on Plate Type Heat Exchanger Using Miscible And Immiscible Liquids

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ABSTRACT: *Heat exchangers are used extensively and regularly in process and allied industries and are very important during design and operation. The choice of heat exchanger type directly affects the process performance and also influences plant size, plant layout, length of pipe runs, and the strength and size of supporting structures. Compact heat exchangers are characterized by having a comparatively large surface area to a given volume, when compared with traditional heat exchangers, in particular the shell and tube type. Two-phase (liquid-liquid) flow is frequently encountered in chemical process industries. In the present work the performance of plate type heat exchanger have been studied experimentally and comparison was made between the co-current and counter-current flow pattern with different cold side fluids that involve both immiscible and miscible systems. Hot water was taken as the hot side fluid for all the experimentation. The cold fluids used were water, kerosene-water system, acetic acid-water system of different compositions say 9%, 10%, 20% and 25% on volume basis in different flow rates. Also the flow rate of cold fluid was varied to find the effect of flow rate and composition on heat transfer coefficients, effectiveness and efficiencies. The hot fluid flow rate was kept constant at 1lpm and the cold fluid flow rate was varied from 12.5 to 42.5 lph. The above experiments indicate that the plate type heat exchanger performs well when operated under counter current flow pattern.*
KEYWORDS: *Water-Kerosene, Water – Acetic acid*

Date of Submission: 06-06-2018 Date of acceptance: 21-06-2018

I. INTRODUCTION

A heat exchanger is process equipment used for transferring heat from one fluid to another fluid through a separating wall. "*When none of the fluid condenses or evaporates, the unit is called as Heat Exchanger*." In this only the sensible heat transfers from the one fluid to another. They are widely used in petroleum refineries, chemical plants, petrochemical plants, natural gas processing, refrigeration, power plants, air conditioning and space heating. Heat exchangers could be classified in many different ways such as according to flow arrangements, number of fluids, surface compactness, process function, heat transfer mechanisms, type of fluids (gas-gas, gas-liquid, liquid-liquid, gas-two-phase, liquid-two-phase, etc.) and construction type (R.K. Shah *et.al.*,2000). There are several types of heat exchanger:

- Recuperative type, in which fluids exchange heat on either side of a dividing wall
- Regenerative type, in which hot and cold fluids occupy the same space containing a matrix of material that works alternatively as a sink or source for heat flow
- Evaporative type, such as cooling tower in which a liquid is cooled evaporatively in the same space as coolant.

1.1 OBJECTIVE OF THE PROPOSED WORK

The experimental work in plate type heat exchanger (Parallel and Counter flow) involved in the determination of outlet temperature of both cold and hot fluid for various flow rates. The water-water system, water-acetic acid system, and water-kerosene system at 9%, 10%, 20% and 25% composition on volume basis of kerosene and acetic acid, were used to determine the performance of plate type heat exchanger. i.e. overall heat transfer coefficient (U_0), effectiveness (ε), cold side efficiency (η_c) and hot side efficiency (η_h).

II. PLATE TYPE HEAT EXCHANGER

2.1EXPERIMENTAL STUDIES

Experiments were carried out on a plate type heat exchanger with both parallel and counter flow patterns with miscible (acetic acid) and immiscible (Kerosene) systems in cold side and water in hot side

2.2 Experimental Set-up

The plate type heat exchanger under study consists of 5 plates and 2 end plates made of Aluminium of dimensions, 150 mm x150 mm inner dimension and 250 mm x 250 mm outer dimension. The heat transfer plates are arranged to form a network of parallel or counter flow channels. The plate pack is mounted on upper and lower rails and compressed between two end frames using compression bolts. The hot fluid is hot water which is obtained from an electric geyser and it flows through one plate while the cold fluid is flowing through the other plate. The hot water flows always in one direction and the flow rate is controlled by means of a gate valve. The cold water can be admitted at one of the ends enabling the heat exchanger to run as a parallel flow apparatus or a counter flow apparatus by simple valve operation.

2.3 HEAT EXCHANGER SPECIFICATIONS

- No. of plates: 5 plates and 2 end plates.
- Size of the plate: outer diameter 215 mm x 215 mm inner diameter 150 mm x 150 mm.
- Material: Aluminium
- Gasket: silicon 6 nos.
- Temperature scanner 5 point 1 nos.
- Thermocouple 4 nos. 2 nos. for cold water inlet and outlet, 2 nos. for hot water inlet and outlet.
- Measuring tank 70mm in diameter length 500 mm 2nos.
- Stop watch- digital- 1 no.
- Geyser- single phase 230v-3kW-2 nos. total 6 nos. with main switch
- Insulation material: Asbestos

2.4 EXPERIMENTAL PROCEDURE

The experimental setup was operated in counter-current flow pattern by adjusting the valves. The flow of water on hot side was started. The flow rate of water entering the hot side of exchanger was adjusted with the help of a ball valve.

The geysers were switched ON and waited till temperature reaches a steady state. The temperature scanner was switched ON and inlet temperature of hot side (T_1) was noted. The pumps were operated and the rotameters on cold side were adjusted to get the required flow rate of cold fluid with required composition (9% or 10% or 20% or 25% on the basis of volume).

The inlet temperature of cold fluid (t_1) was noted from temperature scanner. The flow rates on the hot and cold side were unaltered until steady state is reached. When steady state is reached, outlet temperature of hot fluid (T_2) and cold fluid (t_2) were noted. The flow rate of cold fluid was varied and the above procedure was repeated. After completing a run with different flow rates for a particular solution at a particular composition, the procedure was repeated for different compositions and different systems (Kerosene-Water, Acetic acid-Water). Similar procedure was followed for the co-current flow operation.

2.5 EXPERIMENTAL OBSERVATION
2.5.1 Counter Current Flow Pattern

2.5.1.1 IMMISCIBLE SYSTEMS

Volumetric flow rate of cold fluid lph	Volumetric flow rate of hot fluid lpm	Inlet Temperature °C		Outlet Temperature °C	
		Cold Fluid	Hot Fluid	Cold Fluid	Hot Fluid
9% kerosene-water sytem					
12.5	1	31	74	50	59
17.5	1	31	74	49	58
22.5	1	33	73	48	57
27.5	1	34	75	48	56
32.5	1	32	75	47	55
37.5	1	35	76	46	57
42.5	1	33	76	43	57
10% kerosene- water system					
12.5	1	29	76	50	67
17.5	1	30	77	51	65
22.5	1	31	76	51	64
27.5	1	33	75	48	63
32.5	1	35	76	51	63
37.5	1	36	75	52	64
42.5	1	37	75	51	65
20% kerosene-water system					
12.5	1	34	78	51	69
17.5	1	35	78	50	67
22.5	1	35	79	48	68
27.5	1	36	79	48	67
32.5	1	37	79	47	66
37.5	1	38	80	46	65
42.5	1	39	80	47	65
25% kerosene- water system					
12.5	1	31	73	48	59
17.5	1	33	76	47	67
22.5	1	34	75	50	64
27.5	1	33	74	48	62.9
32.5	1	35	72	48	61.9
37.5	1	32	77	46	59.9
42.5	1	36	78	45	58.9

Table 2.1 Kerosene- water system

2.5.1.2 MISCIBLE SYSTEMS

Volumetric flow rate of cold fluid lph	Volumetric flow rate of hot fluid lpm	Inlet Temperature °C		Outlet Temperature °C	
		Cold Fluid	Hot Fluid	Cold Fluid	Hot Fluid
9% Acetic acid –water sytem					
12.5	1	33	72	56.9	63
17.5	1	33	72	54.9	61
22.5	1	33	72	53.9	58
27.5	1	33	72	49.9	57
32.5	1	33	72	47.9	56
37.5	1	33	72	47.9	55
42.5	1	33	72	42.9	54
10% Acetic acid – water system					
12.5	1	33	72	53.9	63.9
17.5	1	33	72	51.9	62.9
22.5	1	33	72	50.9	58.9

