ISSN 2395-1621

Performance Analysis Of Compact Heat Exchanger

#1C N Jadhav

1chetanjadhav84@gmail.com

#1Mechanical Engineering-Heat & Power, Pune University
JSPM institute of technology, Hadapsar Campus, Pun.

ABSTRACT

Compact heat exchangers are one of the most critical components of many cryogenic components; they are characterized by a high heat transfer surface area per unit volume of the exchanger. The heat exchangers having surface area density (β) greater than 700 m2/m3 in either one or more sides of two-stream or multi stream heat exchanger is called as a compact heat exchanger. Plate fin heat exchanger is a type of compact heat exchanger which is widely used in automobiles, cryogenics, space applications and chemical industries. The plate fin heat exchangers are mostly used for the nitrogen liquefiers, so they need to be highly efficient because no liquid nitrogen is produced, if the effectiveness of heat exchanger is less than 87%. So it becomes necessary to test the effectiveness of these heat exchangers before putting them in to operation. The plate fin heat exchanger will be having rectangular offset strip geometry and will be tested in the laboratory using the new heat exchanger test rig in the product validation department. The effectiveness of heat exchanger will be found out for different mass flow rates. Various correlations are available in the literature for estimation of heat transfer and flow friction characteristics of the plate fin heat exchanger, so the various performance parameters like effectiveness, heat transfer coefficient and pressure drop will be obtained through experiments is compared with the values obtained from the different correlations. The longitudinal heat conduction through walls may decreases the heat exchanger effectiveness, especially of cryogenic heat exchangers, so the effectiveness and overall heat transfer coefficient will be found out by considering the effect of longitudinal heat conduction using the Kroeger's equation.

Keywords— **Compact heat exchangers, offset fin geometry,**

ARTICLE INFO

Article History

Received :18th November 2015

Received in revised form :

19th November 2015

Accepted : 21st November , 2015

Published online :

22nd November 2015

I. Introduction

A heat exchanger is a device to transfer heat from a hot fluid to cold fluid across an impermeable wall. Fundamental of heat exchanger principle is to facilitate an efficient heat flow from hot fluid to cold fluid. This heat flow is a direct function of the temperature difference between the two fluids, the area where heat is transferred, and the conductive/convective properties of the fluid and the flow state. This relation was formulated by Newton and called Newton's law of cooling, which is given in Equation (1.1)

$$Q = h*A*\Delta T$$

Where h is the heat transfer coefficient [W/m2K], where fluid's conductive/convective properties and the flow state comes in the picture, A is the heat transfer area [m2], and T is the temperature difference [K].Figure. 1.1 shows the basic heat transfer mechanism.

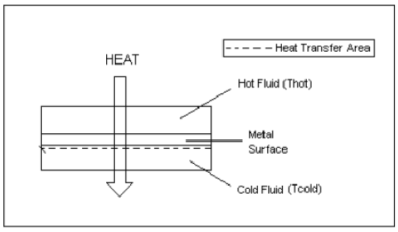


Fig. 1.1 Basic heat transfer mechanism

1.1 Plate fin heat exchanger

Plate fin exchanger is a type of compact heat exchanger where the heat transfer surface area is enhanced by providing the extended metal surface interface between the two fluids and is called as the fins. Out of the various compact heat exchangers, plate-fin heat exchangers are unique due to their construction and performance. They are characterized by high effectiveness, compactness, low weight and moderate cost. As the name suggests, a plate fin heat exchanger (PFHE) is a type of compact exchanger that consists of a stack of alternate flat plates called parting sheets and corrugated fins brazed together as a block. Streams exchange heat by flowing along the passages made by the fins between the parting sheets. Separating plate acts as the primary heat transfer surface and the appendages known as fins act as the secondary heat transfer surfaces intimately connected to the primary surface. Fins not only form the extended heat transfer surfaces, but also work as strength supporting member against the internal pressure. The side bars prevent the fluid to spill over and mix with the second fluid. The fins and side bars are brazed with the parting sheet to ensure good thermal link and to provide the mechanical stability. Figure. 1.2 shows the exploded view of two layers of a plate fin heat exchanger. Such layers are arranged together in a monolithic block to form a heat exchanger.

