Design and Analysis of Multi-Stage Intercooler

Samarth. S. Nimbal, M. K. Nalawade

Abstract*: This paper deals with the design and analysis of air-cooled heat exchangers. Heat exchanger means exchange the thermal duty to the next stage compressor by the external source. It will help to get an effective fluid to next stage compressor here working fluid as air so it is divided under air-cooled heat exchanger. In this, we should know what is problem occurs in the current scenario that is our objectives work on those objectives with help of theoretical knowledge, theoretical consideration, an analytical calculation that should be validated with software. For fluid flow use of pressure vessels prepare with the help of ASME codes from pressure vessel calculation we get thickness. Thermal calculations are made with the help of D. Q. Kern method from the thermal calculation we get a Heat load and required area for heat transfer. Use of that software like ANSYS, HTRI they give results if it satisfied our condition we compare that results with experimental values. It will conclude whatever we get an outputs those are right are wrong.

***Index Terms*: Duty, Pressure vessel, Heat load, Thickness, Thermal, Heat transfer.**

I. INTRODUCTION

Inter-stage coolers are a thermally mechanical device used to cool a fluid, between two stages of a multi-stage compressor process. It improves the efficiency of air to efficient air will supply to next stage compressor. The intercooler is a device that facilitates the transfer of heat energy from the hot process fluid to fan forced ambient air. The hot forces fluid is cooled by passing in a finned tube. Designing thermal systems that can utilize the waste heat will recycle to result in efficiency improvement.

These pressure vessels which cools an internal fluid within finned tubes by forcing ambient air over the exterior of the tubes. The basic components of system are served by axial flow fans, fan drivers, speed reducers and enclosing and supporting structure. The engine components must be cooled to keep them from overheating in system due to friction and the combustion process of compressor. One of the simplest ways is to use forced ambient air. Air-cooled heat exchangers do not require any cooling water from a cooling tower because of air cooled heat exchanger.

Inter-coolers are utilized to remove the heat from each stage of multi-stage air compressors. Multi-stage air compressors are used because of their inherent efficiency and utilization of air. The cooling action of the inter-cooler is principally responsible for reduce high temperature to low temperature of system's higher efficiency, bringing it closer to Carnot efficiency of the compressor. Removing heat-of-compression from the discharge of the first stage has the effect of densifying the air charge. This, in turn, allows the second stage to produce more work from its fixed compression ratio compared to next stage. Adding an intercooler to the setup requires additional investments like to cool the air fan will be there also it requires motor to run the system.

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II. LITERATURE SURVEY

A. Fin related

Air-cooled heat exchanger for process use consists of finned-tube bundle with rectangular box headers on both ends of the tubes to store the cooled air by finning the tubes for heat transfer. Cooling air is provided by one or more fans in a system by force cooled. Usually, the air blows upwards through a horizontal tube bundle. The fans can be either forced or induced draft, depending on whether the air is pushed or pulled through the tube bundle with the requirement to system. The space between the fan(s) and the tube bundle is enclosed by a plenum chamber which directs the air to cooler and some air will evaporated in surrounding. The whole assembly is usually mounted on legs or pipe rack on base frame of system. [1]

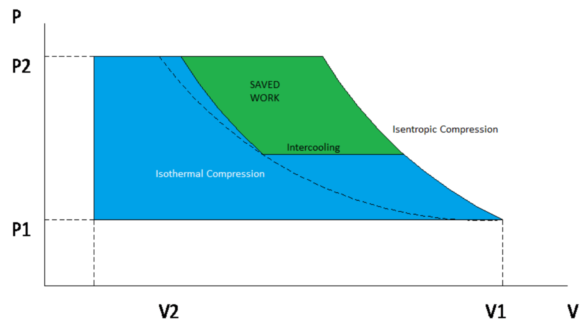

Figure 1-Working Design

B. Work saving

Using intercooler is one of a good method in a compressor. First, we get 8-1-4-7 as a work path for Low Pressure and 7-4-5-6 as a work path for High Pressure because of intercooler we get 8-1-2-7 is a work path for Low Pressure and 7-2-3-6 is a work path for High-Pressure Compressor. Due to this, we can reduce the work of the system. So energy consumption also reduced then we get a good result and good air for the compressor. [2]