27.5	1	33	72	50.9	57.9
32.5	1	33	72	49.9	55.9
37.5	1	33	72	48.9	52.9
42.5	1	33	72	46.9	54.9
20% Acetic acid –water system					
12.5	1	33	72	54	67
17.5	1	33	72	52	64
22.5	1	33	72	52	63
27.5	1	33	72	52	62
32.5	1	33	72	51	61
37.5	1	33	72	50	61
42.5	1	33	72	49	60
25% Acetic acid – water system					
12.5	1	33	72	60	64
17.5	1	33	72	58	63
22.5	1	33	72	58	62
27.5	1	33	72	57	62
32.5	1	33	72	54	61
37.5	1	33	72	55	61
42.5	1	33	72	54	60

Table 2.2 Acetic acid- water system

2.5.2 Co-Current Pattern

2.5.2.1 IMMISCIBLE SYSTEMS

Volumetric flow rate of cold fluid lph	Volumetric flow rate of hot fluid lpm	Inlet Temperature °C		Outlet Temperature °C	
		Cold Fluid	Hot Fluid	Cold Fluid	Hot Fluid
9% kerosene-water sytem					
12.5	1	31	74	45	65
17.5	1	31	74	46	63
22.5	1	33	73	45	61
27.5	1	34	75	45	63
32.5	1	32	75	43	63
37.5	1	35	76	44	64
42.5	1	33	76	43	64
10% kerosene- water system					
12.5	1	29	76	45	68
17.5	1	30	77	46	67
22.5	1	31	76	46	66
27.5	1	33	75	44	65
32.5	1	35	76	47	65
37.5	1	36	75	48	66
42.5	1	37	75	47	67
20% kerosene-water system					
12.5	1	34	78	48	71
17.5	1	35	78	48	68
22.5	1	35	79	47	68
27.5	1	36	79	48	67
32.5	1	37	79	47	66
37.5	1	38	80	46	65
42.5	1	39	80	47	65
25% kerosene- water system					
12.5	1	31	73	43	64
17.5	1	33	76	44	67
22.5	1	34	75	45	64
27.5	1	33	74	43	62
32.5	1	35	72	44	62
37.5	1	32	77	42	63
42.5	1	36	78	43	63

Table 2.3 Kerosene – Water system

2.5.2.2 MISCIBLE SYSTEMS

Volumetric flow rate of cold fluid lph	Volumetric flow rate of hot fluid lpm	Inlet Temperature °C		Outlet Temperature °C	
		Cold Fluid	Hot Fluid	Cold Fluid	Hot Fluid
9% Acetic acid -water sytem					
12.5	1	33	72	49	68
17.5	1	33	72	47	67
22.5	1	33	72	46	64
27.5	1	33	72	44	64
32.5	1	33	72	44	62
37.5	1	33	72	43	61
42.5	1	33	72	42	61
10% Acetic acid - water system					
12.5	1	33	72	48	66
17.5	1	33	72	47	65
22.5	1	33	72	46	63
27.5	1	33	72	44	62
32.5	1	33	72	43	61
37.5	1	33	72	43	61
42.5	1	33	72	42	60
20% Acetic acid -water system					
12.5	1	33	72	50	69
17.5	1	33	72	48	68
22.5	1	33	72	48	68
27.5	1	33	72	48	67
32.5	1	33	72	47	66
37.5	1	33	72	46	66
42.5	1	33	72	45	65
25% Acetic acid - water system					
12.5	1	33	72	50	67
17.5	1	33	72	48	66
22.5	1	33	72	48	65
27.5	1	33	72	47	64
32.5	1	33	72	46	62
37.5	1	33	72	45	61
42.5	1	33	72	44	60

Table 2.4 Acetic acid – water system

2.6 CALCULATION METHOD

The performance of the heat exchanger for different solutions of different solutions of different concentrations is evaluated by calculating the overall heat transfer coefficient, NTU, exchanger effectiveness and efficiencies. The heat exchanger specifications are taken from the section 3.2.2. The calculation method is similar for co-current and counter-current operations. The calculation involves the following steps,

1. Average Temperature:

The average temperature of hot and cold fluid are calculated using the formula, For cold fluid, $t_{avg} = \frac{(t_1 + t_2)}{2}$

For hot fluid, $T_{avg} = \frac{(T_1 + T_2)}{2}$

t_1 – Inlet temperature of cold fluid
t_2 – Outlet temperature of cold fluid
T_1 – Inlet temperature of hot fluid
T_2 – Outlet temperature of hot fluid

2. Log Mean Temperature Difference:

For counter-current flow, $\text{LMTD} = \frac{((T_2 - t_1) - (T_1 - t_2))}{\ln \frac{(T_2 - t_1)}{(T_1 - t_2)}}$

For co-current flow, $\text{LMTD} = \frac{((T_2 - t_2) - (T_1 - t_1))}{\ln \frac{(T_2 - t_2)}{(T_1 - t_1)}}$

3. Fluid Properties:

Fluid properties such as density, viscosity, specific heat capacity and thermal conductivity at average temperature of hot and cold fluid should be calculated. Properties of pure substance at average temperature are taken from Perry's chemical engineering handbook. To find the properties of fluid mixture the following formulas are used,

$$\mu_{mix} = \mu_{pure}(x_1) + \mu_{water}(1 - x_1)$$
$$\rho_{mix} = \rho_{pure}(x_1) + \rho_{water}(1 - x_1)$$
$$c_{p\,mix} = c_{p\,pure}(x_1) + c_{p\,water}(1 - x_1)$$
$$k_{mix} = k_{pure}(x_1) + k_{water}(1 - x_1)$$

4. Mass Flow Rate:

The volumetric flow rate of hot and cold fluid are converted in to mass flow rate by multiplying it with their respective densities at average temperature.

Mass flow rate (m) = Volumetric flow rate x Density

5. Dimensionless Numbers:

Reynolds number, Nusselt number and Prandtl number for hot and cold fluids are calculated as follows;

Reynolds number $= \frac{(D_e V \rho)}{\mu}$.

Prandtl number $= \frac{(c_p \mu)}{k}$.

Nusselt number $= \frac{(hD_e)}{k} = (0.28)(N_{\text{Re}})^{0.65}(N_{\text{Pr}})^{0.4}$.

6. Heat Transfer Coefficient:

Individual heat transfer coefficient is calculated from respective Nusselt number. Overall heat transfer is found using the formula,

$$U_o = \frac{1}{\frac{1}{h_c} + \frac{x}{k} + \frac{1}{h_h}}$$

7. Capacity Rate Ratio:
Capacity rate = Mass flow rate (m) x Specific heat capacity (cp)

Capacity rate ratio = $\frac{C_{\min}}{C_{\max}}$

$$C_{\min} = m_c x c_{pc}$$

$$C_{\max} = m_h x c_{ph}$$

8. Number of Transfer Units:

$$NTU = \frac{(U_o x A)}{C_{\min}}.$$

9. Efficiency:
Efficiency for both hot and cold side are calculated using the formula,

Cold side efficiency = $\eta_c = \frac{(m_c x c_{pc} x \Delta T)}{(m_c x c_{pc} x \Delta T_{\max})}.$

Hot side efficiency = $\eta_h = \frac{(m_h x c_{ph} x \Delta T)}{(m_h x c_{ph} x \Delta T_{\max})}.$