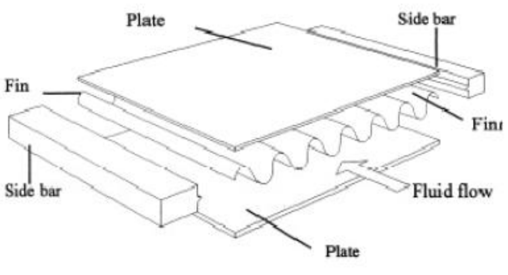


Fig. 1.2 Exploded view of a plate fin heat exchanger

1.2 Advantages and Disadvantages

Plate fin heat exchangers offer several advantages over the other heat exchangers:

1. **Compactness:** Large heat transfer surface area per unit volume (Typically 1000 m2/m3), is usually provided by the plate fin heat exchanger. This in turn produces a high overall heat transfer coefficient due to the heat transfer associated with the narrow passages and corrugated surfaces.
2. **Effectiveness:** very high thermal effectiveness more than 95% can be obtained.
3. **Temperature control:** The plate heat exchanger can operate with relatively small temperature differences. A close temperature approach (Temperature approach as low as 3K between single phase fluid streams and 1K between boiling and condensing fluids is fairly common.),This is an advantage when high temperatures must be avoided. Local overheating and possibility of stagnant zones can also be reduced by the form of the flow passage.
4. **Flexibility:** Changes can be made to heat exchanger performance by utilizing a wide range of fluids and conditions that can be modified to adapt to the various design specifications. Multi steam operation is possible upto 10 streams.
5. True counter-flow operation (Unlike the shell and tube heat exchanger, where the shell side flow is usually a mixture of cross and counter flow.).

The main disadvantages of a plate fin heat exchanger are:

1. Limited range of temperature and pressure.
2. Difficulty in cleaning of passages, which limits its application to clean and relatively noncorrosive fluids, and
3. Difficulty of repair in case of failure or leakage between passages.

1.3 Applications

The plate-fin heat exchanger is suitable for use over a wide range of temperatures and pressures for gas-gas, gas-liquid and multi-phase duties. They are used in a variety of applications. They are mainly employed in the field of cryogenics for cryogenic separation and liquefaction of air, natural gas processing and liquefaction, production of petrochemicals and large refrigeration systems. The exchangers that are used for cryogenic air separation and LPG fractionation are the largest and most complex units of the plate fin type and a single unit could be of several meters in length. Brazed aluminum plate fin exchangers are widely used in the aerospace industries because of their low weight to volume ratio and compactness. They are being used mainly in environment control system of the aircraft, avionics and hydraulic oil cooling and fuel heating. Making heat exchangers as compact as possible has been an everlasting demand in automobile and air conditioning industries as both are space conscious. In the automobile sector they are used for making the radiators. The other miscellaneous applications are:

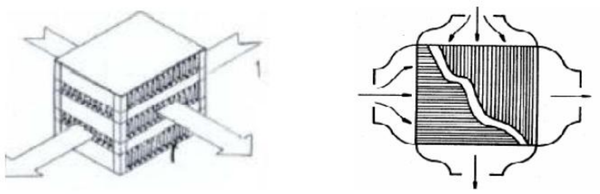
1. Fuel cells
2. Process heat exchangers.
3. Heat recovery plants.
4. Pollution control systems
5. Fuel processing and conditioning plants.
6. Ethylene and propylene production plants.

1.4 Flow arrangement

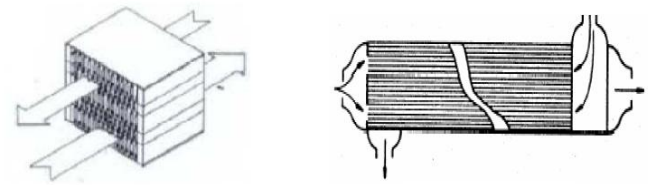
A plate fin heat exchanger can have two or more than two streams, which may flow in directions parallel or perpendicular to one another. When the flow directions are parallel, the streams may flow in the same or in opposite sense.

In general engineering practice, there are three main configurations for the plate fin heat exchangers: (a) cross flow, (b) counter-flow and (c) cross-counter flow.

Cross flow:



Counter-flow:



Cross-Counter flow:

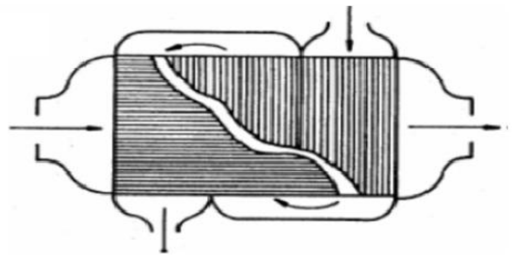


Fig.1.5 Cross-counter flow arrangement

1.5 Plate Fin heat transfer surfaces

The plate fin exchangers are mainly employed for liquid-to-gas and gas-to-gas applications. Due to the low heat transfer coefficients in gas flows, extended surfaces are commonly employed in plate-fin heat exchangers. By using specially configured extended surfaces, heat transfer coefficients can also be enhanced.