C. Baffle plates

Baffles are designed to direct fluid across the tube bundle as efficiently as possible also it will help to arrange tube in a system. Forcing the fluid across the tube bundle ultimately results in a pressure loss because of the surrounding conditions it will give a losses in system. The most common type of baffle is the single segmental or cut segmental baffle which changes the direction of the shell side fluid to achieve cross flow. Deficiencies of the segmented baffle include the potential for dead spots in the heat exchanger and excessive tube vibration of bundle it will effect on system. [3]

D. Orientation

The air-cooled heat exchanger is controlled by some factors that will be effect on the tube bundle size and configuration, and the ability to pass air across the surface area that the bundle provides by tubes. In design of cooler total force will consider not only selection of fan but also design of outer case of cooler to pass air across the surface area. The common way of moving air across the air cooler bundle is an axial flow to cooler, propeller type fan that will forced air bombard on tube either pushes (forced draft) the air across the bundle or pulls (induced draft) it across the tubes of cooler in a system by using motor power for strikes an air on
tube.[4]

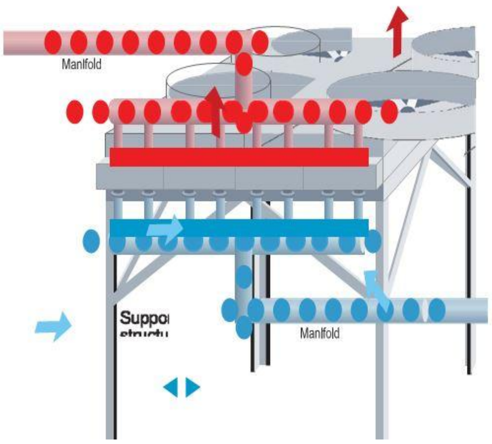

Figure 2-Orientation

III. THEORY AND CONSIDERATION

A. Past research

We can say that after doing some research in the past it is seen that so many factors that affect the properties of material like strength of the machine, design parameters, material selection, raw material defect, and surface imperfection. It is seen that design parameter that is operating modes like operating temperature, operating pressure and imperfections, as we saw as the temperature increases the strength of material decreases. Also with less temperature difference and flow rate it will affect overall thermal performance.

B. Objectives

The major objectives of the proposed work are, Design of Intercooler, and performance of Intercooler taking into account the various factors that might affect the functionality of the Compressor. Design and analysis of the model and Assembling of the model carried out, the process is studied and optimized for effective results of a compressor. The main objective of this project to minimize or overcome the problem which can be faced in Intercooler. Also increased overall efficiency. Design and analysis of air-cooled Intercooler for Reciprocating Compressor.

1. Reduce the number of tubes and weight of system for reducing size as well as cost of system.
2. Increase Fins effective surface area to heat transfer by limiting acceptable pressure drop by FEA analysis.
3. Optimization thermal performance of Inter stage cooler by using HTRI.

IV. SELECTION OF MATERIAL

The material selection is consider from various factors like strength, stiffness, plasticity, elasticity, ductility from these point of view. For a designer engineer, it is must that he is familiar with the effect, which the manufacturing the process & heat treatment have on the properties of materials.

The selection of material for engineer purposes depends upon the following factors.

1. Physical and chemical properties of material.
2. Mechanical properties of material.
3. Suitability of the material for the working condition in service.
4. Availability of the material.
5. The cost of material.