10. Effectiveness:

Effectiveness = $\frac{(NTU)}{(1 + NTU)} x 100.$

III. PERFORMANCE ANALYSIS OF PLATE TYPE HEAT EXCHANGER

3.1 COUNTER CURRENT FLOW PATTERN

3.1.1 Immiscible Systems

Table 3.1 Kerosene -water system

Cold Fluid					Hot Fluid (hot water)					Heat Transfer coefficient			Capacity Rate Ratio	No. of Transfer units	Effectiveness	Efficiency	
Fluid Temperature		Mass flow rate	Reynolds number	Nusselts number	Fluid temperature		Mass Flow rate	Reynolds number	Nusselts number	Cold side	Hot side	Overall				cold side	hot side
K		Kg/sec			K		Kg/sec			W/m²K	W/m²K	W/m²K			%	%	%
t_1	t_2	m_c	N_{Re}	N_{Nu}	T_1	T_2	m_h	N_{Re}	N_{Nu}	h_c	h_h	U_o	R_c	NTU	ε	η_c	η_h
9% Kerosene– Water System																	
304.17	323.17	0.00336	12.4555	2.52857	347.17	332.17	0.01623	85.4683	7.4868	148.76	493.89	113.38	0.197022	2.47244	71.2018	44.186	34.884
304.17	322.17	0.0047	17.2782	3.1409	347.17	331.17	0.01624	84.8646	7.4765	184.61	492.83	132.99	0.275804	2.07129	67.4404	41.86	37.209
306.17	321.17	0.00604	22.4199	3.70512	346.17	330.17	0.01625	83.6641	7.4558	217.98	490.72	149.29	0.354402	1.8086	64.3951	37.5	40
307.17	321.17	0.00738	27.6535	4.22913	348.17	329.17	0.01624	84.2632	7.4662	249.05	491.78	163.35	0.433199	1.61937	61.8228	34.146	46.341
305.17	320.17	0.00873	31.7927	4.68808	348.17	328.17	0.01625	83.6641	7.4558	275.27	490.72	174.1	0.512044	1.45985	59.347	34.884	46.512
308.17	319.17	0.01007	37.3664	5.16421	349.17	330.17	0.01623	85.4683	7.4868	303.83	493.89	185.55	0.591065	1.34877	57.4246	26.829	46.341
306.17	316.17	0.01143	40.4245	5.54983	349.17	330.17	0.01623	85.4683	7.4868	324.86	493.89	193.19	0.670298	1.23831	55.3234	23.256	44.186
10% Kerosene– Water System																	
302.17	323.17	0.00335	12.3096	2.52427	349.17	340.17	0.01618	91.6062	7.5893	146.97	504.22	112.86	0.196026	2.47921	71.2579	44.681	19.149
303.17	324.17	0.00469	17.5538	3.15307	350.17	338.17	0.01619	90.9864	7.5791	183.94	503.21	133.39	0.274309	2.09349	67.6741	44.681	25.532
304.17	324.17	0.00603	22.7761	3.71946	349.17	337.17	0.0162	89.7494	7.5587	217.2	501.18	149.86	0.352481	1.82961	64.6595	44.444	26.667
306.17	321.17	0.00737	27.5845	4.22985	348.17	336.17	0.01621	88.5174	7.5382	246.76	499.11	163.15	0.430667	1.62948	61.9696	35.714	28.571
308.17	324.17	0.0087	34.1026	4.7584	349.17	336.17	0.0162	89.1327	7.5484	278.89	500.15	176.73	0.508771	1.49448	59.9114	39.024	31.707
309.17	325.17	0.01003	40.049	5.24112	348.17	337.17	0.0162	89.1327	7.5484	307.72	500.15	187.88	0.586891	1.37731	57.9357	41.026	28.205
310.17	324.17	0.01137	45.3889	5.68534	348.17	338.17	0.0162	89.7494	7.5587	333.8	501.18	197.46	0.665293	1.27719	56.0863	36.842	26.316
20% Kerosene– Water System																	
307.17	324.17	0.00326	13.9502	2.60983	351.17	342.17	0.01616	94.0871	7.63	139.85	508.15	108.79	0.18151	2.58342	72.0937	38.636	20.455
308.17	323.17	0.00457	19.5303	3.24785	351.17	340.17	0.01617	92.847	7.6096	174.04	506.21	128.29	0.253998	2.17605	68.5143	34.884	25.581
308.17	321.17	0.00588	24.6673	3.81009	352.17	341.17	0.01616	94.0871	7.63	203.8	508.15	143.93	0.326748	1.89854	65.4999	29.545	25
309.17	321.17	0.00718	30.4194	4.34898	352.17	340.17	0.01616	93.4673	7.6198	232.84	507.19	157.73	0.39925	1.70244	62.9964	27.907	27.907
310.17	320.17	0.00849	35.9502	4.84781	352.17	339.17	0.01617	92.847	7.6096	259.54	506.21	169.44	0.471733	1.54746	60.7453	23.81	30.952
311.17	319.17	0.00979	41.481	5.32037	353.17	338.17	0.01617	92.847	7.6096	284.84	506.21	179.87	0.544307	1.42369	58.7406	19.048	35.714
312.17	320.17	0.01109	47.8508	5.79256	353.17	338.17	0.01617	92.847	7.6096	310.67	506.21	189.84	0.616819	1.32593	57.0065	19.512	36.585
25% Kerosene– Water System																	
304.17	321.17	0.00323	13.7402	2.61369	346.17	332.17	0.01624	84.8646	7.4765	132.82	492.83	103.83	0.173828	2.56579	71.9557	40.476	33.333
306.17	320.17	0.00452	19.4125	3.25882	349.17	340.17	0.01618	91.6062	7.5893	165.77	504.22	123.62	0.243964	2.18208	68.574	32.558	20.93
307.17	323.17	0.0058	25.8709	3.86598	348.17	337.17	0.0162	89.1327	7.5484	197.38	500.15	140.07	0.313381	1.92302	65.7888	39.024	26.829
306.17	321.17	0.0071	30.783	4.37997	347.17	336.1	0.01621	87.8609	7.5272	223.01	498	152.31	0.382845	1.71085	63.1112	36.585	27
308.17	321.17	0.00839	37.0386	4.90069	345.17	335.1	0.01623	86.0316	7.4964	249.98	494.86	164.09	0.452148	1.55955	60.9306	35.135	27.216
305.17	319.17	0.00969	40.8442	5.3279	350.17	333.1	0.01621	87.8609	7.5272	270.49	498	173.06	0.52206	1.42554	58.7721	31.111	37.933
309.17	318.17	0.01097	47.5737	5.81243	351.17	332.1	0.01621	87.8609	7.5272	295.94	498	183.14	0.59167	1.33107	57.1012	21.429	45.405

