Experimental Investigation on Evaluation of Heat Recovery in Air Compressor

Vinod C. Bodhale[1], R. S. Shelke[2]
[1]M.Tech. Student, Department of Mechanical Engineering, G. H. Raisoni College of Engineering, Nagpur, India
[2]Professor & HoD, Dept. of Mechanical Engineering, G. H. Raisoni College of Engineering, Nagpur, India

***Abstract*: This work is an experimental set up of air compressor, heat exchanger, PPRC pipe, control valve, storage tank, pump, etc. An air compressor is a produced reach amount of heat and this heat is used to the interchange oil into the water with the help of heat exchanger. The air compressor medium of cooling is used oil to maintain an internal temperature of wear and tear in moving parts and this hot oil to the source of the heat exchanger. The heat exchanger one side hot fluid enters and other side water enters and heat is exchanged. The previous heat exchanger is very less efficiency as well as more time consumed to reach the required temperature. We have a decision to make a modified design of the heat exchanger and compare it to the old heat exchanger in the industry. The comparison between the rate of heat transfer, NTU, heat transfer coefficient, efficiency, Reynolds number, Nusselt number, etc. with time.**

***Keywords*: Air compressor, heat exchanger, PPRC pipe, control valve, storage tank, pump.**

1. Introduction

The rise in energy prices is an unwelcome reality in today's manufacturing and business environment. While the rate of price increases for natural gas, heating oil and electricity may vary from year to year. Energy cost reduction strategies are vital to staying competitive. The law of thermodynamics and the principle of the conservation of energy tell us that energy isn't created or destroyed; it can only change form. An air compressor is a device that convert electric power, diesel engine into potential energy stored pressurized air. It is used to pneumatic system (operated tool) in plant. After the compression process increases the air pressure and raises its temperature, the energy becomes available for transfer. The heat must be removed to maintain proper compressor operating temperatures and to cool the compressed air to make it suitable for plant use. The heat generated by compressed air systems can be a very good source of energy savings. In fact, nearly all (96%) of the electrical energy used by an industrial air compressor is converted into heat. The amount of heat recovered using these systems will vary if the compressor has a variable load. But in general, very good results will be achieved when the primary air compressor package is an oil-injected rotary screw type design.

The global air compressor market size was valued USD at 31.26 billion in 2018 and is projected to expand further at Compound annual growth rate (CAGR) 3.8% from 2019 to 2025. High demand from the food & beverage market, mainly due to strict regulations on health and food safety, is anticipated to drive the market.

Global Heat Exchanger Market is estimated to reach $25,042 million by 2024; growing at a CAGR of 8.1% from 2016 to 2024. A heat exchanger is equipment used to transfer heat energy between two different fluids or a fluid and a solid object that may be parted by a wall to prevent mixing. Heat exchangers are devices used to transfer energy between two fluids at different temperatures. They improve energy efficiency, because the energy already within the system can be transferred to another part of the process, instead of just being pumped out and wasted. In the new era of sustainability, the growing urgency to save energy and reduce overall environmental impacts has placed greater emphasis on the use of heat exchangers with better thermal efficiency. In this new scenario, the plate heat exchanger can play an important role.

2. Literature review

Nikhil Patel, Prof. B. Shah, Dr. A. Raman This paper offers with the design and evaluation of screw compressor. The twin-screw compressor is a effective displacement system used for compressing air to slight pressures. It contains of a couple of intermeshing rotors with helical grooves machined on them, contained in a casing which suits closely round them.

R. Saidur, N. A. Rahim, Hasanuzzaman In this paper are evaluation is compressed air is the use of to the keep the electrical power and playback duration of electricity efficient methods and heat recuperation of wasted gases thru saving power and utilization of the power. On this paper has been attention that strength is waste in which location and answer of the paper is education in addition to attention of the people.

Sreejith, Deepak Das, On this paper major benefit over a conventional heat exchanger in that the fluids are uncovered to a much larger floor place because the fluids unfold out over the plates. the heat switch charge of the heat exchanger is excessive and alternatively temperature modifications. on this paper designed the plate warmness exchanger for the specified running situations.

