ANALYSIS OF COMPACT HEAT EXCHANGERS

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Abstract: *The present paper deals with the analysis of compact heat exchangers for different hot fluid (air) and cold fluid (water) flow rates. It involves how the heat transfer rate, effectiveness and overall heat transfer conductance are influenced by varying the flow rates of hot fluid and cold fluid in the conventional as well as the compact heat exchangers. The available heat exchanger in the lab is a double pipe heat exchanger and experiments are carried out at different mass flow rates of water and air. The effectiveness and overall heat transfer conductance of heat exchanger is found out for different mass flow rates. Various correlations are available in the literature for estimation of heat transfer and various characteristics of the plate fin heat exchanger, so the various performance parameters like effectiveness, heat transfer coefficient obtained through experiments is compared with the values obtained from the different correlations.*

IndexTerms –Convectional, Double Pipe,Compact heat exchanger,Plate fin heat exchanger, performance parameters.

I. INTRODUCTION

A heat exchanger is a device designed to efficiently transfer or "exchange" heat from one matter to another. When a fluid is used to transfer heat, the fluid could be a liquid, such as water or oil, or could be moving air. The most well known type of heat exchanger is a car radiator. In a radiator, a solution of water and ethylene glycol, also known as antifreeze, transfers heat from the engine to the radiator and then from the radiator to the ambient air flowing through it. This process helps to keep a car's engine from overheating. These are designed to remove excess heat from aircraft engines, optics, X-ray tubes, lasers, power supplies, military equipment , and many other types of equipment that require cooling beyond what air-cooled heat sinks can provide. They find widespread use in power generation, chemical processing, electronics cooling, air-conditioning, refrigeration, and automotive applications.

The two basic types of heat exchangers are compact and conventional heat exchangers. The ratio of the heat transfer surface area of a heat exchanger to its volume is called the area density β. A heat exchanger with β >700 m2/m3 is classified as a Compact heat exchanger (CHEs) and if β< 700 m2/m3 then they are the Conventional heat exchangers. CHEs can have advantages, such as space savings, superior heat recovery and a higher resistance to fouling, which make them well worth considering when compared to the Conventional heat exchangers.

Classification of heat exchangers:

Due to the large number of heat exchanger configurations, a classification system was devised based upon the basic operation, construction, heat transfer, and flow arrangements.

- **Recuperators and regenerators**
- **Transfer processes:** direct contact and indirect contact
- **Geometry of construction:** tubes, plates, and extended surfaces
- **Heat transfer mechanisms:** single phase and two phase flow
- **Flow Arrangement:** parallel flow, counter flow, or cross flow

Compact Heat Exchangers:

Heat exchangers are one of the vital components in diverse engineering plants and systems. So the design and construction of heat exchangers is often vital for the proper functioning of such systems. It has been shown in [Barron, 1985] that the low temperature plants based on Linde – Hampson cycle cease to produce liquid if the effectiveness of the heat exchanger is below 86.9%. On the other hand in aircrafts and automobiles, for a given heat duty, the volume and weight of the heat exchangers should be as minimum as possible. So the main requirement for any heat exchanger is that it should be able to transfer the required amount of heat with a very high effectiveness. In order to increase the heat transfer in a basic heat exchanger mechanism, assuming that the heat transfer coefficient cannot be changed, the area or the temperature differences have to be increased.

Usually, the best solution is that the heat transfer surface area is extended although increasing the temperature difference is logical, too. In reality, it may not be much meaningful to increase the temperature difference because either a hotter fluid should be supplied to the heat exchanger or the heat should be transferred to a colder fluid where neither of them is usually available. For both cases either to supply the hot fluid at high temperature or cold fluid at lower temperature extra work has to be done. Furthermore increasing the temperature difference more than enough will cause unwanted thermal stresses on the metal surfaces between two fluids. This usually results in the deformation and also decreases the life span of those materials. As a result of these facts, increasing the heat transfer surface area generally is the best engineering approach. The above requirements have been the motivation for the development of a separate class of heat exchangers known as **Compact heat exchangers.**

The heat exchanger, which is specifically designed to realize a large heat transfer surface area per unit volume, is the compact heat exchanger. The ratio of the heat transfer surface area of a heat exchanger to its volume is called the area density β. A heat exchanger with β >700 m2/m3 (or 200 ft2/ft3) is classified as being compact. Examples of compact heat exchangers are car radiators (β ≈ 1000 m2/m3), glass ceramic gas turbine heat exchangers (β ≈ 6000 m2/m3), the regenerator of a Stirling engine (β ≈ 15,000 m2/m3), and the human lung (β ≈ 20,000 m2/m3). The compact heat exchangers are lightweight and also have much smaller footprint, so they are highly desirable in many applications. Fig 3.1 is a plate frame heat exchanger which is one of the types of compact heat exchanger.