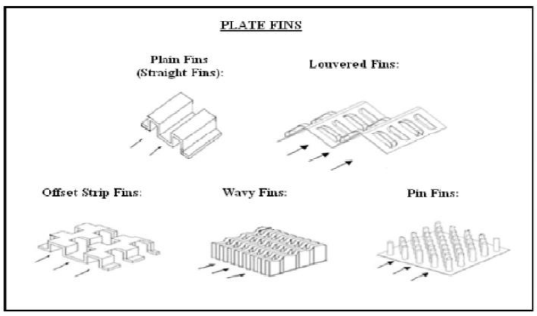


Fig.1.6 some of the common fin geometries

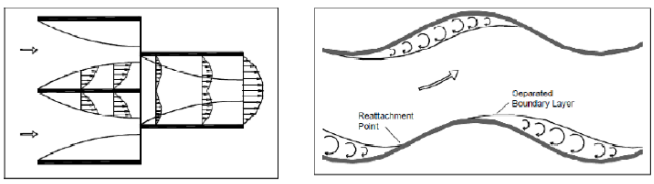


Fig 1.7 Details of boundary layer and flow across offset strip and wavy fin.

II. OBJECTIVES OF STUDY

The main objective of the present work is to evaluate the performance parameters of a counter flow plate fin heat exchanger through hot testing, which includes-

1. To determine the thermal performance parameters like overall heat transfer coefficient, effectiveness and pressure drop of plate fin heat exchanger through hot testing under balanced flow condition.

2. To compare the experimentally obtained values of effectiveness, overall heat transfer coefficient with the values that are obtained from various correlations.

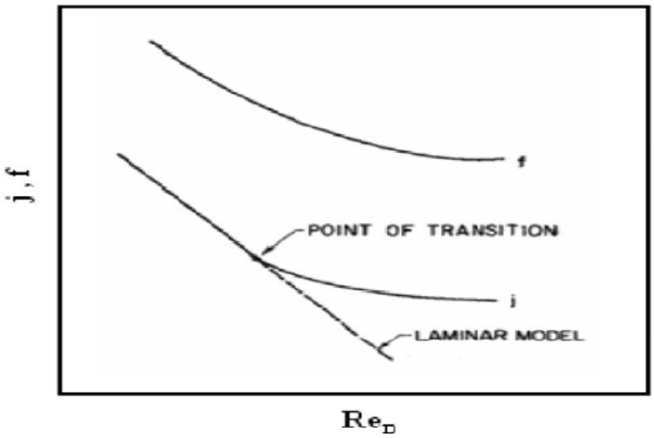
III. LITERATURE SURVEY

Heat exchangers constitute the most important components of many industrial processes and equipment's covering a wide range of engineering applications. Increasing awareness for the effective utilization of energy resources, minimizing operating cost and maintenance free operation have led to the development of efficient heat exchangers like compact heat exchangers. R.K Shah [15] in his elaborate discussion over the classification of heat exchangers has defined the "compact heat exchangers" as one having a surface area density of more than 700 m2/m3. Such compactness is achieved by providing the extended surfaces i.e. fin on the flow passages which work as the secondary heat transfer area.

The main purpose of a recuperative heat exchanger is to facilitate the effective exchange of thermal energy between the two fluids flowing on the either side of a solid portioning wall, during which both the streams experience some viscous resistance and led to pressure drop. So in any heat exchanger the information regarding the quantity oh heat transfer and pressure drop are of utmost importance. Heat transfer and pressure drop characteristics of heat exchanger are mainly expressed in terms of j and f factor respectively. A large amount of study has been conducted to analyze the heat transfer and pressure drop characteristics of compact heat exchangers in the past few decades. But this study mainly focuses on the OSFs type of plate fin heat exchanger. And therefore the emphasis has been given on the literatures related to the prediction of j and f factors and the thermal performance testing of heat exchangers.

Patankar and Prakash [1] presented a two dimensional analysis for the flow and heat transfer in an interrupted plate passage which is an idealization of the OSFs heat exchanger. The main aim of the study is investigating the effect of plate thickness in a non-dimensional form t/H on heat transfer and pressure drop in OSF channels because the impingement region resulting from thick plate on the leading edge and recirculating region behind the trailing edge are absent if the plate thickness is neglected. Their calculation method was based on the periodically fully developed flow through one periodic module since the flow in OSF channels attains a periodic fully developed behaviour after a short entrance region, which may extend to about 5 (at the most 10) ranks of plates (Sparrow, et al. 1977). Steady and laminar flow was assumed by them between Reynolds numbers 100 to 2000. They found the flow to be mainly laminar in this range, although in some cases just before the Reynolds no. 2000 there was a transition from laminar to turbulence. Especially for the higher values of t/H. They used the constant heat flow boundary condition with each row of fins at fixed temperature. They made there analysis for different fin thickness ratios t/H= 0, 0.1, 0.2, 0.3 for the same fin length L/H = 1, and they fixed the Prandtl number of fluid = 0.7. For proper validation they compared there numerical results with the experimental results of [London and Shah] for offset strip fin heat exchangers. The result indicate reasonable agreement for the f factors, but the predicted j factor are twice as large as the experimental data. They concluded that the thick [plate situation leads to significantly higher pressure drop while the heat transfer does not sufficiently improve despite the increased surface area and increased mean velocity.