Stephenraj, M. K. Sathishkumar on this venture, the warmth transfer efficiency is improved by using enforcing the whole baffle design and travel tube layout and reading it thru CFD drift simulation, to discover the heat transfer fees. From the simulation results the most beneficial baffle layout and journey tube layout for max warmth switch price is recognized.

Akshay Kumar Magadum, Mr. T. C. Mestri, in this paper performance of Parallel and Counter drift warmness Exchanger considering temperature changes in water and lubricating oil are to be study. in this paper realize that to heat exchanger performance varies from fluid to fluid and temperature to temperature. Also calculated LMDT by using varying go with the flow rate and temperature of warm water and cold fluid.

3. Schematic of Experimental Set Rig

In this project methodology process are discuses. It consists of air compressor, heat exchanger, pump, pprc (polypropylene random copolymer) pipeline, control valve, storage tank, fabrication material, etc., first upon looking to the construction space as per block diagram or design of the project. Then seen all fabrication work are completed with the help of industrial employee and vender employee including welding, drilling, cutting etc. Then I was concentrated to the make required design of the heat exchanger and made by heat exchanger to ready the work. The air compressor outlet hot fluid pipeline (hot oil line) is assembled to the inlet of modified heat exchanger and outlet of heat exchanger pipeline (cold oil pipeline) to assembled the inlet air compressor. Just like installation of the heat exchanger nearby air compressor to reduce heat inlet and outlet of pipeline through atmosphere and nearby centrifugal pump, because of reduce the pipeline cost and materials There are three types of heat exchanger but why choose of counter flow heat exchanger and other explain like as air compressor, PPRC pipe, Control valve etc.

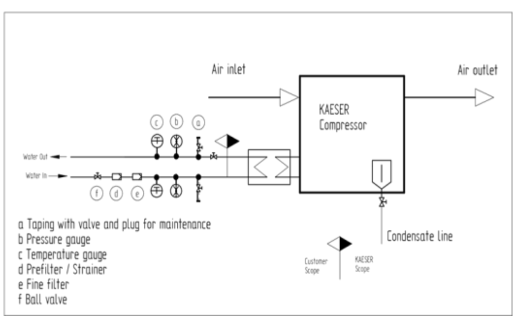

Fig. 1. Schematic of experimental set

Now a days industrial is continues improvement in heat and improve to the thermal efficiency. This will provide the necessary knowledge to the Heat Exchanger design error and overcome to the errors. Once the Heat flow rate is determined, improvement of the NTU. There are following details of the projects. The other side of heat exchanger inlet port is assembling to outlet centrifugal pump pipeline and outlet of heat exchanger is fabrication pipeline through robot cleaning machine. Give the Permission of the authority person (maintenance manager and vendor manager) to the installation of the storage water tank nearest to centrifugal pump. There are seven control valve are used in the work as a control the water. In this project main work on the heat exchanger to make premium design and improve the efficiency, heat transfer rate, etc. This project given the fundamental information about air compressor and design of the Heat Exchanger as shown in figure.

4. Design Parameters

A. Heat Exchanger

The main dimensions of a chevron plate are shown in Figure. The corrugation angle, β, usually varies between extremes of 25° and 65° and is largely responsible for the pressure drop and heat transfer in the channels.

B. Plate types Heat Exchanger Dimension

- Plate area enlargement factor (Φ) = 1.15
- Plate width (WP) = 0.457m
- Plate length (LP) = 0.762m
- Horizontal port distance (LH)= 0.377 m
- Vertical port distance (LV)= 0.862 m
- Port diameter of the plate (DP) = 4mm, =0.04 m
- Chevron corrugation inclination angle (β)=50 degrees
- Plate effective heat transfer area (AP) =0.4178 m^2

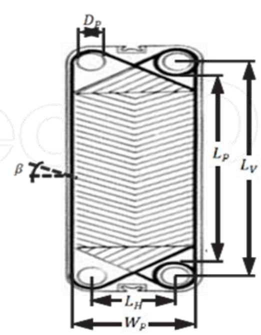

Fig. 2. Parameters of chevron plate.