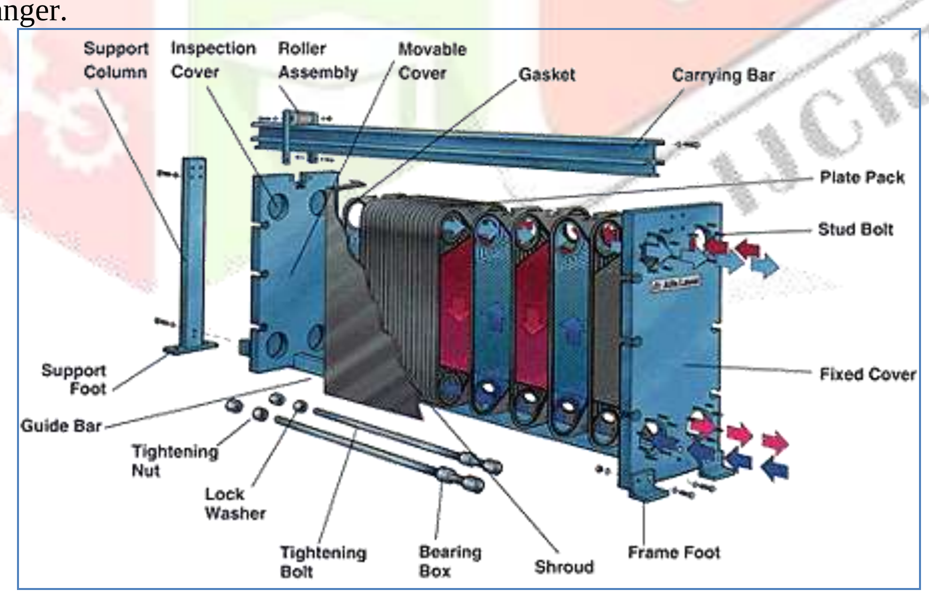

Fig: 1.1 A Plate Frame Heat Exchanger

2. FORMULATION AND ANALYSIS

- Heat capacity of hot fluid, $C_h = m_h c_h$
  Heat capacity of cold fluid, $C_C = m_c c_c$

- Heat transfer rate of hot fluid, $q_h = m_h c_h (T_{h1} - T_{h2})$
  Heat transfer rate of cold fluid, $q_c = m_c c_c (T_{c2} - T_{c1})$
- Logarithmic mean temperature difference (LMTD)

$$LMTD = \frac{(T_{h1}-T_{c1}) - (T_{h2}-T_{c2})}{\ln\left[\frac{T_{h1}-T_{c1}}{T_{h2}-T_{c2}}\right]} \quad \text{(In Parallel)}$$

$$LMTD = \frac{(T_{h1}-T_{c2}) - (T_{h2}-T_{c1})}{\ln\left[\frac{T_{h1}-T_{c2}}{T_{h2}-T_{c1}}\right]} \quad \text{(In Counter)}$$

- Effectiveness (€)

$$€ = \frac{T_{h1}-T_{c2}}{T_{h2}-T_{c1}}$$

$$€ = \frac{1 - \exp(-N(1+C))}{1 + C} \quad \text{(In Parallel)}$$

$$€ = \frac{1 - \exp(-N(1-C))}{1 - C\exp[-N(1-C)]} \quad \text{(In Counter)}$$

- Capacity ratio(C)

$$C = \frac{C_{min}}{C_{max}}$$

- Overall heat transfer coefficient (U)

$$U = \frac{N\, C_{min}}{A}$$

- Core mass Velocity, $G = \frac{m}{A_{ffh}}$
- Reynolds Number, $Re = \frac{GDe}{\mu}$
- Colburn Factor, $J = 0.53\, Re^{-0.5} (1/D_h)^{-0.5}\, \alpha^{-0.14}$
- Convective heat transfer coefficient, $h_h = \frac{j*C*G}{(pr)^{0.667}}$
- Fin Parameter, $M = \sqrt{\frac{2*h}{K*t}}$
- Fin Effectiveness, $\eta_f = \frac{\tanh(Ml_h)}{Ml_h}$
- Overall Surface Effectiveness, $\eta_{oh} = 1-(a_f/a_s)*(1-\eta_f)$
- Overall heat transfer coefficient, $\frac{1}{(U_o A_o)} = \frac{1}{\acute{\eta}_h h_h A_h} + \frac{a}{K_w A_w} + \frac{1}{A_c h_c \acute{\eta}_c}$
- No. of Transfer Units, $NTU = \frac{U_o A_o}{C_{min}}$

- Effectiveness of the heat exchanger, € = $\frac{1-e^{-N_{tu}(1-C_r)}}{1-C_r e^{-N_{tu}(1-C_r)}}$

3. EXPERIMENTAL ANALYSIS OF CONVENTIONAL HEAT EXCHANGERS

The Heat Exchanger available in our laboratory is a double pipe heat exchanger which is manufactured by IND-LAB ENGINEERS Kengeri, Benguluru. Fig 3.1 shows the double pipe heat exchanger with all its arrangements of inlet and outlet ports. The properties such as Heat transfer rate, Effectiveness, NTU, Overall heat transfer coefficient, LMTD, and etc are calculated in order to measure its performance.

Experimental setup:

The experimental setup consists of, Inner copper tube through which hot air flows, Outer stainless steel tube through which cold water flows, Heater to heat the air, Valve system to control direction of flow for parallel and counter flows, Rota meter to control and measure the water flow rate, Orifice meter to measure the volumetric flow rate, Manometer to measure hot air flow rate in the inner tube, Blower to blow the air through heat exchangers, Channel selector and digital temperature display to note the different temperature, Thermocouples to measure different temperature at required points and Control Panel to house the whole instrumentation.

Specifications of the Double pipe Heat Exchanger:

- Diameter of the inner copper tube through which air flows = 60mm
- Length of the inner copper tube through which air flows =6400mm (in coil form)
- Diameter of the outer stainless steel tube through which hot water flows = 100mm
- Length of the outer stainless steel tube through which hot water flows = 450(each)
- Three Heaters to heat the air, 1kw each.

Fig:3.1 An over view of the experimental set up

Operational procedure: The Operational procedure is carried out as follows:

Switch On the main and console. Allow water to circulate outer stainless steel tube by opening the flow control valve of the rotameter and monitor the flow rate. Operate the value system to make water flow in **Parallel flow** direction. Set the water flow rate of a valve, say 0.016. Start the blower and fix the air flow rate to a required valve, say 0.0175. Switch ON the heater to heat the inlet air.
Switch ON the channel selector to required thermocouple and observe temperature variation with time. Allow sometime for the temperature to become steady. After steady state reached, note the required temperature readings using channel selector. Tabulate the readings and make necessary calculation. Keeping the water and air flow rates constant change the flow direction to **Counter flow** using valve system. Allow sometime for the temperature to become steady. After steady state reached, note the required temperature readings using channel selector. Repeat the same procedure for 3 different flow rates of water and air. Table 3.1 shows the input values that are taken to find the performance of the double pipe heat exchanger.