Joshi and Webb [2] developed an analytical model to predict the heat transfer coefficient and the friction factor of the offset strip fin surface geometry. To study the transition from laminar to turbulent flow they conducted the flow visualization experiments and an equation based on the conditions in wake was developed.



They also modified the correlations of Weiting [17]. There was some difference between there correlation.

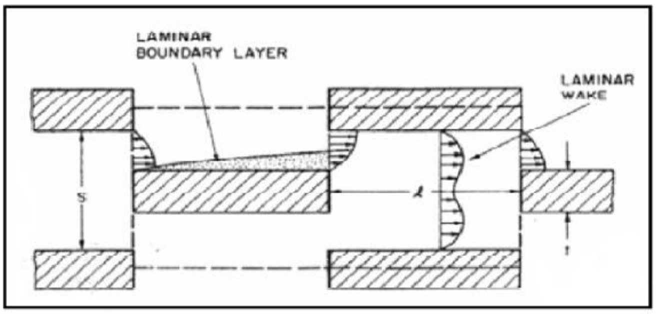


Fig 2.2 Laminar flow on the fins and in the wakes

(Source Joshi and Webb 1987)

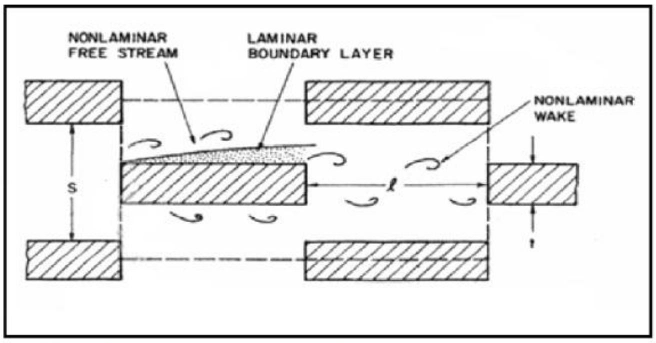


Fig. 2.3 Laminar flow on the fins and oscillating flow on the wakes

(Source Joshi and Webb 1987)

Four different flow regimes (Figure. 2.2 and 2.3) were identified by Joshi and Webb [2] from there experiment. The flow was found to be laminar and steady in the first regime. In the second regime the oscillating flow structures were found in the transverse direction. The flow oscillated in the wake region between two successive fins in the third regime. And in the fourth regime the effect of vortex shedding came into picture. The laminar flow correlation of Joshi and Webb started to under predict the j and f factors at the second regime. So they assumed the Reynolds number at that point as the critical Reynolds number to identify the transition from laminar to turbulent.

Suzuki et al [3] in order to study the thermal performance of a staggered array of vertical flat plates at low Reynolds number has taken a different numerical approach by solving the elliptic differential equations governing the flow of momentum and energy. The validation of their numerical model has been done by carrying out experiments on a two dimensional system, followed by those on a practical offset strip fin heat exchanger. The experimental result was in good agreement with the performance study for the practical offset-strip-fin type heat exchanger in the range of Reynolds number of Re<800.

Tinaut et al [4] developed two correlations for heat transfer and flow friction coefficients for OSFs and plane parallel plates. The working fluid for OSF was engine oil and water was taken for analyzing the parallel plate channels. By using the correlations of Dittus and Boelter and some expressions of Kays and Crawford they obtained there correlations. For the validation of their results they compared there correlations with correlations of Weitng [17]. Although there were some differences between the results but there correlations have been found acceptable upon comparing their results to the data obtained from other correlations.

Manglik and Bergles[5] carried an experimental research on OSFs. They investigated the effects of fin geometries as non dimensional forms on heat transfer and pressure drop, for their study they used 18 different OSFs. After their analysis they arrived upon two correlations, one for heat transfer and another one for pressure drop. The correlations were developed for all the three regions. They compared there results from the data obtained by other researchers in the deep laminar and fully turbulent regions. There correlations can be acceptable when comparing the results of the expressions to the experimental data obtained by Kays and London [16].

Hu and Herold [6] presented two papers to show the effect of Prandtl no. on heat transfer and pressure drop in OSF array. Experimental study was carried out in the first paper to study the effect for which they used the seven OSFs having different geometries and three working fluids with different Prandtl number. At the same time the effect of changing the Prandtl number of fluid with temperature was also investigated. The study was carried out in the range of Reynolds number varying from 10 to 2000 in both the papers. The results of the two studies showed that the Prandtl number has a significant effect on heat transfer in OSF channel. Although there is no effect on the pressure drop.