5. Experimental Set-Up Details

A. Details of Components

- Air compressor
- Heat exchanger
- Pipe
- PPRC Pipe (Polypropylene Random Copolymer.)
- Controlled valves
- Storage tank

1) Air Compressor

Air Compressors are mechanical devices that compress air. It is widely used in industries and has various applications." Rotary screw air compressors have a unique design history that sets them apart from other compressor types. Their list of parts, applications, processes and technical usage can sometimes make even the most industry-savvy engineer pause to consider how to best fix, adjust or maintain the machine's functionality.

2) Heat Exchanger

Heat exchangers are devices used to transfer energy between two fluids at different temperatures. They improve energy efficiency, because the energy already within the system can be transferred to another part of the process, instead of just being pumped out and wasted. In the new era of sustainability, the growing urgency to save energy and reduce overall environmental impacts has placed greater emphasis on the use of heat exchangers with better thermal efficiency. In this new scenario, the plate heat exchanger can play an important role. A heat exchanger is a system used to transfer heat between two or more fluids. Heat exchangers are used in both cooling and heating processes.

3) PPRC Pipe (Polypropylene Random Copolymer)

Polypropylene random copolymers are thermoplastic resins produced through the polymerization of propylene, with ethylene or butane bonds introduced in the polymer chain. During the welding materials suffers neither changes nor burnings thus connections between pipes and fittings are both strong and safe.

4) Pump

A centrifugal pump is a mechanical device designed to move a fluid by means of the transfer of rotational energy from one or more driven rotors, called impellers. Fluid enters the rapidly rotating impeller along its axis and is cast out by centrifugal force along its circumference through the impeller's vane tips. The action of the impeller increases the fluid's velocity and pressure and also directs it towards the pump outlet.

5) Control valves

Devices which are used to regulate and control the flow and pressure in any assigned manner are called control valves or simply valves. However, in this section we shall discuss only the basic features and operating principles of few ordinary and general purpose valves.

6) Tank

Water tanks are used to provide storage of water for use in many applications industrial water, drinking, water, irrigation agriculture, fire suppression, agricultural farming, both for plants and livestock, chemical manufacturing, as well as many other uses.

7) Design of a Modified Plate Heat Exchanger

Basic equations for the design of a plate heat exchanger the methodology employed for the design of a plate heat exchanger (PHE) is the same as for the design of a plate heat exchanger. The equations given in the present chapter are appropriate for the chevron type plates that are used in most industrial applications.

6. Sample Calculation

A. Parameters of a Chevron Plate

The main dimensions of a chevron plate given, the corrugation angle, β, usually varies between extremes of 25° and 65° and is largely responsible for the pressure drop and heat transfer in the channels.

Table 1
Observation table after one hour

S. No.	Name	Dimension
1.	Plate thickness (t_p)	0.4mm, 0.004m
2.	Chevron of plates (degree)	50°
3.	Total number of plates	60
4.	Enlargement factor(Φ)	1.15
5.	Plate width (m)Wp	0.4572 m
6.	Plate length (m) Lp	0.762 m
7.	Diameter of plate (m) Dp	0.1 m
8.	Hot fluid inlet Temperature(ºC)	108 ºC
9.	Hot fluid outlet Temperature(ºC)	86 ºC
10.	Cold fluid inlet Temperature(ºC)	32 ºC
11.	Cold fluid outlet Temperature(ºC)	78 ºC
12.	Specific heat of water $C_{p\ oil}$	4.0187kj/Kg°C
13.	Specific heat of oil Cp oil	1.6 kj/Kg °C
14.	Mass flow rate of Water	8.25 kg/s
15.	Mass flow rate of oil	11.92 kg/s

Given dimension:

D_P= 100mm =0.1m, W_P= 457mm, = 0.457m,

L_P=762mm =0.762m, t_p= 0.4mm =0.004m,

b= 2.1mm =0.0021m, K_P= 13 w/m.ºC

β = 50°, Φ= 1.15, Nt=60,

The corrugations must be taken into account in calculating the total heat transfer area of a plate (effective heat transfer area):

$A_P = \Phi * W_P * D_P$

$=1.15*0.457*0.762$

$A_P=0.4178\ m^2$.