water flow rate	Air flow rate
0.016	0.019
0.025	0.022
0.033	0.023

Table: 3.1 Input Table

4. THEORETICAL ANALYSIS OF COMPACT HEAT EXCHANGER

Since there is no availability of compact heat exchanger, data needed for the analysis of compact heat exchanger is taken from the literature mentioned in the references and the performance parameters of compact heat exchangers were found out by taking the same input values as that of the conventional heat exchangers. Table: 3.1 show the input table of compact heat exchanger.
In order to make theoretical calculations, the heat exchanger considered is a plate fin heat exchanger with offset strip fin geometry, and geometry of the offset strip fin surface is described by the following parameters:

i) Fin spacing (s), excluding the fin thickness,
ii) Fin height (h), excluding the fin thickness,
iii) Fin thickness (t) and,
iv) Fin strip length (l or L_f)

The lateral fin offset is generally the same and equal to half the fin spacing (including fin thickness). Figure 5.1 shows a schematic view of the rectangular offset strip fin surface and defines the basic geometric parameters. But the present heat exchanger has different fin geometries for the hot and cold side fluids. Table 4.2 shows the fin specifications for hot and cold side of the heat exchanger.

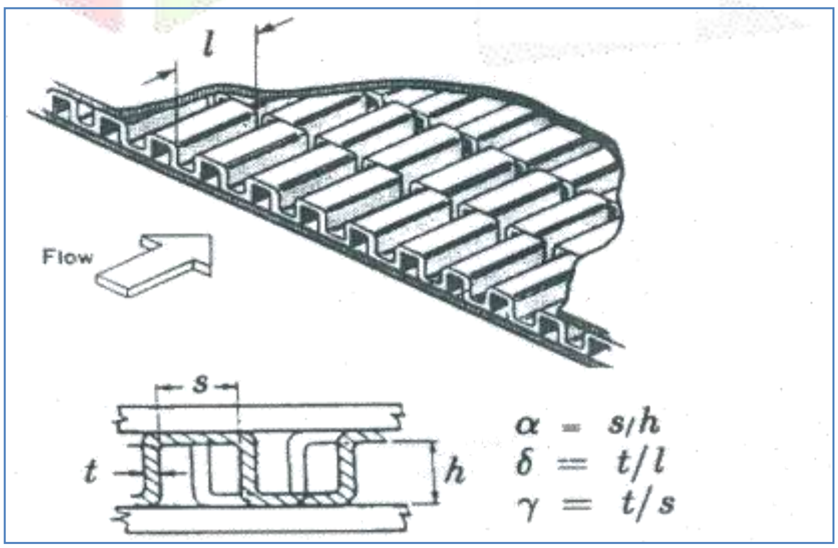

Fig:4.1 Geometry of Typical Offset Strip Fin Surface

	Hot Fluid	Cold Fluid
No. Of passes (N)	4	5
Fin thickness (t)	0.2mm	0.2mm
Fin frequency (f)	588	714
Fin length (l)	5mm	3mm
Fin height (h)	9.5mm	9.5mm
Plate thickness (a)	0.8mm	0.8mm

Table: 4.2 Core Data (fin specifications)

There are some secondary geometrical parameters which are derived from the above basic fin geometries, which are calculated as follows. The calculation is done for the hot side fluid and by following the same steps the results can be obtained for cold side.

i) Fin spacing, $s = \frac{(1 - f * t)}{(f)} = 0.001501$ m

ii) Free flow area to Frontal area,

$$\sigma = \frac{(s-t)h}{(h+t)(s+t)} = \frac{(0.001501 - 0.0002) \cdot 0.0093}{(0.0093 + 0.0002)(0.001501 + 0.0002)} = .00001615$$

iii) Heat transfer area per fin, a_s

$$a_s = 2hl + 2ht + 2sl = 2 * 0.0093 * 0.005 + 2 * 0.001501 * 0.005 + 2 * 0.0093 * 0.0002 = 0.0001117$$

iv) Ratio of fin area to heat transfer area of fin,

$$\frac{2h(l+t)}{2(hl+sl+ht)} = \frac{2 \cdot 0.0093(0.005 + 0.0002)}{2(0.0093 \cdot 0.005 + 0.005 \cdot 0.001501 + 0.0093 \cdot 0.0002)} = 0.86565$$

v) Equivalent diameter, $De = \frac{(4 * Free\ flow\ area * length)}{Heat\ transfer\ area}$

$$= \frac{2(s-t)hl}{hl+sl+ht} = \frac{2(0.001501 - 0.0002) \cdot 0.0093 \cdot 0.005}{(0.0093 \cdot 0.005 + 0.001501 \cdot 0.005 + 0.0093 \cdot 0.0002)} = 0.002165810m$$

vi) Distance between plates, $b = h + t = 0.0093 + .0002 = .0095m$

5. CONCLUSIONS

- The theoretical as well as experimental effectiveness (€) increases with increasing air and water flow rates.
- The theoretical as well as experimental overall heat transfer conductance (UA) increases with increasing air and water flow rates.

- With the increase in hot inlet temperature, the Effectiveness (€) also increases.
- With the increase in hot inlet temperature, Overall heat transfer conductance (UA) also increases.
- From the above performance analysis it is very clear that the performance parameters **Effectiveness (€)** and **Overall heat transfer conductance (UA)** of compact heat exchanger (plate fin heat exchanger) are high when compared to that of the conventional heat exchanger (double pipe heat exchanger).

  So it can be concluded that the Compact heat exchangers are more efficient than the Conventional heat exchangers.

Scope for Future Work:

- Engine oil, lubricating oil and exhaust gases can be used as hot fluid.
- Air can be used as cold fluid.
- More number of thermocouples can be used for obtaining precise readings.
- This project can even be done for different insulating materials.
- It can even be done on more different heat exchangers with different modes of flow and different mediums.