Zhang et al [7] investigated the mechanisms for heat transfer enhancement in parallel plate fin heat exchangers including the inline and staggered arrays of OSFs. They have also taken into account the effect of fin thickness and the time dependent flow behavior due to the vortex shedding by solving the unsteady momentum and energy equation. The effect of vortices which are generated at the leading edge of the fins and travel downstream along the fin surface was also studied. From there study they found that only the surface interruptions increase the heat transfer because they cause the boundary layers to start periodically on fin surfaces and reduce the thermal

resistance to transfer heat between the fin surfaces and fluid. However after a critical
Reynolds number the flow becomes unsteady and in this regime the vortices play a major role to increase the heat transfer by bringing the fresh fluids continuously from the main stream towards the fin surface.

Dejong et al [8] carried out an experimental and numerical study for understanding the flow and heat transfer in OSFs. In the study the pressure drop, local Nusselt number, average heat transfer and skin friction coefficient on fin surface, instantaneous flow structures and local time averaged velocity profiles in OSF channel were investigated. They compared there results with the experimental results obtained by Dejong and Jacobi [1997] and unsteady numerical simulation of Zhang et al [1997]. There results indicate that the boundary layer development, flow separation and reattachment, wake formation and vortex shedding play an important role in the OSF geometry.

H. Bhowmik and Kwan-Soo Lee [9] studied the heat transfer and pressure drop
characteristics of an offset strip fin heat exchanger. For their study they used a steady state three dimensional numerical model. They have taken water as the heat transfer medium, and the Reynolds number (Re)in the range of 10 to 3500. Variations in the Fanning friction factor f and the Colburn heat transfer j relative to Reynolds number were observed. General correlations for the f and j factors were derived by them which could be used to analyze fluid flow and heat transfer Characteristics of offset strip fins in the laminar, transition, and turbulent regions of the flow.

Saidi and Sudden [10] carried out a numerical analysis of the instantaneous flow and heat transfer for OSF geometries in self-sustained time-dependent oscillatory flow. The effect of vortices over the fin surfaces on heat transfer was studied at intermediate Reynolds numbers where the flow remains laminar, but unsteadiness and vortex shedding tends to dominate. They compared there numerical results with previous numerical and experimental data done by Dejong, et al. (1998).

From the studies of few researchers like Patankar and Prakash [1], Kays and London [16] it is easy to get information regarding the effects of OSFs on heat transfer and pressure drop. But most of the researchers have not taken into account the effect of manufacturing irregularities such as burred edges, bonding imperfections, separating plate roughness which also affect the heat transfer and flow friction characteristics oh the heat exchanger.

Dong et al [11] made experiments and analysis considering the above factors to get better thermal and hydraulic performance from the OSFs. Sixteen types of OSFs and flat tube heat exchangers were used to make the experimental studies on heat transfer and pressure drop characteristics. A number of tests were made by changing the various fin parameters and all the tests were carried out in specific region of air side Reynolds number (500- 7500), at a constant water flow crate. The thermal performance data were analyzed using the effectiveness-NTU method in order to obtain the heat transfer coefficient. They also derived the j factor and f factor by using regression analysis. Results showed that the heat transfer coefficient and pressure drop reduce with enlarging the fin space, fin height and fin length.

Various experiments are carried out in order to find out the j and f factors of the various heat exchangers and are called as the thermal performance testing. These testing are needed for heat exchangers, which do not have reported j and f data. Therefore, this test is conducted for any new development or modification of the finned surfaces. T. Lestina & K. Bell, Advances in Heat Transfer, told for heat exchangers already existing in the plants this test is done for the following reasons

a) Comparison of the measured performance with specification or manufacturing design rating data.
b) Evaluation of the cause of degradation or malfunctioning.
c) Assessment of process improvements such as those due to enhancement or heat exchanger replacement.

Another reason for developing these correlations is that, generally in most heat exchanger problems the working fluid, the heat flow rate and mass flow rate are usually known, so if certain correlations between geometry and fin performance is also known, then the problem can be greatly simplified. For that purpose developing the correlations for fanning friction factor f and Colbourn factor j are important for heat exchanger. Some of the correlations and their investigators are given in Table 2.1. Generally the correlations include three distinct non dimensional ratios depending on OSF geometry. These are the ratio of free flow area (α= s/h), the ratio of heat transfer area (β= t/l), and the ratio of fin density (γ= t/s).