The plate length L_P and the plate width W_P can be estimated by the orifices distances. L_V, L_H, and the port diameter Dp are given by Equation,

$L_P = L_V - Dp$

$0.762 = L_V - 0.1$

$L_V = 0.862$ m and

$W_P = L_H + D_P$

$0.457 = L_H + 0.1$

$L_H = 0.377$m

For the effective heat transfer area, the hydraulic diameter of the channel is given by the equivalent diameter, De, which is given by:

$D_e = \frac{2b}{\emptyset}$

$= \frac{2*0.004}{1.15} = 0.069$ m

The effective number of plates is

N e = Nt − 2

= 60 – 2 = 58

The number of channels per pass, *Ncp*, from Equation

$Ncp = \frac{Nt-1}{2Np}$

$= \frac{60-1}{2*1} = 29.5$

B. Heat Transfer in the Plates

The heat transfer area is expressed as the global design equation:

Q= UA* ΔTM

The total area of heat transfer can be given by:

$A = 2\pi.r.L_V$

$=2\pi.*0.05*0.862$
$=0.2708\ m^2$

The overall heat transfer coefficient can be determined by:

$$= \frac{1}{\frac{1}{h1}+\frac{tp}{kp}+\frac{1}{h2}+Rfc+Rfh}$$

Convective heat transfer coefficient of the cold fluid,

Local heat flux density,

$q= - kp.\frac{dt}{dx} = - 13*(-1)/0.004$
$= 3250\ W.m^{-2}$

$h= \frac{q}{\Delta Tc} = 3250/ (78- 32)$
$= 70.65\ W.m^{-2}.°C$

Convective heat transfer coefficient of the hot fluid,

$q= - kp.\frac{dt}{dx} = - 13*(-1)/0.004$
$= 3250\ W.m^{-2}$

$h1= \frac{q}{\Delta Th} = 3250/(108- 86)$
$= 147.72\ W.m^{-2}.°C$

Then, Fouling factor of cold,

$Rf_C= 0.001\ m^2.°C/w$ (Given from below table)

Fouling factor of hot,

$Rf_C= 0.002\ m^2.°C/w$ (Given from below table)

Then,

$$U = \frac{1}{\frac{1}{147.72}+\frac{0.004}{13}+\frac{1}{70.6}+0.001+0.002}$$

U= 38.10 Kw.

C. Design Methods

There are two main approaches used in the design of PHEs, namely the log-mean temperature difference and the thermal effectiveness methods. For the first method, the rate of heat transfer is given by:

$Q= UA*\Delta T_M$

But, first upon find out of log-mean temperature difference,

$\Delta T_M= \frac{\Delta T1-\Delta T2}{In\frac{\Delta T1}{\Delta T2}}$ ($\Delta T1= T_{h1}- T_{c2} =108-78= 30°C$)

$\Delta T_M= \frac{(108-78)-(86-32)}{In\frac{(108-78)}{(86-32)}}$ ($\Delta T2=T_{h2}- T_{c2} =86-32= 54\ °C$)

$\Delta T_M=40.83°C$

Then,

$Q= UA*\Delta T_M =38.10*0.2708*40.83$

Q= 421.26 kw.

The dimensional parameters R e PC is defined as:

$$R = \frac{Th1-Th2}{Tc2-Tc1}$$

$R = \frac{108-86}{78-32} = 0.478$

Temperature effectiveness,

$PC = \frac{Tc2-Tc1}{Th1-Tc1} = \Delta Tc/\Delta T_{max.}$

$PC = \frac{78-32}{108-32} = 0.6052$

Heat capacity rate of cold fluid,

$C_C = M * C_P = 8.25* 4.2$
$=34.65\ kW$

Heat capacity rate of hot fluid,

$C_H = M * C_P = 11.92* 1.6$
$= 19.02\ kW$

The second method provides a definition of heat exchanger effectiveness in terms of the ratio between the actual heat transfer and the maximum possible heat transfer, the PHE effectiveness can be calculated as the ratio of temperatures:

E= Q/Qmax.