6. REFERENCES

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7. PERFORMANCE ANALYSIS

7.1 Output table of the Conventional heat exchanger

S no	Air flow rate (kg/sec)	Type of flow	Water flow rate (kg/sec)	Heat transfer rate (Kw) (q)	LMTD(t_m)	Effectiveness(€)	Overall heat transfer conductance (U) in (w/k)
Heater 1							
		Parallel	0.016	0.484	29.37	0.594	21.38
1.		Counter	0.016	0.487	29.86	0.602	19.52
2.	0.019	Parallel	0.025	0.442	29.83	0.608	20.48
3.		Counter	0.025	0.496	31.25	0.600	20.69
4.		Parallel	0.033	0.443	28.61	0.616	20.23
5.		Counter	0.033	0.488	29.15	0.612	19.01
6.	0.022	Parallel	0.016	0.440	25.6	0.560	22.39
7.		Counter	0.016	0.520	29.53	0.610	23.08
8.		Parallel	0.025	0.490	28.68	0.596	23.07
9.		Counter	0.025	0.521	30.63	0.612	22.38
10.		Parallel	0.033	0.501	27.60	0.591	22.03
11.		Counter	0.033	0.486	26.50	0.600	21.44
12.		Parallel	0.016	0.452	23.41	0.581	26.11
13.		Counter	0.016	0.456	24.65	0.585	23.64
14.		Parallel	0.025	0.519	23.84	0.587	25.12
15.	0.023	Counter	0.025	0.565	25.68	0.598	24.44
16.		Parallel	0.033	0.453	24.28	0.605	24.24
17.		Counter	0.033	0.502	26.19	0.608	22.98
Heater 1+2							
18.		Parallel	0.016	0.900	53.47	0.611	22.83
19.		Counter	0.016	0.914	55.50	0.611	20.10
20.	0.019	Parallel	0.025	0.861	52.06	0.621	21.38
21.		Counter	0.025	0.878	54.14	0.615	19.51
22.		Parallel	0.033	0.909	54.64	0.627	20.79
23.		Counter	0.033	0.893	49.05	0.657	21.69
24.	0.022	Parallel	0.016	0.87	46.35	0.59	25.27
25.		Counter	0.016	0.795	51.7	0.59	22.58
26.		Parallel	0.025	0.74	48.8	0.59	22.73
27.		Counter	0.025	1.09	45.98	0.618	22.38
28.		Parallel	0.033	0.861	46.57	0.616	23.86
29.		Counter	0.033	0.931	50.54	0.61	22.06
30.		Parallel	0.016	0.897	47.97	0.58	26.02
31.		Counter	0.016	0.894	47.74	0.585	23.11
32.		Parallel	0.025	0.920	48.84	0.589	24.03
33.	0.023	Counter	0.025	0.932	49.14	0.611	23.68
34.		Parallel	0.033	0.867	45.56	0.616	25.12
35.		Counter	0.033	0.931	46.92	0.627	24.26

7.2 Output Table of the Compact Heat Exchanger

S NO	AIR FLOW RATE (kg/sec)	Types of flow	Water flow rate (kg/sec)	Effectiveness(€)	Overall heat transfer conductance(U)
1.	0.019	Parallel	0.016	0.99901	176.45
2.		Counter	0.016	0.998	172.37
3.		Parallel	0.025	0.99957	176.72
4.		Counter	0.025	0.99958	177.03
5.		Parallel	0.033	0.99924	187.97
6.		counter	0.033	0.99943	186.19
7.	0.022	Parallel	0.016	0.9973	183.25
8.		Counter	0.016	0.9974	184.83
9.		Parallel	0.025	0.9990	187.93
10.		Counter	0.025	0.99752	196.91
11.		Parallel	0.033	0.99938	190.89
12.		counter	0.033	0.99939	191.09
13.	0.023	Parallel	0.016	0.9973	195.3
14.		Counter	0.016	0.9972	194.85
15.		Parallel	0.025	0.99875	188.74
16.		Counter	0.025	0.99918	193.12
17.		Parallel	0.033	0.9991	193.57
18.		counter	0.033	0.9990	188.19
19.	0.019	Parallel	0.016	0.99912	179.92
20.		Counter	0.016	0.99918	181.83
21.		Parallel	0.025	0.9996	182.08
22.		Counter	0.025	0.9998	182.12
23.		Parallel	0.033	0.9996	190.75
24.		counter	0.033	0.99956	197.87
25.	0.022	Parallel	0.016	0.99755	183.35
26.		Counter	0.016	0.9978	190.7
27.		Parallel	0.025	0.9991	193.57
28.		Counter	0.025	0.9990	188.19
29.		Parallel	0.033	0.9994	195.45
30.		counter	0.033	0.9994	196.16
31.	0.023	Parallel	0.016	0.99875	191.41
32.		Counter	0.016	0.99687	189.29
33.		Parallel	0.025	0.9989	198.18
34.		Counter	0.025	0.99901	198.77
35.		Parallel	0.033	0.99921	193.3
36.		counter	0.033	0.99925	195.59

7.3 Graphs and Discussions:

In order to compare our experimental results with the values that are obtained from theoretical correlations, some graphs are plotted for the evaluation of the performance of heat exchangers.