The mechanical properties of the metals are those, which are associated with the ability of the material to reset mechanical forces and load. We shall now discuss as follows:

1. Strength: It is the property of a material to resist an externally applied force.
2. Stress: The resistance occurred by a part to an externally applied force on an area is called stress.
3. Stiffness: It is the capacity of material to resist deformation under stress. The modulus of elasticity of the measure of stiffness.
4. Elasticity: When removing external force it regains its original shape after deformation called as modulus of elasticity. This property is desirable for material used for tools and, machines it may be noted that steel is more elastic than rubber.
5. Plasticity: When removing external force it not regains its original shape after permanently deformation. This property of materials are necessary for forging, like in stamping images on coins and in ornamental work.
6. Ductility: due to tensile enabling it to be down into wire with the application of tensile force. A ductile material must be both strong and plastic in nature. The ductility is usually measured by terms, percentage elongation and percent reduction in area. The ductile materials are commonly used in engineering practice are mild steel, copper, aluminum,

7. nickel, zinc, tin and lead.
8. Toughness: Due to high impact load it resist from fracture. The toughness of the materials are decreased when it is heated. It is measured by the amount of absorbed after being stressed up to the point of fracture. This characters are desirable in parts subjected to shock an impact loads to tubes.
9. Resilience: Due to absorb energy and to resist rock and impact loads to system. It is measured by the amount of energy absorbed per unit volume with an elastic limit. This property is essential for spring material.[5]

V. PRESSURE VESSEL CALCULATION

A. Intercooler-1(Tube)

1) Input data
- Inner Diameter=I.D=17.831mm
- Inner Radius=R=8.9155mm
- Number of Pass=1
- Number of Tubes=24
- Length of Tube=955mm
- Total Length=23370mm
- Design Pressure=4kg/cm^2
- Design Temperature=250°C
- Material= SB 111 Alloy 120 Light drawn

2) Output data
- From above ASME Reference we get,
  - i. Tensile Strength=F_t=2550 kg/cm^2
  - ii. Yield Strength= F_y=1550 kg/cm^2
  - iii. Allowable Stress= S=645 kg/cm^2
- Considerations,
  - i. As pipe material is copper so less corrosion allowance considered as 0.5mm.

    C.A=0.5mm
  - ii. Considering radiography as 100 percentage so joint efficiency taken as 1.

    E=1

a) Circumferential Stress (Longitudinal Stress)

t<0.5*R, P<0.385*SE

$$t = \frac{(P * R)}{[(S * E) - (0.6 * P)]} + C.A$$

t=0.5555mm

b) Longitudinal Stress (Circumferential Stress)

t<0.5*R, P<0.385*SE

$$t = \frac{(P * R)}{[(2 * S * E) + (0.4 * P)]} + C.A$$

t=0.5276mm

- From above calculation we choose maximum thickness value that is 0.5555mm.
- As standard pipe available in market for copper material sustaining this pressure is 1.219mm as a thickness.

B. Intercooler-1(Purge bottle shell)

1) Input data
- Inner Diameter=I.D=160.9mm
- Inner Radius=R=80.45mm
- Length of Tube=472mm
- Design Pressure=4kg/cm^2
- Design Temperature=250°C
- Material= SA-106 Grade-B

2) Output data
- From above ASME Reference we get,
  - iv. Tensile Strength=F_t=4233kg/cm^2
  - v. Yield Strength= F_y=2020kg/cm^2
  - vi. Allowable Stress= S=1204kg/cm^2
- Considerations,

  C.A=4mm
  - i. Considering radiography as 100 percentage so joint efficiency taken as 0.85.

    E=0.85

a) Circumferential Stress (Longitudinal Stress)

t<0.5*R, P<0.385*SE

$$t = \frac{(P * R)}{[(S * E) - (0.6 * P)]} + C.A$$

t=4.3153mm

b) Longitudinal Stress (Circumferential Stress)

t<0.5*R, P<0.385*SE

$$t = \frac{(P * R)}{[(2 * S * E) + (0.4 * P)]} + C.A$$

t=4.1572mm

- From above calculation we choose maximum thickness value that is 4.3153mm.
- As standard pipe available in market for copper material sustaining this pressure is 7.11mm as a thickness.