The second method provides a definition of heat exchanger effectiveness in terms of the ratio between the actual heat transfer and the maximum possible heat transfer,

Q= (M*Cp)*(Tc2- Tc1), = 34.65 *(78-32)

Q= 1593 kw,

Thermodynamically, Qmax represents the heat transfer that would be obtained in a pure countercurrent heat exchanger with infinite area. This can be expressed by:

Qmax= (M*Cp)*(Th1- Tc1) = 34.65* (108- 32)

Qmax= 2584kw,

E= Q/Qmax.

E= 1593/ 2584

E= 0.616 = 61.6%

The effectiveness depends on the PHE(Plate heat Exchanger) configuration, the heat capacity rate ratio (R), and the number of transfer units (NTU). The NTU is a dimensionless parameter that can be considered as a factor for the size of the heat exchanger, defined as:

NTU= UA/ (M*Cp)
= 38.10* 0.2701/ (11.92*1.6)
= 0.54

D. Pressure Drop in a Plate Heat Exchanger

It is recommended to keep this loss lower than 10% of the available pressure drop, although in some cases it can exceed 30%. GP is the fluid mass velocity in the port, given by the ratio of the mass flow, M, and the flow cross-sectional area, πDP2/4.

$$Gp = \frac{4M}{\pi Dp^2}$$

$Gp = \frac{4*8.25}{\pi*0.1^2} = 1050\ kgm^{-2}s^{-1}$

Then,

$$\Delta P = 4*\frac{Gp^2}{2\rho}+\rho*g*Lv$$

$$\Delta P = 4*\frac{1050^2}{2*1000}+1000*9.81*0.862$$

=10661.22 Pascal

E. Experimental Heat Transfer and Friction Correlations for the Chevron Plate PHE

Gc mass flow per channel is the and may be defined as the ratio between the mass velocity per channel m ˙ and the cross sectional area of the flow channel (bWP):

Gc= m/b*Wp

(m= 0.135 kg/s) per channel

Gc= 0.135/0.004*0.457

Gc= 73.85 (kg/m^2s)

Then,

Reynolds number (Re),

Re= Gc*De/ μ $\mu= 4.04 \times 10^{-4}\ Pa\cdot s$

Re= 73.85* 0.069/ 4.04*10, = 12613
Prandtl number (Pr) from table
Pr= 4.34
Then,
Nusselt number (Nu)
$Nu= C_h*(Re)^n*(Pr)^{0.33}*(\mu/ \mu_w)^{0.17}$
C_h=0.130, n= 0.732)
$Nu= 0.130*(12613)^{0.732}*(4.34)^{0.33}*(4.04*10^{-4}/900)^{0.17}$
Nu= 17.65

7. Results Analysis

The experiments were carried out on the initially result analysis is based on to design the Number Transfer Unit (NTU), Heat Exchange Effectiveness, efficiency and coefficient heat transfer rate.

A. Graphical Representations

Based on above calculations and results following graphs are plotted for interpretation of performance.

1. Modified overall heat transfer Vs. old overall heat transfer for all test specimen.
2. Modified log-mean temperature difference Vs. Modified log-mean temperature difference
3. Modified heat transfer effectiveness Vs. Old heat transfer effectiveness
4. Modified NTU Vs. old NTU
5. Modified heat exchanger efficiency Vs. old heat exchanger efficiency
6. Modified rate of heat transfer Vs. old rate of heat transfer
7. Modified Nusselt number vs. old Nusselt number
8. Modified Reynolds number vs. Reynolds number

1) Modified overall heat transfer vs. old overall Heat transfer for all test specimen.

Variation of modified overall heat transfer with respect to old overall heat transfer is shown in fig. 3. It is observed that the modified overall heat transfer increases with old overall heat transfer.