3.1.2 Miscible Systems

Table 3.2 acid -water system

Cold Fluid					Hot Fluid (hot water)					Heat Transfer coefficient			Capacity Rate Ratio	No. of Transfer units	Effectiveness	Efficiency	
Fluid Temperature		Mass flow rate	Reynolds number	Nusselts number	Fluid temperature		Mass Flow rate	Reynolds number	Nusselts number	Cold side	Hot side	Overall				cold side	hot side
K		Kg/sec			K		Kg/sec			W/m^2K	W/m^2K	W/m^2K			%	%	%
t_1	t_2	m_c	N_{Re}	N_{Nu}	T_1	T_2	m_h	N_{Re}	N_{Nu}	h_c	h_h	U_c	R_c	NTU	ε	η_c	η_h
9% Acetic acid – Water System																	
306.17	330.1	0.00343	12.2165	2.52736	345.17	336.17	0.01622	86.682	7.5074	150.56	495.99	114.53	0.201772	2.4398	70.9289	61.359	23.077
306.17	328.1	0.00481	16.7936	3.1334	345.17	334.17	0.01623	85.4683	7.4868	186.35	493.89	133.97	0.282452	2.0379	67.0825	56.231	28.205
306.17	327.1	0.00619	21.3954	3.68253	345.17	331.17	0.01625	83.6641	7.4558	218.82	490.72	149.68	0.362972	1.7705	63.906	53.667	35.897
306.17	323.1	0.00757	25.2118	4.16453	345.17	330.17	0.01625	83.0673	7.4454	246.58	489.66	162.05	0.443838	1.5673	61.0484	43.41	38.462
306.17	321.1	0.00895	29.2574	4.62521	345.17	329.17	0.01626	82.4728	7.435	273.34	488.6	173.06	0.524599	1.4158	58.6057	38.282	41.026
306.17	321.1	0.01033	33.7586	5.07606	345.17	328.17	0.01626	81.8806	7.4245	299.99	487.54	183.22	0.605173	1.2991	56.5041	38.282	43.59
306.17	316.1	0.01172	36.5612	5.45687	345.17	327.17	0.01627	81.2908	7.4141	320.89	486.48	190.65	0.686295	1.1917	54.3731	25.462	46.154
10% Acetic acid – Water System																	
306.17	327.1	0.00344	11.83	2.51335	345.17	337.1	0.01622	87.2492	7.517	148.17	496.96	113.19	0.200962	2.4216	70.7739	53.667	20.692
306.17	325.1	0.00482	16.2614	3.11609	345.17	336.1	0.01622	86.6394	7.5067	183.38	495.91	132.58	0.281378	2.0252	66.9447	48.538	23.256
306.17	324.1	0.00619	20.7173	3.66224	345.17	332.1	0.01624	84.2212	7.4654	215.33	491.7	148.13	0.36151	1.7596	63.7632	45.974	33.513
306.17	324.1	0.00757	25.3211	4.17248	345.17	331.1	0.01625	83.6222	7.4551	245.33	490.64	161.62	0.441747	1.5708	61.1018	45.974	36.077
306.17	323.1	0.00895	29.6529	4.64246	345.17	329.1	0.01626	82.4313	7.4343	272.72	488.52	172.8	0.521922	1.4209	58.6928	43.41	41.205
306.17	322.1	0.01033	33.9044	5.08564	345.17	326.1	0.01627	80.6622	7.4028	298.47	485.34	182.35	0.601921	1.2993	56.5076	40.846	48.897
306.17	320.1	0.01171	37.7323	5.49658	345.17	328.1	0.01626	81.8393	7.4238	321.97	487.46	191.19	0.682706	1.2016	54.5778	35.718	43.769
20% Acetic acid – Water System																	
306.17	327.17	0.00345	11.3042	2.51875	345.17	340.17	0.0162	89.1327	7.5484	136.69	500.15	106.51	0.19148	2.3932	70.3373	53.846	12.821
306.17	325.17	0.00483	15.5328	3.1223	345.17	337.17	0.01622	87.2919	7.5177	169.16	497.03	125.05	0.267965	2.0064	66.5437	48.718	20.513
306.17	325.17	0.00622	19.9707	3.67637	345.17	336.17	0.01622	86.682	7.5074	199.18	495.99	140.65	0.344449	1.7551	63.5107	48.718	23.077
306.17	325.17	0.0076	24.4086	4.18858	345.17	335.17	0.01623	86.0741	7.4971	226.93	494.94	153.84	0.420899	1.5707	60.9088	48.718	25.641
306.17	324.17	0.00898	28.581	4.66008	345.17	334.17	0.01623	85.4683	7.4868	252.26	493.89	164.96	0.497384	1.4249	58.5735	46.154	28.205
306.17	323.17	0.01037	32.6769	5.10468	345.17	334.17	0.01623	85.4683	7.4868	276.09	493.89	174.82	0.573985	1.3086	56.4996	43.59	28.205
306.17	322.17	0.01175	36.6984	5.52702	345.17	333.17	0.01624	84.8646	7.4765	298.66	492.83	183.47	0.650461	1.2116	54.6032	41.026	30.769
25% Acetic acid – Water System																	
306.17	333.17	0.00345	11.7229	2.55533	345.17	337.17	0.01622	87.2919	7.5177	133.28	497.03	104.3	0.186379	2.4059	70.6394	69.231	20.513
306.17	331.17	0.00484	16.0908	3.16648	345.17	336.17	0.01622	86.682	7.5074	164.92	495.99	122.66	0.260935	2.0205	66.8931	64.103	23.077
306.17	331.17	0.00622	20.6882	3.72839	345.17	335.17	0.01623	86.0741	7.4971	194.19	494.94	138.06	0.335413	1.7688	63.8839	64.103	25.641
306.17	330.17	0.0076	25.0391	4.23892	345.17	335.17	0.01623	86.0741	7.4971	220.62	494.94	150.91	0.409999	1.5818	61.2668	61.538	25.641
306.17	327.17	0.00899	28.7472	4.69608	345.17	334.17	0.01623	85.4683	7.4868	243.84	493.89	161.32	0.484613	1.4302	58.8509	53.846	28.205
306.17	328.17	0.01037	33.4888	5.16432	345.17	334.17	0.01623	85.4683	7.4868	268.37	493.89	171.7	0.559101	1.3194	56.8857	56.41	28.205
306.17	327.17	0.01176	37.5924	5.59068	345.17	333.17	0.01624	84.8646	7.4765	290.29	492.83	180.27	0.633583	1.2222	54.9996	53.846	30.769

3.2 CO-CURRENT FLOW

3.2.1 Immiscible Systems

Table 3.3 Kerocene -water system

Cold Fluid					Hot Fluid (hot water)					Heat Transfer coefficient			Capacity Rate Ratio	No. of Transfer units	Effectiveness	Efficiency	
Fluid Temperature		Mass flow rate	Reynolds number	Nusselts number	Fluid temperature		Mass Flow rate	Reynolds number	Nusselts number	Cold side	Hot side	Overall				cold side	hot side
K		Kg/sec			K		Kg/sec			W/m^2K	W/m^2K	W/m^2K			%	%	%
t_1	t_2	m_c	N_{Re}	N_{Nu}	T_1	T_2	m_h	N_{Re}	N_{Nu}	h_c	h_h	U_c	R_c	NTU	ε	η_c	η_h
9% Kerosene– Water System																	
304.17	318.17	0.00336	11.8896	2.50506	347.17	338.17	0.01621	88.5174	7.5382	146.63	499.11	112.4	0.197368	2.44965	71.0116	32.558	20.93
304.17	319.17	0.0047	16.8028	3.12334	347.17	336.17	0.01621	87.9038	7.528	183.02	498.08	132.54	0.276218	2.06345	67.357	34.884	25.581
306.17	318.17	0.00605	21.8066	3.6845	346.17	334.17	0.01622	86.682	7.5074	216.12	495.99	148.89	0.354933	1.8031	64.3252	30	30
307.17	318.17	0.00739	26.9015	4.20569	348.17	336.17	0.01623	86.0741	7.4971	246.94	494.94	162.78	0.433655	1.61313	61.7317	26.829	29.268
305.17	316.17	0.00874	30.6216	4.65297	348.17	336.17	0.01623	85.4683	7.4868	272.07	493.89	173.21	0.512645	1.45163	59.2108	25.581	27.907
308.17	317.17	0.01008	36.6839	5.14507	349.17	337.17	0.01623	85.4683	7.4868	302.1	493.89	184.91	0.591215	1.34374	57.3332	21.951	29.268
306.17	316.17	0.01143	40.4245	5.54983	349.17	337.17	0.01624	84.8646	7.4765	324.86	492.83	193.03	0.670148	1.23727	55.3027	23.256	27.907
10% Kerosene– Water System																	
302.17	318.17	0.00335	11.7442	2.50058	349.17	341.17	0.01618	92.2265	7.5994	144.83	505.22	111.64	0.196188	2.45105	71.0233	34.043	17.021
303.17	319.17	0.00469	16.7568	3.12372	350.17	340.17	0.01618	92.2265	7.5994	181.31	505.22	132.14	0.274597	2.0726	67.4543	34.043	21.277
304.17	319.17	0.00603	21.748	3.68497	349.17	339.17	0.01619	90.9864	7.5791	214.11	503.21	148.57	0.352851	1.8127	64.447	33.333	22.222
306.17	317.17	0.00737	26.5809	4.19838	348.17	338.17	0.0162	89.7494	7.5587	243.94	501.18	162.13	0.431067	1.61851	61.8104	26.19	23.81
308.17	320.17	0.0087	32.8988	4.72373	349.17	338.17	0.01619	90.3674	7.5689	275.84	502.2	175.75	0.509254	1.48547	59.7662	29.268	26.829
309.17	321.17	0.01004	38.6528	5.20326	348.17	339.17	0.01619	90.3674	7.5689	304.41	502.2	186.93	0.587457	1.36963	57.7994	30.769	23.077
310.17	320.17	0.01138	43.8065	5.64428	348.17	340.17	0.01619	90.9864	7.5791	330.21	503.21	196.51	0.665936	1.27041	55.9551	26.316	21.053
20% Kerosene– Water System																	
307.17	321.17	0.00327	13.5814	2.59538	351.17	344.17	0.01615	95.3232	7.6502	138.7	510.04	108.18	0.181618	2.56849	71.9769	31.818	15.909
308.17	321.17	0.00457	19.1857	3.23588	351.17	341.17	0.01616	93.4673	7.6198	173.09	507.19	127.84	0.25408	2.1681	68.4354	30.233	23.256
308.17	320.17	0.00588	24.4466	3.80302	352.17	341.17	0.01616	94.0871	7.63	203.23	508.15	143.65	0.326763	1.89472	65.4544	27.273	25
309.17	321.17	0.00718	30.4194	4.34898	352.17	340.17	0.01616	93.4673	7.6198	232.84	507.19	157.73	0.39925	1.70244	62.9964	27.907	27.907
310.17	320.17	0.00849	35.9502	4.84781	352.17	339.17	0.01617	92.847	7.6096	259.54	506.21	169.44	0.471733	1.54746	60.7453	23.81	30.952
311.17	319.17	0.00979	41.481	5.32037	353.17	338.17	0.01617	92.847	7.6096	284.84	506.21	179.87	0.544307	1.42369	58.7406	19.048	35.714
312.17	320.17	0.01109	47.8508	5.79256	353.17	338.17	0.01617	92.847	7.6096	310.67	506.21	189.84	0.616819	1.32593	57.0065	19.512	36.585
25% Kerosene– Water System																	
304.17	316.17	0.00323	13.1165	2.58872	346.17	337.17	0.01621	87.9038	7.528	130.9	498.08	102.87	0.174024	2.54213	71.7684	28.571	21.429
306.17	317.17	0.00452	18.8854	3.24026	349.17	340.17	0.01618	91.6062	7.5893	164.34	504.22	122.83	0.243963	2.16805	68.4349	25.581	20.93
307.17	318.17	0.00581	24.7324	3.82985	348.17	337.17	0.0162	89.1327	7.5484	194.63	500.15	138.68	0.313383	1.90391	65.5637	26.829	26.829
306.17	316.17	0.00711	29.4026	4.33848	347.17	335.17	0.01622	87.2919	7.5177	219.82	497.03	150.73	0.382765	1.69307	62.8677	24.39	29.268
308.17	317.17	0.00839	35.7246	4.86392	345.17	335.17	0.01623	86.0741	7.4971	247.18	494.94	162.88	0.452155	1.5481	60.755	24.324	27.027
305.17	315.17	0.0097	39.3495	5.28705	350.17	336.17	0.0162	89.7494	7.5587	267.33	501.18	172.14	0.522427	1.41793	58.6423	22.222	31.111
309.17	316.17	0.01098	46.7168	5.79049	351.17	336.17	0.01619	90.3674	7.5689	294.27	502.2	183.06	0.592213	1.33046	57.09	16.667	35.714