7.3.1 Variation of effectiveness with water flow rate

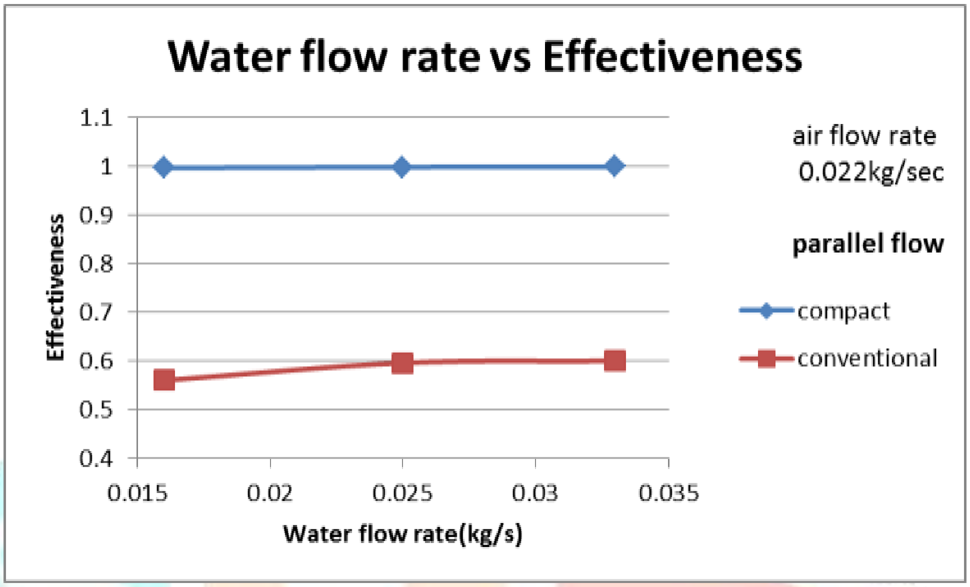

Fig: 7.1

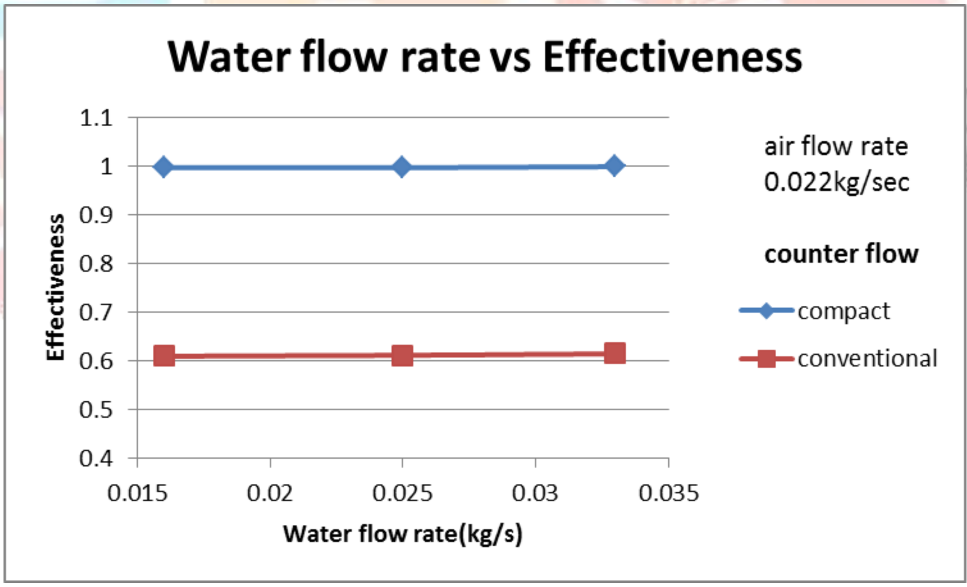

Fig: 7.2

Figure 7.1 and 7.2 shows the variation of effectiveness obtained experimentally as well as with theoretical correlations with water flow rate for Parallel and Counter flows respectively. It is seen that in both the cases effectiveness increases with water flow rate.