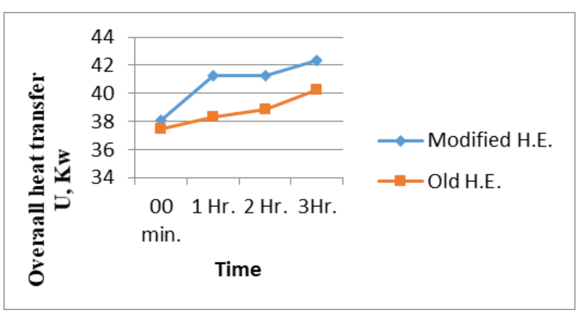

Fig. 3. Variation of overall heat transfer with time

2) Modified log-mean temperature difference vs. modified log-mean temperature difference

Variation of modified Log-Mean Temperature Difference with respect to old Log-Mean Temperature Difference is shown in fig. 4. It is observed that the modified Log-Mean Temperature Difference decreases with old Log-Mean Temperature Difference.

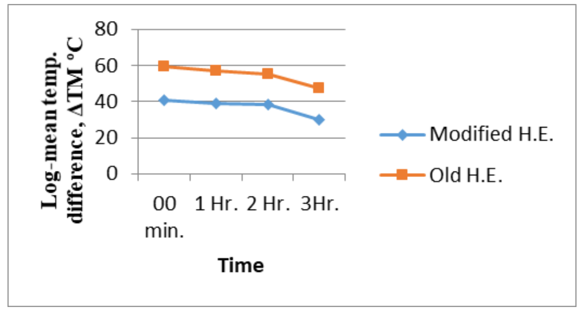

Fig. 4. Variation of log-mean temperature difference with time

3) Modified heat transfer effectiveness vs. old heat transfer effectiveness for all test specimens

Variation of modified Heat Transfer Effectiveness with respect to old Heat Transfer Effectiveness is shown in fig. 5. It is observed that the modified Heat Transfer Effectiveness increase with old Heat Transfer Effectiveness.

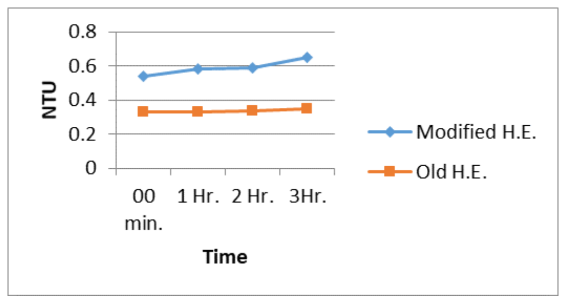

Fig. 5. Variation of heat transfer effectiveness with time

4) Modified NTU Vs old NTU for all test specimens

Variation of modified NTU with respect to old NTU is shown in fig. 6. It is observed that the modified NTU increase with old NTU.

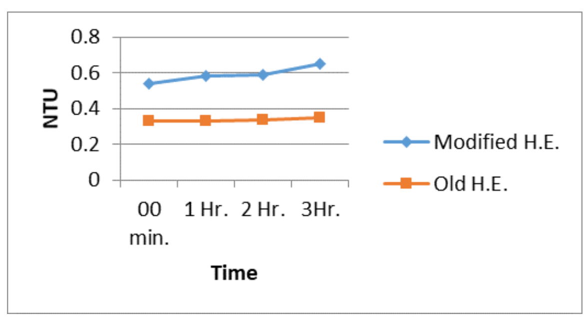

Fig. 6. Variation of NTU with time

5) Modified heat exchanger efficiency vs. old heat exchanger efficiency for all test specimens.

Variation of modified heat exchanger efficiency with respect to old heat exchanger efficiency is shown in fig. 7. It is observed that the modified heat exchanger efficiency increase with old heat exchanger efficiency.

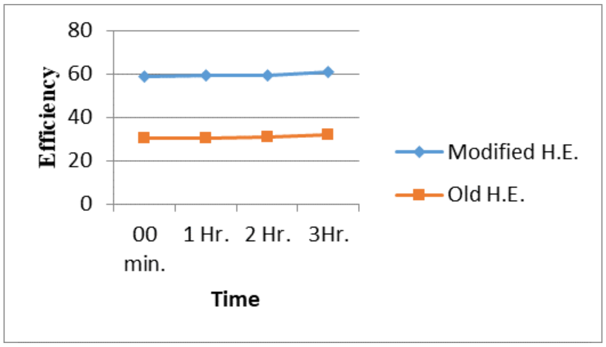

Fig. 7. Variation for heat exchanger efficiency with time

6) Modified rate of heat transfer Vs old rate of heat transfer for all test specimens.