3.2.2 Miscible Systems

Table 3.4 Acetic acid -water system

Cold Fluid					Hot Fluid (hot water)					Heat Transfer coefficient			Capacity Rate Ratio	No. of Transfer units	Effectiveness	Efficiency	
Fluid Temperature		Mass flow rate	Reynolds number	Nusselts number	Fluid temperature		Mass Flow rate	Reynolds number	Nusselts number	Cold side	Hot side	Overall				cold side	hot side
K		Kg/sec			K		Kg/sec			W/m^2K	W/m^2K	W/m^2K			%	%	%
t_1	t_2	m_c	N_{Re}	N_{Nu}	T_1	T_2	m_h	N_{Re}	N_{Nu}	h_c	h_h	U_o	R_c	NTU	ε	η_c	η_h
9% Acetic acid – Water System																	
306.17	322.17	0.00344	11.3631	2.49028	345.17	341.17	0.0162	89.7494	7.5587	147.32	501.18	112.91	0.20227	2.4021	70.6066	41.026	10.256
306.17	320.17	0.00482	15.6212	3.08778	345.17	340.17	0.0162	89.1327	7.5484	182.32	500.15	132.32	0.28322	2.01	66.7775	35.897	12.821
306.17	319.17	0.0062	19.9026	3.62913	345.17	337.17	0.01622	87.2919	7.5177	214.07	497.03	148.01	0.36395	1.7484	63.6151	33.333	20.513
306.17	317.17	0.00758	23.8877	4.11991	345.17	337.17	0.01622	87.2919	7.5177	242.53	497.03	161.07	0.44498	1.5563	60.8807	28.205	20.513
306.17	317.17	0.00896	28.231	4.59246	345.17	335.17	0.01623	86.0741	7.4971	270.35	494.94	172.63	0.52565	1.4114	58.5298	28.205	25.641
306.17	316.17	0.01034	32.2803	5.03113	345.17	334.17	0.01623	85.4683	7.4868	295.87	493.89	182.55	0.60649	1.2932	56.3937	25.641	28.205
306.17	315.17	0.01172	36.2548	5.44786	345.17	334.17	0.01623	85.4683	7.4868	320.05	493.89	191.48	0.68747	1.1967	54.4766	23.077	28.205
10% Acetic acid – Water System																	
306.17	321.17	0.00344	11.2062	2.48586	345.17	339.17	0.01621	88.5174	7.5382	145.76	499.11	111.89	0.20126	2.3914	70.5136	38.462	15.385
306.17	320.17	0.00482	15.5467	3.08795	345.17	338.17	0.01621	87.9038	7.528	180.9	498.08	131.42	0.28174	2.0059	66.7326	35.897	17.949
306.17	319.17	0.0062	19.8081	3.62934	345.17	336.17	0.01622	86.682	7.5074	212.4	495.99	147.11	0.36214	1.7462	63.5856	33.333	23.077
306.17	317.17	0.00758	23.7759	4.12019	345.17	335.17	0.01623	86.0741	7.4971	240.65	494.94	160.02	0.44266	1.5535	60.8382	28.205	25.641
306.17	316.17	0.00896	27.8465	4.58462	345.17	334.17	0.01623	85.4683	7.4868	267.5	493.89	171.34	0.52312	1.4073	58.4589	25.641	28.205
306.17	316.17	0.01034	32.1306	5.03152	345.17	334.17	0.01623	85.4683	7.4868	293.57	493.89	181.68	0.6036	1.2932	56.3926	25.641	28.205
306.17	315.17	0.01173	36.0883	5.44833	345.17	333.17	0.01624	84.8646	7.4765	317.57	492.83	190.43	0.68404	1.1958	54.459	23.077	30.769
20% Acetic acid – Water System																	
306.17	323.17	0.00346	10.8923	2.49942	345.17	342.17	0.01619	90.3674	7.5689	135.18	502.2	105.69	0.19167	2.3733	70.3553	43.59	7.6923
306.17	321.17	0.00484	14.9754	3.09895	345.17	341.17	0.0162	89.7494	7.5587	167.31	501.18	124.29	0.26836	1.9931	66.5896	38.462	10.256
306.17	321.17	0.00622	19.2541	3.64887	345.17	341.17	0.0162	89.7494	7.5587	197	501.18	139.96	0.34503	1.7456	63.5783	38.462	10.256
306.17	321.17	0.00761	23.5327	4.15725	345.17	340.17	0.0162	89.1327	7.5484	224.44	500.15	153.18	0.42161	1.5631	60.9854	38.462	12.821
306.17	320.17	0.00899	27.5639	4.62569	345.17	339.17	0.01621	88.5174	7.5382	249.5	499.11	164.35	0.49822	1.4188	58.6579	35.897	15.385
306.17	319.17	0.01038	31.5239	5.06754	345.17	339.17	0.01621	88.5174	7.5382	273.08	499.11	174.26	0.57495	1.3036	56.5903	33.333	15.385
306.17	318.17	0.01177	35.4149	5.48739	345.17	338.17	0.01621	87.9038	7.528	295.43	498.08	182.95	0.65156	1.2075	54.6999	30.769	17.949
25% Acetic acid – Water System																	
345.17	340.17	0.0162	89.1327	7.54843	306.17	323.17	0.00346	10.6511	2.5038	129.58	500.15	102.15	0.18673	2.3535	70.18	43.59	12.821
345.17	339.17	0.01621	88.5174	7.5382	306.17	321.17	0.00485	14.6445	3.1043	160.38	499.11	120.31	0.26143	1.9794	66.4367	38.462	15.385
345.17	338.17	0.01621	87.9038	7.52796	306.17	321.17	0.00624	18.8286	3.6552	188.84	498.08	135.57	0.33605	1.7348	63.4346	38.462	17.949
345.17	337.17	0.01622	87.2919	7.5177	306.17	320.17	0.00762	22.8095	4.1569	214.57	497.03	148.24	0.41068	1.5519	60.814	35.897	20.513
345.17	335.17	0.01623	86.0741	7.49714	306.17	319.17	0.00901	26.7215	4.6255	238.54	494.94	159.09	0.4852	1.4091	58.4899	33.333	25.641
345.17	334.17	0.01623	85.4683	7.48684	306.17	318.17	0.0104	30.567	5.0676	261.1	493.89	168.69	0.55979	1.2947	56.422	30.769	28.205
345.17	333.17	0.01624	84.8646	7.47651	306.17	317.17	0.01179	34.3482	5.4877	282.48	492.83	177.23	0.63437	1.2001	54.5472	28.205	30.769