C. Intercooler-1(Purge bottle dish end)

1) Input
- Distance=d=89mm
- No. of Dish end=n=2
- Inner Diameter=I.D=160.9mm
- Inner Radius=R=80.45mm
- Crown radius=L=134.8mm
- Knuckle radius=r=25.6mm
- Design Pressure=4 kg/cm^2
- Design Temperature=250°C
- Material= SA-234 WPB as per ANSI-B16.9

2) Output
- From above Reference we get,
  - vii. Tensile Strength=F_t=4233kg/cm^2
  - viii. Yield Strength= F_y=2020kg/cm^2
  - ix. Allowable Stress= S=1204kg/cm^2
- Considerations,

  C.A=4mm
  - i. Considering radiography as 100 percentage so joint efficiency taken as 0.85.

    E=0.85

a) Tori Spherical head
- Knuckle radius is equal to 6percentage of crown radius of inside.
- Inside crown radius is equal to outside diameter of skirt.
- If heads material has minimum tensile strength is exceeding 80000psi it will be designed using a value of allowable stress equal to 20000psi at room temperature.

$$t = \frac{(P * L)}{[(S * E) - (0.2 * P)]} + C.A$$

t=4.2636mm

- As standard pipe available in market for copper material sustaining this pressure is 7.11mm as a thickness.

Input condition for remaining stages,

- Design temperature=250°C
- Inner Diameter, Crown radius (mm),

Stage	Tube Diameter	Purge bottle shell side Diameter	Purge Bottle Dish end side Crown radius
2	17.831	160.9	134.8
3	17.831	158.48	134.8
4	7	103.18	89.4
5	5	59	50

- Corrosion allowance and Joint efficiency

Stage	Corrosion allowance(mm)			Joint efficiency		
	Tube	PB shell	PB dish end	Tube	PB shell	PB dish end
2	0.5	4	4	1	0.85	0.85
3	0.3	4	4	1	1	1
4	0.8	3	3	1	1	1
5	1.6	5	3	1	1	1

- Design Pressure is as below(kg/cm^2)

Stage	Tube	Purge bottle shell side	Purge Bottle Dish end side
2	15.65	15.65	15.65
3	57	57	57
4	168.5	168.5	168.5
5	255	255	255

- Similarly thickness will be (mm),

Stage	Tube	Purge bottle shell side	Purge Bottle Dish end side
2	1.219	7.11	7.11
3	1.219	9.52	9.52
4	1.5	11.12	11.12
5	2.5	14	14

VI. HEAT LOAD CALCULATION [6]

A. Intercooler-1

Input data

- Inlet air pressure at compressor (Pia)=1.013kg/cm2
- Inlet air temperature at compressor(tia) =35degC=308 deg K
- Outlet air temperature at compressor(toa) =55degC=328 deg K
- Relative humidity(RH)= 100percentage
- Air flow rate(Ua)=2.83m3/min
- Intercooler inlet air temperature(T1)=182.4degC
- Intercooler outlet air temperature(T2)=55degC
- Intercooler inlet air pressure(P1)=3.9kg/cm2
- Cooling air inlet temperature(t1)=32degC
- Specific heat of dry air= 0.245kcal/kg degC
- Specific heat of dry vapour= 0.45kcal/kg degC
- Specific heat of dry water= 1kcal/kg degC

Output data

- Saturated pressure of water vapour in suction

P_{isv}={EXP(77.34+(0.0057*t_{oa}) -(7235/t_{oa}))}/{t_{oa} ^ {8.2}}
=0.0574 kg/cm^2

- Specific Humidity of suction

w_{i}={ṁ_{v}}/{ ṁ_{da}}
= 0.0373kg/kg of air

- Saturated pressure of water vapour in delivery

P_{osv}={EXP(77.34+(0.0057*t_{oa})-(7235/t_{oa}))}/{t_{oa} ^ {8.2}}
=0.1607 kg/cm^2