Variation of modified rate of heat transfer with respect to old rate of heat transfer is shown in fig. 8. It is observed that the modified rate of heat transfer increase with old rate of heat transfer.

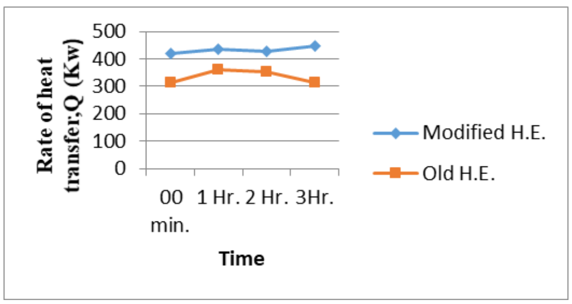

Fig. 8. Variation for rate of heat transfer with time

7) Modified Nusselt number vs. old Nusselt number for all test specimens.

Variation of modified Nusselt number with respect to old Nusselt number is shown in fig. 9. It is observed that the modified Nusselt number increase with old Nusselt number.

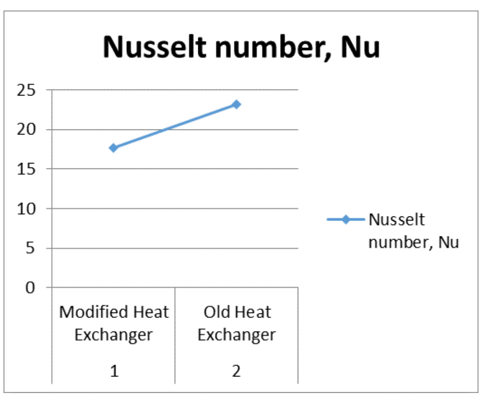

Fig. 9. Variation for Nusselt number with time

8) Modified Reynolds number vs. Reynolds number for all test specimens

Variation of modified Reynolds number with respect to old Reynolds number is shown in fig. 10. It is observed that the Reynolds number increase with old Reynolds number.

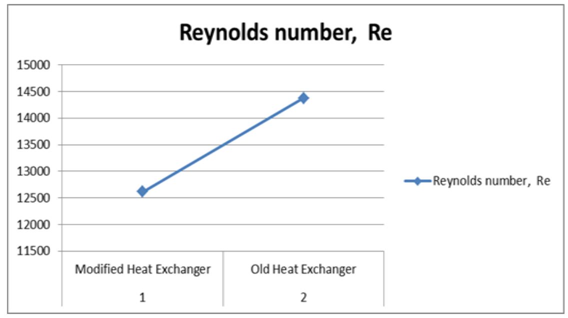

Fig. 10. Variation for Reynolds number with time

8. Conclusion

Experimental investigation has been carried-out in heat exchanger to study the effect of different parameter like Number Transfer Unit (NTU), Heat Exchange Effectiveness, efficiency and coefficient heat transfer rate and comparison between modified and old heat exchanger with the time. Following conclusion is drawn.

From the above obtained results it is concluded that the:

1. Modified heat exchanger have higher heat transfer rate as compare to old heat exchanger. The increase in heat transfer effectiveness of modified heat exchanger is 30% higher for old heat exchanger.
2. The percentage increase of overall heat transfers higher for 10% than old heat exchanger and reduce the log-mean temperature difference lesser than 18ºC than old heat exchanger.
3. The modified Heat Exchanger used in this project gives higher efficiency and a good amount of Heat transfer rate, NTU as compared to the design of the existing model.
4. This work is beneficial for use as it reduces the power utilization to some extent which is required in the present days.
5. Therefore, from all these conclusions, it is desirable to use the modified heat exchanger design in the industry which will reduce their heat losses and provide a good atmosphere for the worker and smooth running of the air compressor.

References

[1] Nikhil Patel, B. Shah, A. Raman "design and analysis for screw compressor" journal of information, knowledge and research in mechanical engineering, vol. 2, no. 2, 2013.

[2] R. Saidur, N. A. Rahim, Hasanuzzaman "A review on compressed air energy use and energy saving'' Renewable and Sustainable Energy Reviews 14 (2010), 1135–1153.