7.3.2 Variation of effectiveness with air flow rate

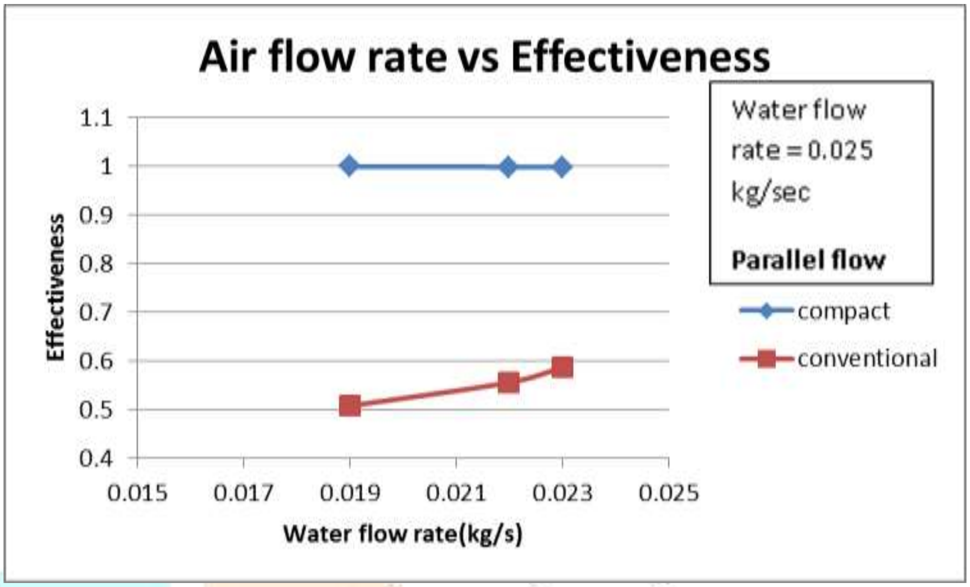

Fig: 7.3

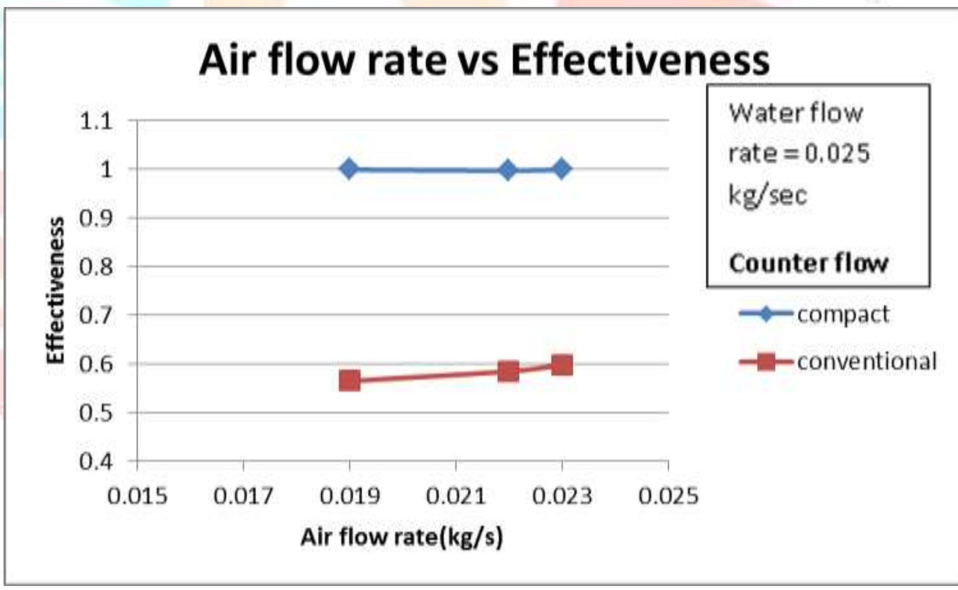

Fig: 7.4

Figure 7.3 and 7.4 shows the variation of effectiveness obtained experimentally as well as with theoretical correlations with air flow rate for Parallel and Counter flows respectively. It is seen that in both the cases effectiveness increases with mass flow rate.

7.3.3 Variation of effectiveness with temperature

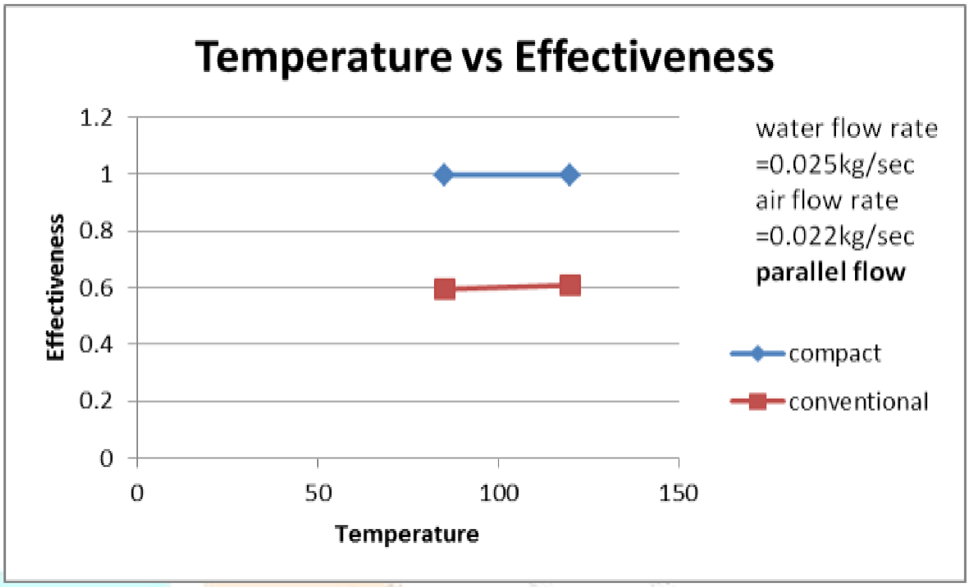

Fig: 7.5

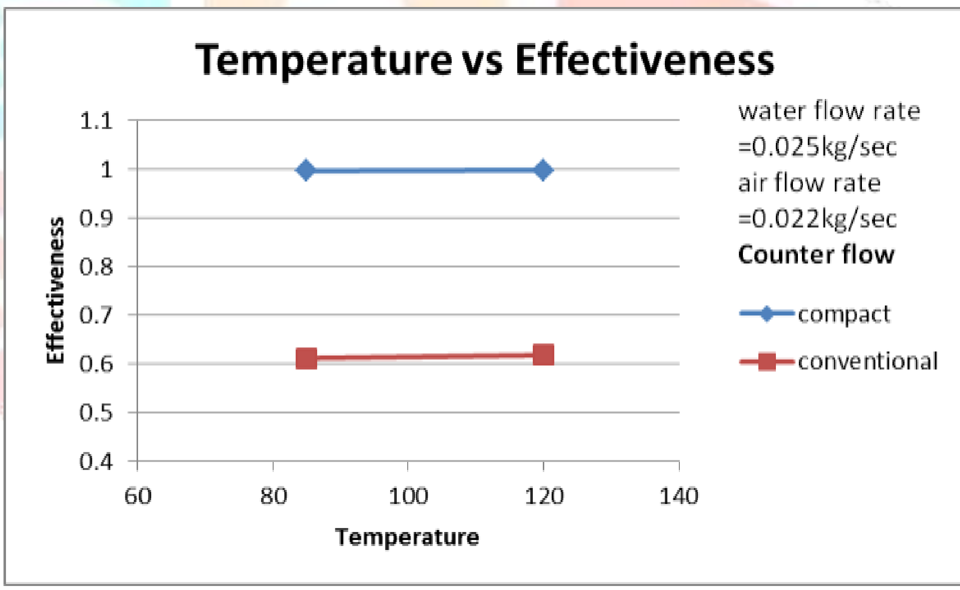

Fig: 7.6

Figure 7.5 and 7.6 shows the variation of effectiveness with temperature for Parallel and Counter flows respectively. It can be seen that the value of effectiveness is more when hot inlet temperature is 120ºC as compared to effectiveness value when hot inlet temperature is 80ºC. So it can be concluded that with increase in hot inlet temperature effectiveness increases.