IV. RESULTS AND DISCUSSION

5.1 COUNTER-CURRENT FLOW PATTERN

5.1.1 Effect Of N_{Re} (Cold) On Efficiency % (Cold)

5.1.1.1 Kerosene – Water System

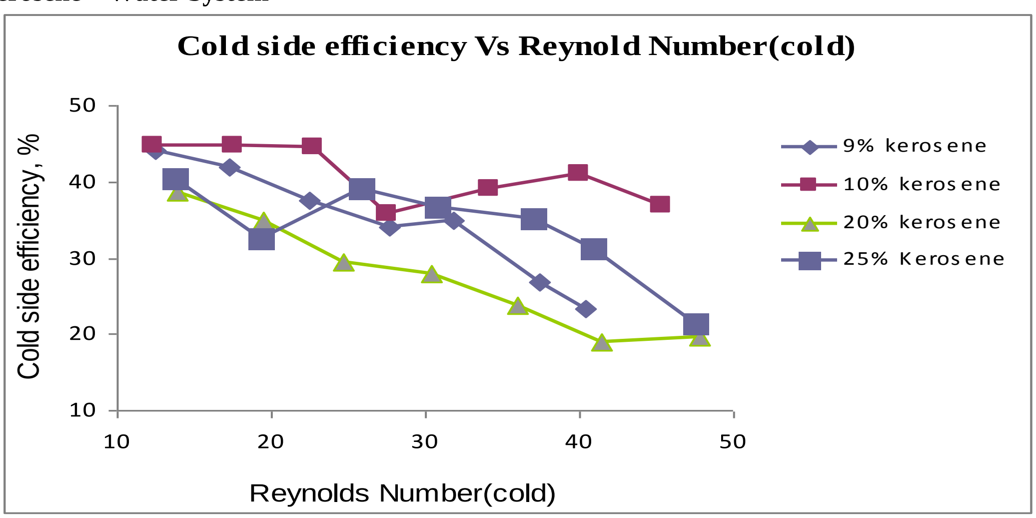

Fig. 5.1 Effect of cold side flow rate and composition on η_c of kerosene-water system

From the above graph it can be observed that, as N_{Re} (cold) increases the efficiency (cold) decreases. The graph also shows that as the composition of kerosene increases the efficiency of cold side increases and then decreases gradually for same flow rate of cold fluid.

5.1.2 Acetic acid-water System

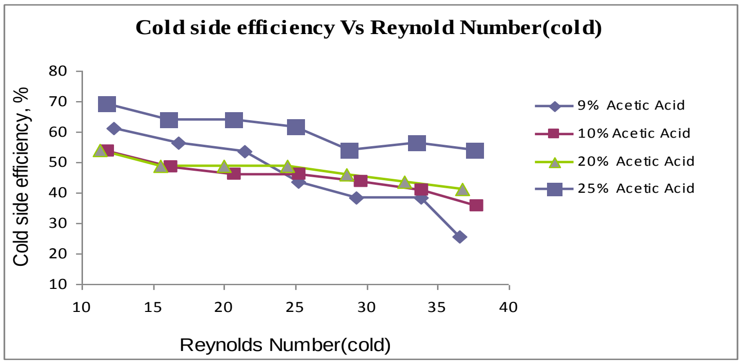

Fig. 5.2 Effect of cold side flow rate and composition on η_c of acetic acid-water system

It can be observed that, as flow rate of cold fluid increases the efficiency of cold side decreases. The graph also shows that as the composition of acetic acid increases the efficiency decreases for same flow rate of cold fluid. Maximum cold side efficiency is seen for 25% acetic acid -water system

5.1.2 Effect of N_{Re} (Cold) On Hot Side Efficiency (%)

5.1.2.1 Kerosene – Water System

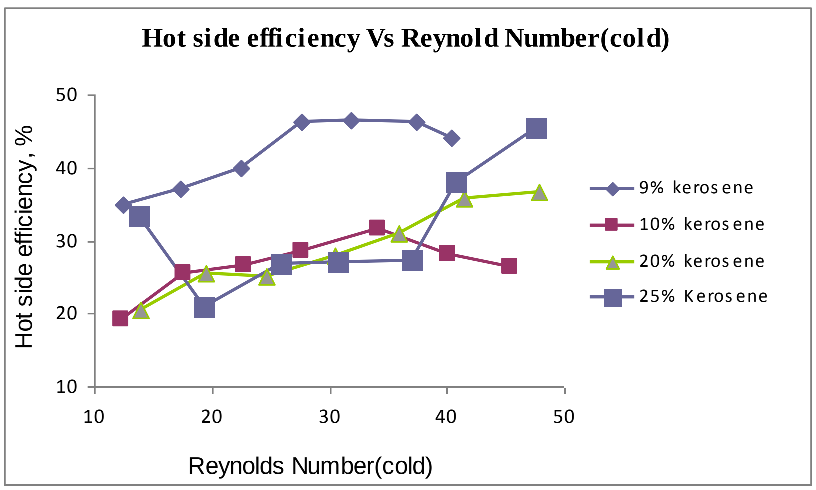

Fig. 5.3 Effect of cold side flow rate and composition on η_h of kerosene-water system

From the graph Reynolds number of cold fluid Vs Hot side efficiency it can be observed that, as flow rate of cold fluid increases the efficiency of hot side gradually increases. When the flow rate on cold side is increased, heat transfer from hot to cold side is also increased. As the composition of kerosene increases from 9 % to 25 %, the efficiency of hot side decreases gradually for same flow rate of cold fluid.

5.1.2.2 Acetic Acid – Water System

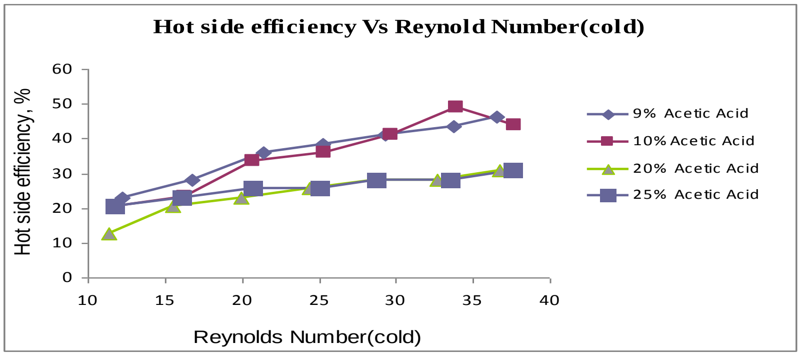

Fig. 5.4 Effect of cold side flow rate and composition on η_h of acetic acid-water system

From the graph it can be observed that, as flow rate of cold fluid increases the efficiency of hot side gradually increases. When the flow rate on cold side is increased, heat transfer from hot to cold side is also increased. As the composition of acetic acid increases, the efficiency of hot side decreases for same flow rate of cold fluid.

5.2 CO-CURRENT FLOW PATTERN

5.2.1 Effect of N_{Re} (Cold) On Cold Side Efficiency (%)

5.2.1.1 Kerosene – Water System

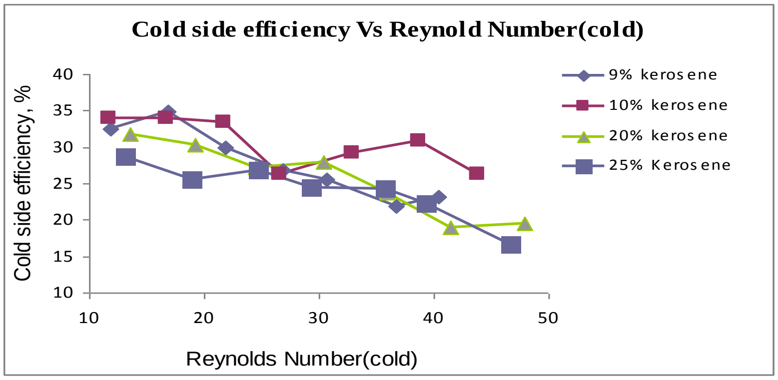

Fig. 5.5 Effect of cold side flow rate and composition on η_c of kerosene-water system

From the above graph it can be observed that, as N_{Re} (cold) increases the efficiency (cold) decreases. The graph also shows that as the composition of kerosene increases the efficiency of cold side decreases gradually for same flow rate of cold fluid.