The plate fin heat exchangers find a variety of applications in the field of cryogenics, where high heat transfer performance and high effectiveness are the foremost requirement. But there are many factors which affect their performance, like flow maldistribution, heat in leak from the atmosphere and wall longitudinal heat conduction. Prabhat Gupta, M.D. Atrey [13], have evaluated the performance of a counter-flow heat exchangers for low temperature applications by considering the effect of heat in leak and longitudinal conduction. They developed a numerical model considering the effect of heat in leak and the longitudinal wall heat conduction and made predictions which were compared with the experimental results to understand the quantitative effect of heat in leak and axial conduction parameters on degradation of heat exchanger performance. From there study it was found that in addition to operating and design parameters, the thermal performance of these heat exchangers is strongly governed by various losses such as longitudinal conduction through wall, heat in leak from surrounding, and flow maldistribution, etc.

Randall F Barron, Cryogenic heat exchanger [14], has showed the effect of longitudinal wall heat conduction on the performance of cryogenic heat exchangers. Cryogenic heat exchangers operate at low temperatures where the longitudinal wall heat conduction results in serious performance deterioration these is because they have small distances (on the order of 100 to 200 mm or 4 to 8 in) between the warm and cold ends i.e. they have short conduction lengths. Because of the inherent requirement of high effectiveness for cryogenic heat exchangers, the NTU values are usually large (as high as 500 to 1000), so the effect of longitudinal conduction is most pronounced for heat exchangers having short conduction lengths and large NTU. The wall longitudinal heat conduction reduces the local temperature difference between the two streams, thereby reducing the heat exchanger effectiveness and the heat transfer rate.

IV. EXPERIMENTAL SETUP AND PROCEDURE

4.1.1 Plate fin heat exchanger:

The test section consists of a counter flow plate fin heat exchanger with offset strip fin geometry. This Plate Fin Heat Exchanger has sent in Enginemates heat transfer pvt ltd. for its performance analysis & enhancement of heat exchanger options which is originally manufactured by Apollo Heat Transfer solutions. Mumbai, for Reliance Industries Ltd Mumbai. Reliance Industries wants standby heat exchanger. Figure shows the plate fin heat exchanger with all its dimensions and arrangements of Inlet and Outlet ports. This plate fin heat exchanger consists of offset strip fins. And table 4.1 and 4.2 provides the details of core dimensions and thermal data respectively. This Project is basically an experimental set-up, which is build up for the thermal performance testing of the plate fin heat exchanger for studying its performance. The procured heat exchanger is an Aluminium Plate Fin Heat Exchanger and which was originally manufactured at Apollo Heat Transfer solutions. For Reliance Industries Ltd. Mumbai. As per the information gathered from the Reliance Industries Ltd. Mumbai this heat exchanger is designed for operating at high pressure and is to be used for low temperature applications. The properties such as effectiveness, NTU, overall heat transfer coefficient, colburn factor j and skin friction co-efficient f etc are calculated in order to measure its performance. As per client analysis current heat exchanger is not performing at desired effectiveness.

Table 4.1(a) Dimensions of procured plate fin heat exchanger.

CORE DATA

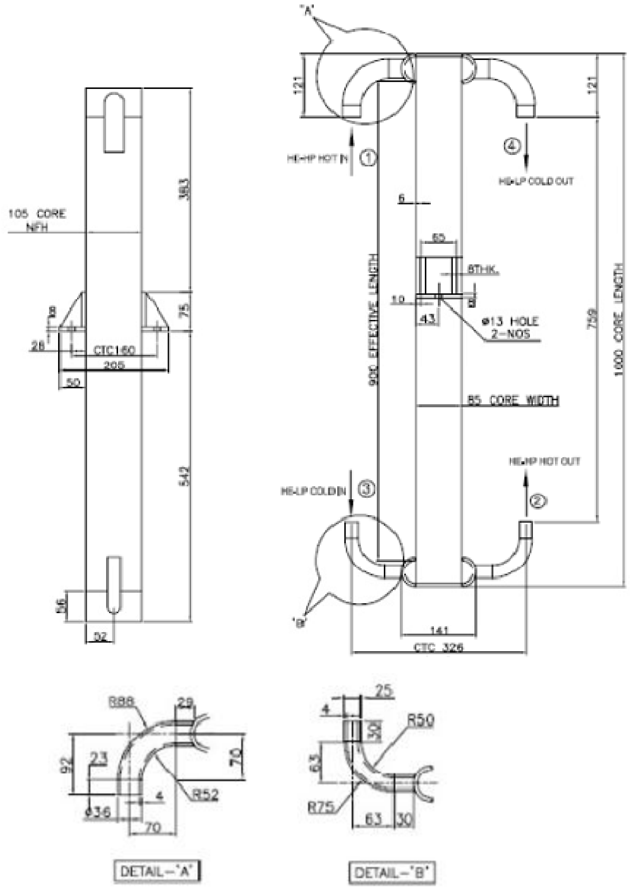
	INTERNAL (Hot side)	EXTERNAL (Cold side)
FIN	OSF	OSF
No of passage	4	5
No of Pass	1	1
Flow Rate	Counter flow	Counter flow