7.3.4 Variation of Overall heat transfer conductance with water flow rate

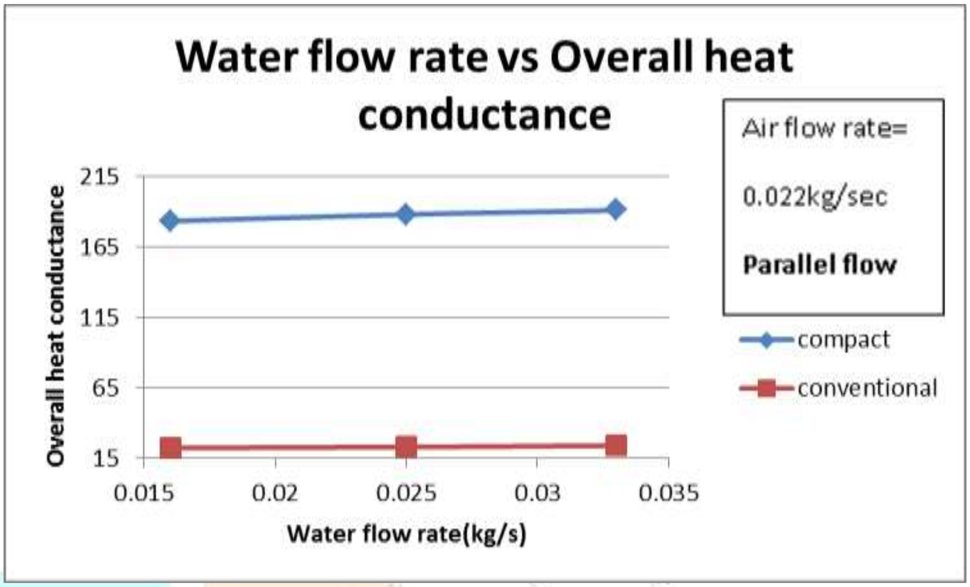

Fig: 7.7

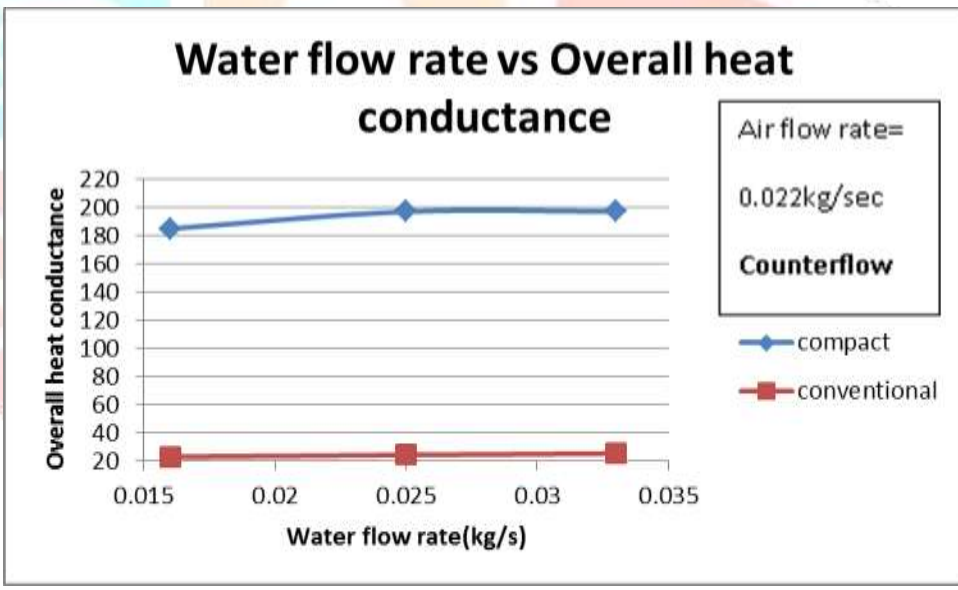

Fig: 7.8

Figure 7.7 and 7.8 shows the variation of overall heat transfer conductance with water flow rate for Parallel and Counter flows respectively. It can be seen that the theoretical as well as experimental overall heat transfer conductance increases with increasing water flow rate. It is due to the fact that with increasing mass flow rate of water the Reynolds number increases and as a result Colburn factor (j) also increases which is directly proportional to heat transfer coefficient, so overall heat transfer conductance also increases.