- Specific Humidity of delivery

w_{o}={ ṁ_v}/{ ṁ_{da}}
= 0.0267kg/kg of air

- Dry air mass flow rate

={(P_{ia}-(RH*P_{isv}))*10000*U_{a}*60}{R*(t_{ia}+273)}
=179.99kg/hr

- Vapour mass flow rate

ṁ _{v}= ṁ_{da}*w_{i}
=6.72kg/hr

- Total mass flow rate

ṁ = ṁ _{da}+ ṁ _{v}
=186.71kg/hr

- Condensate drained

= ṁ_{da}*(w_{i}-w_{0})
=1.9kg/hr

- Dry air Heat Load

= ṁ_{da}*C_{p}*(T_{1}-T_{2})
=5618kcal/hr

- Vapour Heat Load

= ṁ_{v}*C_{p}*(T_{1}-T_{2})
=385kcal/hr

- Condensate Heat Load

=Condensate drained*570
=1089kcal/hr

- Total Heat Load

={Dry air heat load}+{Vapor heat load}+{Condensate heat load}
=7092kcal/hr

- Cooling air flow

={Total flow}/{No. of stages}}
=3443kg/hr

- Cooling air temperature rise

={Total heat load}/{Cooling air flow}*C_{p}
=8.4°C

- Cooling air outlet temperature

={Cooling air inlet temperature}+{Cooling air temperature rise}
T_{4} =43.4°C

- Greatest temperature difference(GTD)

GTD=T_{1}-T_{4}
=139°C

- Smallest temperature

difference(STD)

$STD=T_{2}-T_{3}$

$=20°C$

- Log mean temperature difference(LMTD)

$LMTD=\frac{(GTD)-(STD)}{\ln(GTD/STD)}$

$=61.4°C$

- Heat transfer area required

$A_{req}=\frac{Total\ heat\ load}{LMTD*120*0.9}$

$=1.07m^2$

Similarly we get Heat load and Area for heat transfer,

Stage	Heat load(kcal/hr)	Area(m^2)
2	9806	1.27
3	7286	0.99
4	5627	0.85
5	1990	0.50