5.2.1.2 Acetic Acid – Water System

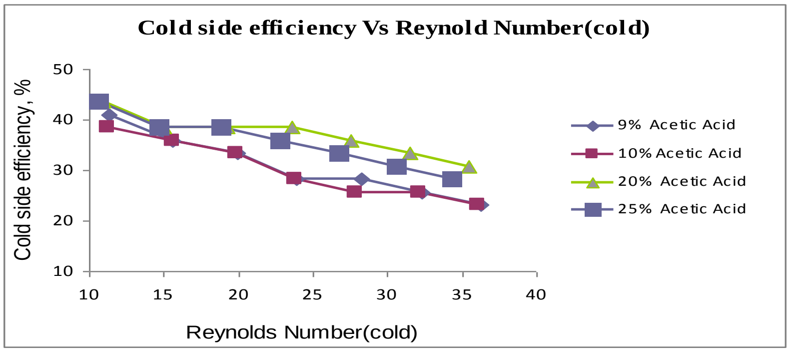

Fig. 5.6 Effect of cold side flow rate and composition on η_c of acetic acid-water system

The graph shows that, as N_{Re} (cold) increases the cold side efficiency decreases. As flow rate of cold side is increased the cold side efficiency decreases. The graph also shows that as the composition of acetic acid increases the efficiency of cold side increases gradually, for the same flow rate of cold fluid.

5.2.2 Effect of N_{Re} (Cold) On Hot Side Efficiency (%)
5.2.2.1 Kerosene – Water System

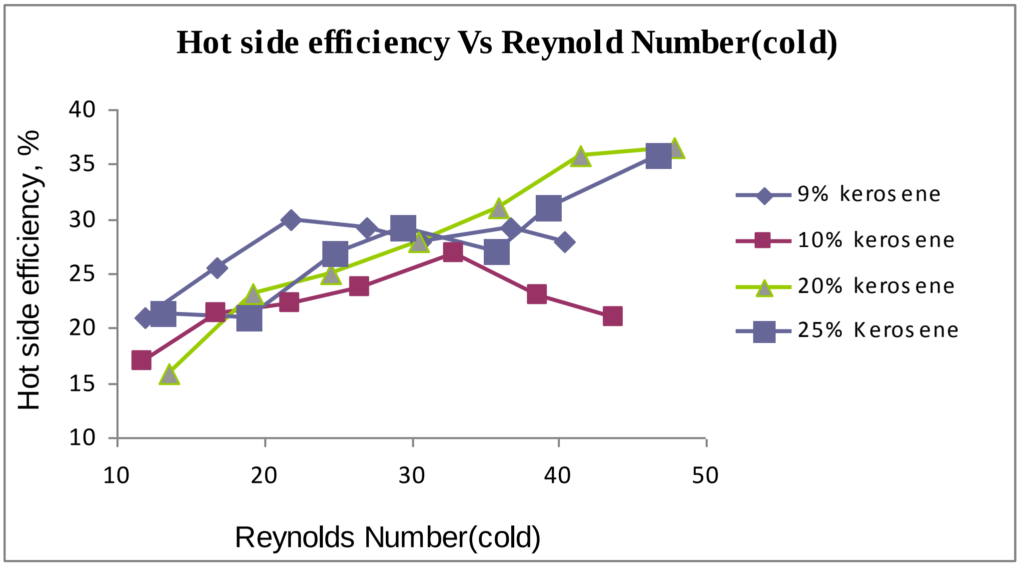

Fig. 5.7 Effect of cold side flow rate and composition on η_h of kerosene-water system

From the graph Reynolds number of cold fluid Vs Hot side efficiency it can be observed that, as flow rate of cold fluid increases the efficiency of hot side gradually increases. When the flow rate on cold side is increased, heat transfer from hot to cold side is also increased. As the composition of kerosene increases, the efficiency of hot side decreases at first and later it increases gradually for same flow rate of cold fluid.

5.2.2.2 Acetic Acid – Water System

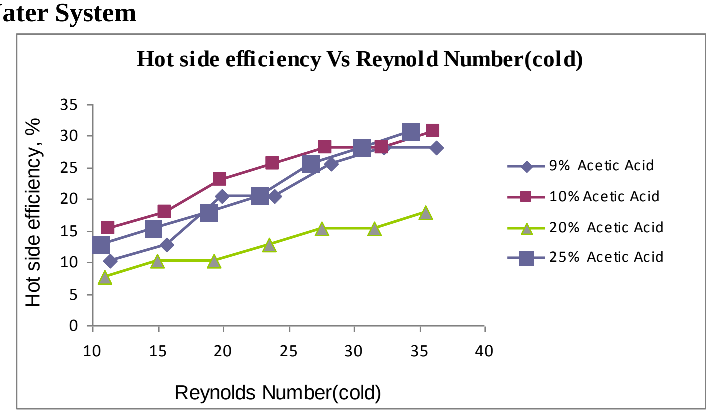

Fig. 5.8 Effect of cold side flow rate and composition on η_h of acetic acid-water system

From the graph Reynolds number of cold fluid Vs Hot side efficiency it can be observed that, as flow rate of cold fluid increases the efficiency of hot side gradually increases. When the flow rate on cold side is increased, heat transfer from hot to cold side is also increased. As the composition of acetic acid increases, the efficiency of hot side increases for same flow rate of cold fluid.

V. CONCLUSION

Experiments were conducted on a Plate type heat exchanger with different flow rates and compositions of cold side fluid in both co-current and counter-current flow pattern. The effect of these parameters on heat transfer coefficient, efficiency and effectiveness were studied and comparison was made between co-current and counter-current flow operation.

It was found that as the flow rate of cold fluid increases, Reynolds number increases thereby increasing the cold side heat transfer coefficient. Consequently the overall heat transfer coefficient also increases with increase in flow rate of cold fluid for both counter-current and co-current flow pattern. The graphs also show that as the composition of cold fluid increases the N_{Nu} number decreases gradually for immiscible system, and increases for miscible systems. Therefore the cold side heat transfer coefficient and overall heat transfer coefficient decreases for immiscible systems and increases for miscible systems.

For both counter-current and co-current flow pattern as N_{Re} (cold) increased the N_{Nu} (hot) decreased thereby, decreasing the heat transfer coefficient of the hot side. As the flow rate on cold side increased the heat transfer coefficient on hot side (h_h) decreased thereby decreasing the overall heat transfer coefficient but as the composition of cold fluid increases the heat transfer coefficient of hot side increases for the same flow rate of cold fluid

It was observed that the cold side efficiency and hot side efficiency for counter flow pattern is greater than the co-current flow pattern

From the results and discussion it can be concluded that, as flow rate of cold fluid increased the effectiveness gradually decreased. As the composition of cold fluid increased from 9% to 25%, the effectiveness of exchanger increased for immiscible systems and decreased for miscible systems for same flow rate of cold fluid for both counter current and co-current flow pattern.

Based on the overall results and discussion it was found that the overall heat transfer coefficient, hot side efficiency ,cold side efficiency and effectiveness was greater for counter current flow pattern when compared to co-current flow pattern.

Therefore it can be concluded that the counter-current flow pattern was efficient and feasible compared to co-current flow pattern irrespective of the type of cold fluid used.