CORE SIZE

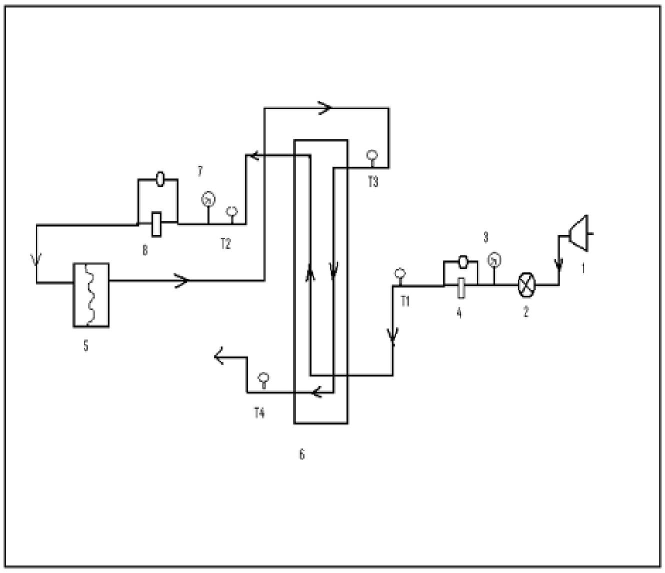
Flow length / Effective flow length	1000mm/900mm
Total height	105mm
Total width/Effective total width	85mm/73mm

Table 4.2 Procured design data of plate fin heat exchanger

Heat load	**5.5KW**	
	Hot side	**Cold side**
Fluid	Helium (HP)	Helium (LP)
flow rate	5g/s	4.8g/s
Inlet temp	36.65 ^{O}C	-189.45 ^{O}C
Outlet temp	-177.25^{O}C	24.39^{O}C
Pressure drop	0.003 kg/cm^2	0.02 kg/cm^2
operating pressure	7.35 kg/cm^2	7.05 kg/cm^2



V. TEST RIG



1: Compressor	2: Control Valve	3,7: Pressure Taps
4,8: U- Tube manometer	5: Heater	6:Test section
T_1, T_2, T_3, T_4 are RTD's		

5.1 Procedure for Hot Testing

Air is used as the as working fluid in this experiment. The apparatus was connected to a compressor system which is capable of continuously delivering dry air .The compressed air from the compressor enters the laboratory through a control valve which is used to regulate the flow rate through the heat exchanger and then routed to the testing heat exchanger. This is the cold side fluid which is made to enter the heat exchanger from the bottom side and when it comes out it is made to pass through the heater, where it gets heated up and which is then again fed into the heat exchanger from top end and which finally results in hot and cold fluid streams. The heat supplied to the heater is controlled with the help two variacs. The pressure taps are located on the upstream and downstream of heat exchanger to measure the pressure drop across the heat exchanger. These pressure taps was connected with tubing and which is connected to a U-tube manometer to give an average reading of the pressure drop. The air inlet and outlet temperatures at both ends of heat exchanger core were measured using four RTD's. The air flow rate was measured using the Rotameter and the mass flow rate of both the fluids can be measured using orifice meter. The orifice meter is used only when the test is carried out in unbalanced condition i.e. when the mass flow rates on both sides is different. The pressure drop across the orifice plate can be measured by using U-tube manometers.

It was ensured that there is no mass leak from the system. And the test section was carefully insulated, by using glass wool sheets and asbestos tapes to eliminate heat losses from the system to the surrounding. The air flow rate through the test section was set using the control valve, and the temperatures, core pressure drop across the heat exchanger and the room pressures were recorded for flow in the required range. The system was then allowed to run until the steady state is achieved. The system was considered to be at steady state when all the temperature readings steadily decrease and steadily increase for at least one minute. Once the steady state was achieved for a particular mass flow rate the air flow rate and the temperature and pressure differentials of the air stream across the core are accurately measured for estimating the rate of heat transfer, pressure drop and various performance parameters like effectiveness, NTU, and heat transfer coefficient. In experimental calculation in order to take into account the effect of wall longitudinal heat conduction the KROGERES formula was used. For theoretical calculation the usual procedure for rating was followed and the calculations were done in the excel sheet.

VI. FUTURE WORK:

- Testing of heat exchanger by Rating method for sample analysis
- Plotting the graph
- Variation of Effectiveness with Mass Flow Rate
- Variation Overall Thermal Conductance with Mas Flow Rate
- Variation of Hot and Cold Effectiveness with Mass Flow Rate
- Variation of Pressure Drop with Mass Flow Rate
-

VII. CONCLUSION:

From the introduction to literature survey, the author has concluded that design of compact heat exchanger has huge scope of design & validation required. The various correlation are required to analyze the design of compact heat exchangers. Trial & error method is adopted for the same. Rating procedure is easiest way to design the heat exchanger. It is important to get the fin density for compact heat exchanger design to decide core dimensions. From exchanger dimension, we will get dimension less numbers. & from different correlations we can get f & j factor.