[3] Mariusz Broniszewski, and Sebastian Werle "The study on the heat recovery from air compressors," January 2018.

[4] Sreejith, Deepak Das "Design and Cost Optimization of Plate Heat Exchanger'' Research Inventy: International Journal of Engineering and Science Vol.4, Issue 10 (October2014), pp. 43-48.

[5] Stephenraj, M. K. Sathishkumar "design and analysis of heat exchanger for maximum heat transfer rate (multi model optimization technique)'' International Research Journal of Engineering and Technology.

[6] A. S. Mota, E. P. Carvalho and Mauro A. S. S. Ravagnani "Modeling and Design of Plate Heat Exchanger."

[7] Sachchidanand, J. Nimankar and Sachin Dahake "Review of heat exchangers" global journal of engineering science and researches, issn2348–8034.
[8] Akshay Kumar Magadum, T. C. Mestri "Review of Experimental Analysis of Parallel and Counter Flow Heat Exchanger," International Journal of Engineering Research & Technology.
[9] Ankush S. Patil, H. S. Farkade "Advances in Design and Development of Heat Exchangers: A Review" International Research Journal of Engineering and Technology.
[10] Suleyman Karsli, "Performance analysis of new-design solar air collectors for drying applications, Ataturk University, Pasinler Meslek Yu¨ksek Okulu, Pasinler, Erzurum 25300, Turkey, Renewable Energy 32(2007) 1645-1660.
[11] Fábio A.S. Mota, E.P. Carvalho and Mauro A.S.S. Ravagnani "Modeling and Design of Plate Heat Exchanger."
[12] Alfa Laval. Canada. Plate Heat Exchanger: Operational and Maintenance Manual. Available in <http://www. schaufcompany.com>.
[13] Lienhard IV, J. H.; Lienhard V, J. H. A Heat Transfer Textbook. 3ed. Cambridge: Phlogiston Press, 2004. Page 103.
[14] Kandlikar, S. G.; Shah, R.K. Asymptotic Effectiveness-NTU Formulas for Multipass Plate Heat Exchangers. Journal of Heat Transfer, vol. 111, pp. 314-321, 1989.
[15] Heggs, P. J. E. Scheidat, H. J. Thermal Performance of Plate Heat Exchangers with Flow Maldistribution. Compact Heat Exchangers for Power and Process Industries, ed. R. K. Shah, T. M. Rudy, J. M. Robertson, e K. M. Hostetler, HTD, vol. 201, ASME, New York, p.621-626, 1996.
[16] Shah, R. K.; Kandlikar, S. G. The Influence of the Number of Thermal Plates on Plate Heat Exchanger Performance. In: MURTHY, M.V.K. et al. (Ed.) Current Research in Heat and Mass Transfer. New York: HemisTCPre P.C., 1988, p.227-241.
[17] Kumar, H. The Plate Heat Exchanger: Construction and Design. 1st UK National Conference of Heat Transfer. no. 86, p. 1275-1286, 1984.
[18] Gut J. A. W., Pinto J. M, Optimal Configuration Design for Plate Heat Exchangers. Int. J. Heat Mass Transfer 2004; 47:4833-4848.
[19] Sreejith K., Basil Varghese, Deepak Das, Delvin Devassy, Harikrishnan K., Sharath G. K. "Design and Cost Optimization of Plate Heat Exchanger" Research Inventy: International Journal of Engineering and Science, Vol. 4, Issue 10 (October 2014), pp. 43-48.
[20] Zhen Hua Jin, GiTae Park, Yong Hun Lee, Soon Ho Choi, Han Shik Chung, Hyo Min Jeong, "Design and Performance of Flow Distribution to the Channel in Plate Heat Exchanger", International Conference on Engineering Optimization, Rio de Janeiro, Brazil, 01 - 05 June 2008.
[21] Aydin Durmus, Huseyin Benli, Irfan Kurtbas, Hasan Gul, "Investigation of heat transfer in plate heat exchangers having different surface profiles", International Journal of Heat and Mass Transfer 52 (2009) 1451–1457.