APPENDIX I

MODEL CALCULATION
Counter-Current Flow Pattern

Average temperature of cold fluid $= \frac{(t_1 + t_2)}{2} = \frac{(304.17 + 323.17)}{2} = 313.67$ K

Average temperature of hot fluid $= \frac{(T_1 + T_2)}{2} = \frac{(347.17 + 332.17)}{2} = 339.67$K

Logarithmic mean temperature difference

$$= \frac{((T_2 - t_2) - (T_1 - t_1))}{\ln \frac{(T_2 - t_2)}{(T_1 - t_1)}}$$

$$= \frac{((347.17 - 304.17) - (332.17 - 323.17))}{\ln \frac{(347.17 - 304.17)}{(332.17 - 323.17)}}$$

= 21.739

Mass flow rate of cold fluid m_c = Volumetric flow rate of cold fluid x Density
= (12.5 x 10^-3 x 966.7414) / (60 x 60) Kg/sec
= 0.0033567 Kg/sec

Mass flow rate of hot fluid m_h = Volumetric flow rate of hot fluid x Density

= (1 x 10^-3 x973.9417) / (60) Kg/sec
= 0.016123 Kg/sec

Mass velocity of cold fluid = Mass flow rate / Flow area
= 0.0033567 /0.0045
= 0.74593 Kg/m^{2}sec

Mass velocity of hot fluid = Mass flow rate / Flow area
= 0.016123 / 0.0045
= 3.582888 Kg/m2sec

Dimensionless numbers for cold fluid,

Reynolds number $N_{Re} = \frac{(D_e V\rho)}{\mu}$ $= \frac{(0.01x0.74593)}{0.000599}$
= 12.455

Prandtl number $N_{Pr} = \frac{(c_p \mu)}{k}$ $= \frac{(3995.857x0.000599)}{0.588332}$
= 4.067

Nusselt number $N_{Nu} = (0.28)(N_{Re})^{0.65}(N_{Pr})^{0.4}$ $= (0.28)(12.455)^{0.65}(4.067)^{0.4}$
=2.52871.

Dimensionless number for hot fluid,

Reynolds number $N_{Re} = \frac{(D_e V\rho)}{\mu}$ $= \frac{(0.01x0.016123)}{0.000422}$
= 85.46826

Prandtl number $N_{Pr} = \frac{(c_p \mu)}{k}$ $= \frac{(4194.033x0.000422)}{0.659672}$
= 2.683293

Nusselt number $N_{Nu} = (0.28)(N_{Re})^{0.65}(N_{Pr})^{0.4}$ $= (0.28)(85.46826)^{0.65}(2.6832)^{0.4}$
= 7.486838

Cold side heat transfer coefficient h_c = (N_{Nu} x k) / (D_e)
= (2.528571 x 0.588332) / (0.01)
= 148.764 W/m^{2}K

Hot side heat transfer coefficient h_h = (N_{Nu} x k) / (D_e)
= (7.486838 x 0.659672) / (0.01)
= 493.8858 W/m^{2}K

Overall heat transfer coefficient $U_o = \frac{1}{\frac{1}{h_c} + \frac{x}{k} + \frac{1}{h_h}}$

$$= \frac{1}{\frac{1}{148.764} + \frac{0.02}{273} + \frac{1}{493.8858}}$$

= 113.3777 W/m^{2}K

Capacity rate ratio = Cmin / Cmax

$C_{\min} = m_c x c_{pc}$ = 0.0033567 x 3995.857 = 13.4129

$C_{\max} = m_h x c_{ph}$ = 0.016123 x 4194.033 = 67.6203

Capacity rate ratio = 13.4129 / 67.6203
= 0.1984

Number of transfer units $NTU = \frac{(U_o x A)}{C_{\min}}$

= (113.3777 x 0.2925) / (13.4129)
= 2.47244

Cold side efficiency $\eta_c = \frac{(m_c x c_{pc} x \Delta T)}{(m_c x c_{pc} x \Delta T_{\max})} = \frac{(13.4129 x 19)}{(13.4129 x 43)}$ = 0.44186 = 44.186%

Hot side efficiency $\eta_h = \frac{(m_h x c_{ph} x \Delta T)}{(m_h x c_{ph} x \Delta T_{\max})} = \frac{(67.6203 x 15)}{(67.6203 x 43)}$ = 0.3488 = 34.88

Effectiveness % $= \frac{(NTU)}{(1 + NTU)} x 100$

$= \frac{(2.47244)}{(1 + 2.47244)} x 100$ = 71.202 %

APPENDIX II

MODEL CALCULATION
Co-Current Flow Pattern

Average temperature of cold fluid = $\frac{(t_1 + t_2)}{2} = \frac{(304.17 + 318.17)}{2}$ = 311.17 K

Average temperature of hot fluid = $\frac{(T_1 + T_2)}{2} = \frac{(347.17 + 338.17)}{2}$ = 342.67 K

Logarithmic mean temperature difference $= \frac{((T_2 - t_2) - (T_1 - t_1))}{\ln \frac{(T_2 - t_2)}{(T_1 - t_1)}}$

$$= \frac{((347.17 - 318.17) - (338.17 - 304.17))}{\ln \frac{(347.17 - 318.17)}{(338.17 - 304.17)}}$$

= 31.433

Mass flow rate of cold fluid m_c = Volumetric flow rate of cold fluid x Density
= (12.5 x 10^-3 x 967.8842) / (60 x 60) Kg/sec
= 0.003361 Kg/sec

Mass flow rate of hot fluid m_h = Volumetric flow rate of hot fluid x Density
= (1 x 10^-3 x 972.4119) / (60) Kg/sec
= 0.016207 Kg/sec

Mass velocity of cold fluid = Mass flow rate / Flow area
= 0.003361 / 0.0045 Kg/m^{2}sec
= 0.74689 Kg/m^{2}sec

Mass velocity of hot fluid = Mass flow rate / Flow area
= 0.016207 / 0.0045 Kg/m^{2}sec
= 3.60156 Kg/m^{2}sec

Dimensionless numbers for cold fluid,

Reynolds number N_{Re} $= \frac{(D_e V \rho)}{\mu}$ $= \frac{(0.01 x 0.003361)}{0.000628}$
= 11.8895

Prandtl number N_{Pr} $= \frac{(c_p \mu)}{k}$ $= \frac{(3993.66 x 0.000628)}{0.585352}$
= 4.28556

Nusselt number N_{Nu} = $(0.28)(N_{Re})^{0.65}(N_{Pr})^{0.4}$ $= (0.28)(11.8895)^{0.65}(4.2856)^{0.4}$
= 2.50506

Dimensionless number for hot fluid,

Reynolds number N_{Re} $= \frac{(D_e V \rho)}{\mu}$ $= \frac{(0.010 x 016207)}{0.000407}$
= 88.51743

Prandtl number N_{Pr} $= \frac{(c_p \mu)}{k}$ $= \frac{(4195.917 x 0.000407)}{0.662113}$
= 2.5784

Nusselt number N_{Nu} = $(0.28)(N_{Re})^{0.65}(N_{Pr})^{0.4}$ $= (0.28)(88.51743)^{0.65}(2.5784)^{0.4}$
= 7.5382

Cold side heat transfer coefficient h_c = (N_{Nu} x k) / (D_e)
= (2.505061 x 0.58535) / (0.01)
= 146.6344W/m^{2}K

Hot side heat transfer coefficient h_h = $(N_{Nu} \text{ x } k) / (D_e)$
= (7.5382 x 0.662113) / (0.01)
= 499.114 W/m^2K

Overall heat transfer coefficient $$U_o = \frac{1}{\frac{1}{h_c} + \frac{x}{k} + \frac{1}{h_h}}$$

$$= \frac{1}{\frac{1}{146.6344} + \frac{10^{\wedge}-2}{273} + \frac{1}{499.114}}$$

= 112.4038 W/m^2K

Capacity rate ratio = C_{min} / C_{max}

$C_{\min} = m_c x c_{pc}$ = 0.0033361 x 3993.663 = 13.42154

$C_{\max} = m_h x c_{ph}$ = 0.016207 x 4195.917 = 68.0027

Capacity rate ratio = 13.42154/ 68.0027
= 0.1974

Number of transfer units $$NTU = \frac{(U_o x A)}{C_{\min}}$$
= (112.4038 x 0.2925) / (13.4215)
= 2.449654

Cold side efficiency $$\eta_c = \frac{(m_c x c_{pc} x \Delta T)}{(m_c x c_{pc} x \Delta T_{\max})} = \frac{(13.42154 x 14)}{(13.42154 x 43)}$$ = 0.3255814 = 32.558 %

Hot side efficiency $$\eta_h = \frac{(m_h x c_{ph} x \Delta T)}{(m_h x c_{ph} x \Delta T_{\max})} = \frac{(68.0027 x 9)}{(68.0027 x 43)}$$ = 0.2093 =20.93 %

Effectiveness % $$= \frac{(NTU)}{(1+NTU)} \text{ x } 100$$
$$= \frac{(2.4497)}{(1+2.44967)} \text{ x } 100 = 71.011 \%$$

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