7.3.5 Variation of Overall heat transfer conductance with air flow rate

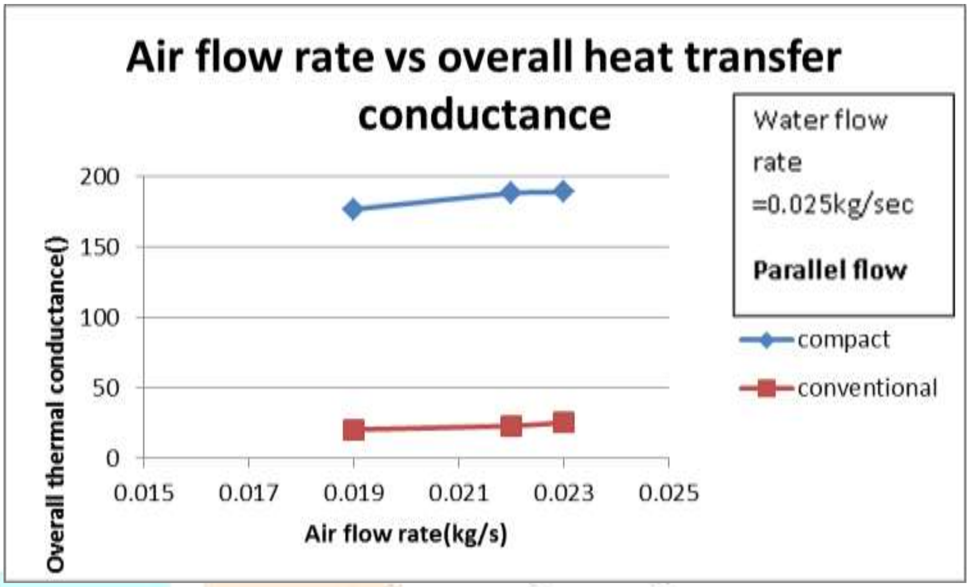

Fig: 7.9

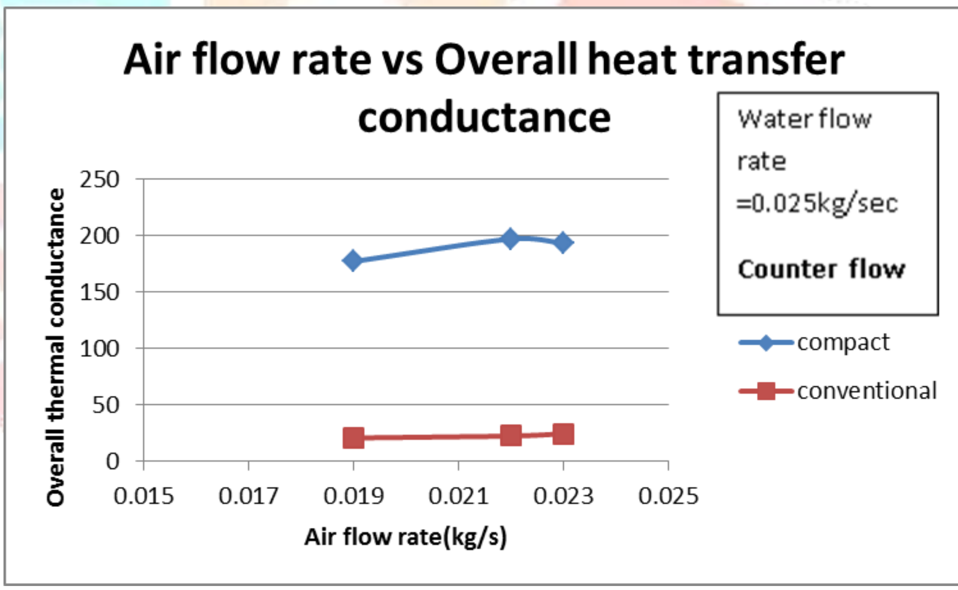

Fig: 7.10

Figure 7.9 and 7.10 shows the variation of overall heat transfer conductance with air flow rate for Parallel and Counter flows respectively. It can be seen that the theoretical as well as experimental overall heat transfer conductance increases with increasing air flow rate. It is due to the fact that with increasing mass flow rate the Reynolds number increases and as a result Colburn factor (j) also increases which is directly proportional to heat transfer coefficient, so overall heat transfer conductance increases.

7.3.6 Variation of Overall heat transfer conductance with temperature

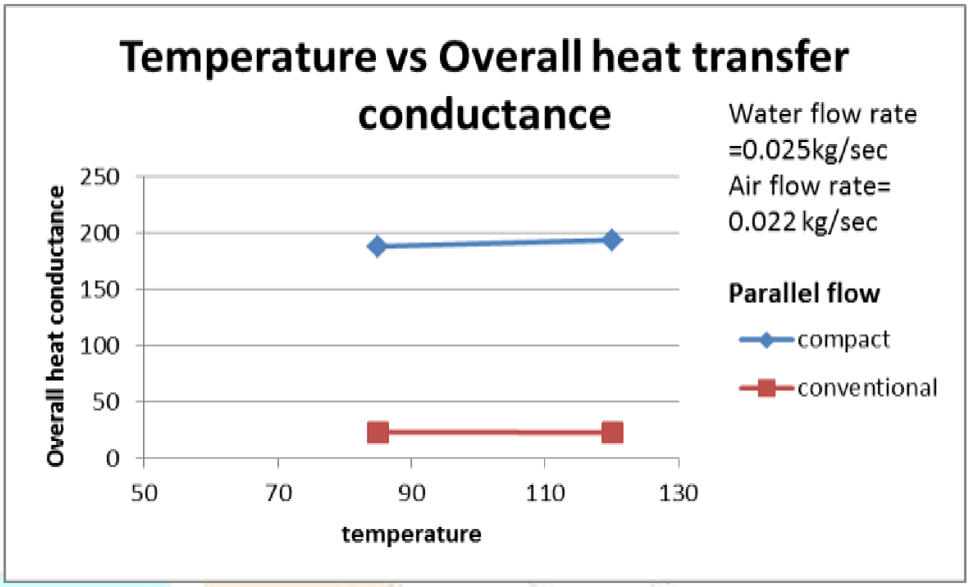

Fig: 7.11

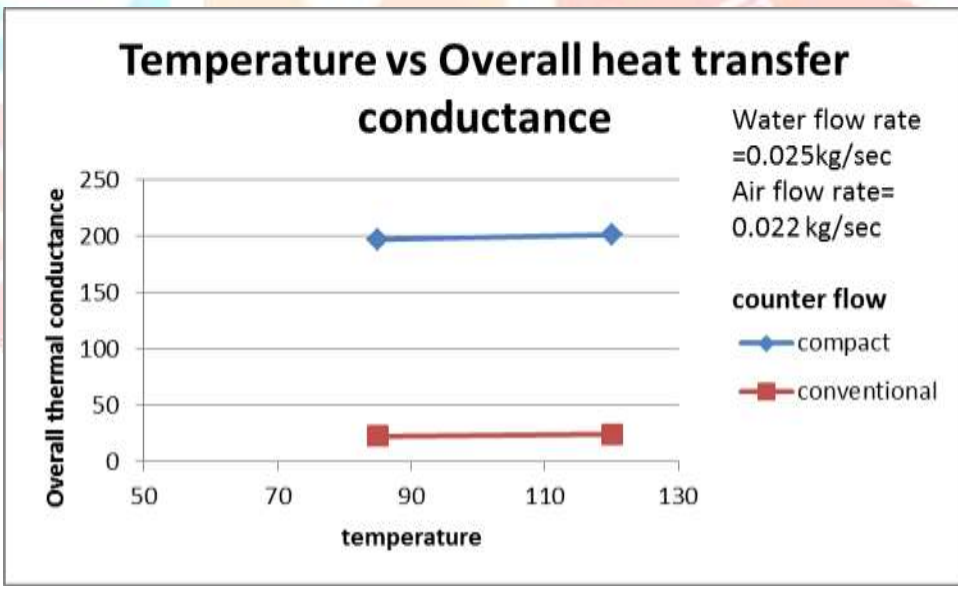

Fig: 7.12

Figure 7.11 and 7.12 shows the variation of overall heat transfer conductance with temperature for Parallel and Counter flows respectively. It can be seen that the value of effectiveness is more when hot inlet temperature is 120ºC as compared to effectiveness value when hot inlet temperature is 80ºC. So it can be concluded that with increase in hot inlet temperature overall heat transfer conductance also increases.