REFERENCES:-

[1] Patankar S. V. and Prakash C. 1981 An Analysis of Plate Thickness on Laminar Flow and Heat transfer in Interrupted Plate passages. International Journal of Heat and Mass Transfer 24:1801-1810.

[2] Tinaut F. V., Melgar A. and Rehman Ali A. A. 1992 Correlations for Heat Transfer and Flow Friction Characteristics of Compact Plate Type Heat Exchangers. International Journal of Heat and Mass Transfer. 35(7):1659:1665

[3] Zhang L. W., Balachandar S., Tafti D. K. and Najjar F. M. 1997. Heat Transfer Enhancement Mechanisms in Inline and Staggered Parallel Plate Fin Heat Exchanger. International Journal of Heat and Mass Transfer 40(10):2307-2325

[4] Bhowmik H., Kwan- Soo Lee 2009. Analysis of Heat Transfer and Pressure Drop

[5] Characteristics in an Offset Strip Fin Heat Exchanger. International Journal of Heat and Mass Transfer 259-263

[6] Prabhat Gupta, Atrey M. D. Performance Evaluation Of Counter Flow Heat Exchangers Considering the Heat In Leak and Longitudinal Conduction for Low Temperature applications. Cryogenics Volume 40, issue 7, Pages 469-474.

[7] Shah R. K. and Sekulic D. P. Fundamentals of Heat Exchangers, John Willey & Sons Inc., pp 10-13

[8] Maiti D.K. Heat Transfer and Flow Friction Characteristics of Plate Fin Heat Exchanger Surfaces- A Numerical Study PhD Dissertation Indian Institute of Technology, Kharagpur (2002).

[9] M. Siddique, A.-R. A. Khaled, N. I. Abdulhafiz, and A. Y. Boukhary-Recent Advances in Heat Transfer Enhancements: AReviewReport, Thermal Engineering and Desalination Technology

Department, King Abdulaziz University, Abu Dhabi

[10] Arthur E. Bergles – High flux process through enhance heat transfer-Massachusetts Institute of Technology-Cambridge

[11] Saidi A. and Sudden B. 2001. A Numerical Investigation of Heat Transfer Enhancement in Offset Strip Fin Heat Exchangers in Self Sustained Oscillatory Flow. International Journal of Numerical Methods for Heat and Fluid Flow. 11(7): 699-716

[12] Dong J., Chen J., Chen Z. and Zhou Y. 2007. Air Side Thermal hydraulic Performance of Offset Strip Fin Heat Exchangers Fin Alumunium Heat Exchangers. Applied Thermal Engineering 27:306-313

[13] Michna J. G., Jacobi A. M. and Burton L. R. 2005. Air Side Thermal- Hydraulic Performance of an Offset Strip Fin Array at Reynolds Number up to 12, 0000. Fifth International Conference on Enhanced Compact and Ultra Compact Heat Exchangers. Science, Engineering and Technology 8-14.

[14] Prabhat Gupta, Atrey M. D. Performance Evaluation Of Counter Flow Heat Exchangers Considering the Heat In Leak and Longitudinal Conduction for Low Temperature applications. Cryogenics Volume 40, issue 7, Pages 469-474.

[15] Barron R. F., Cryogenic Heat Transfer, Taylor and Francis (1999) 311-318.

[16] Shah R. K. and Sekulic D. P. Fundamentals of Heat Exchangers, John Willey & Sons Inc., pp 10-13

[17] Kays W. M. and London A. L. Compact Heat Exchangers. 2nd Edition, McGraw-Hill, New York, 1964

[18] Weiting A. R.1975. Empirical Correlations for Heat Transfer and Flow Friction Characteristics of Rectangular Offset strip Fin Plate Fin Heat Exchangers. Transactions of ASME, Journal of Heat Transfer 97:488-497

[19] Manson S. V. Correlations of Heat Transfer Data and of Friction Data for Interrupted Plane Fins Staggered in successive Rows NACA Technical Note 2237(1950)

[20] Maiti D.K. Heat Transfer and Flow Friction Characteristics of Plate Fin Heat Exchanger Surfaces- A Numerical Study PhD Dissertation Indian Institute of Technology, Kharagpur (2002)

[21] DURMAZ, Gurcan, Experimental and Numerical Analysis of Heat Transfer Performance of Offset Strip Fins, Master of Science thesis, The Graduate School Of Engineering and Science of IZMIR Institute of Technology:2009