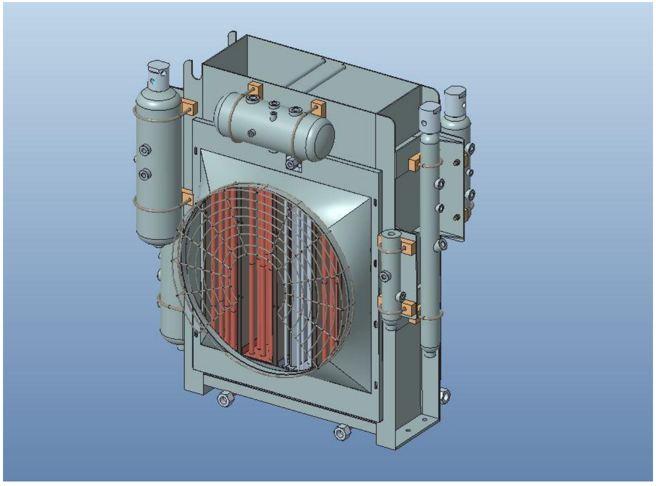

Figure 3-CAD Model

Figure 4-Temperature gun

Figure 5-Thermometer

As comparing results with mechanical analysis,

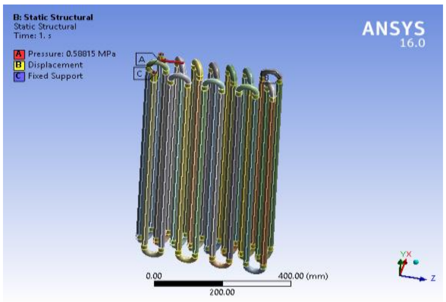

Figure 6-Inputs of Hydro test

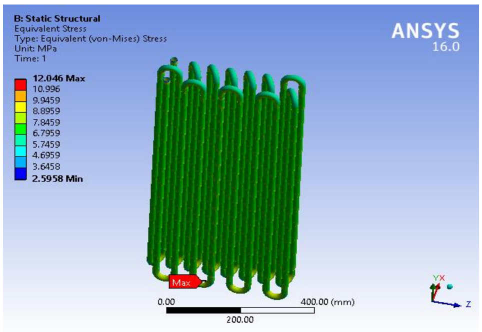

Figure 7-Hydro test

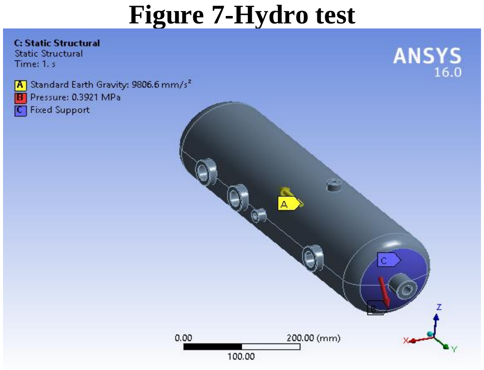

Figure 8-Inputs for Static structure

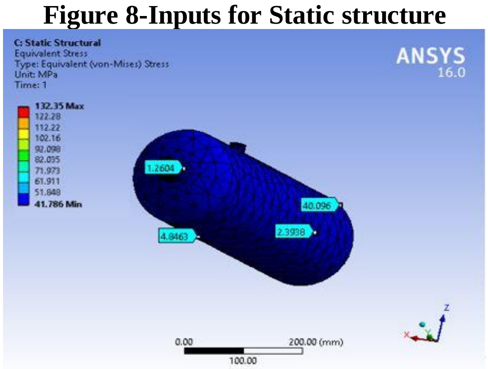

Figure 9-Static structure

As comparing results with thermal analysis,

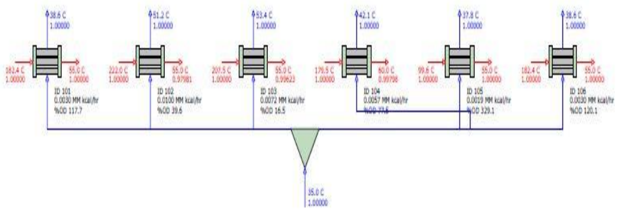

Figure 10-HTRI Model

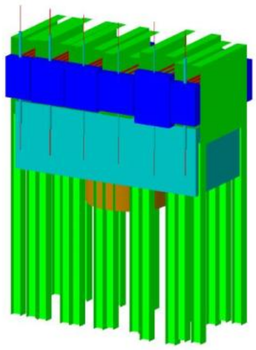

Figure 11-System HTRI 3-D Model

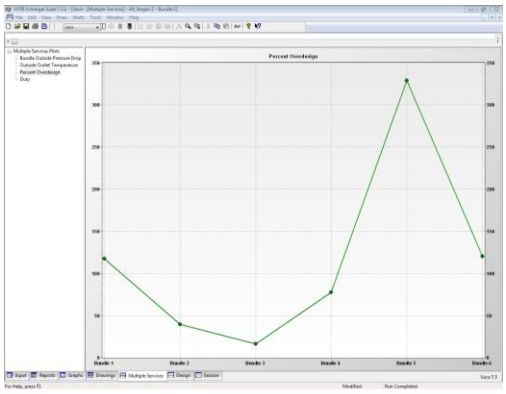

Figure 12-Over design Graph

- Results of Tubes,

Stage	Theoretical results(MPa)	FEA results (MPa)	Experimental results(MPa)
1	65	12.04	10.23
2	65	47.13	43.15
3	65	59.8	57.78
4	126	108.79	105.35
5	126	121.31	119.26

- Results of Purge bottle,

Stage	Static Structural analysis(MPa)	Experimental (MPa)	% Error
1	132.35	135	2
2	130	135	4
3	127	135	6
4	125	135	7
5	123	135	9

- Results by HTRI,

Stage	Overdesign (%)
1	22.38
2	40.88
3	16.70
4	14.35
5	23.71

VII. CONCLUSION

Finite element analysis of a tubes and Purge bottles we get a Von-Mises stress value as 132.36MPa for tubes compared with the analytical consideration of maximum allowable stress is 135MPa so there is 2% of error that means nearly close to results. Maintaining the pressure drop of 0.1 kg/cm^2 throughout the process for maintain the tube burst pressure. As calculating the heat load by analytical method 37kW compared by experimental results of temperature and flow rate this should be compared by HTRI results from that we get a design is in safe of 23.60%.

As comparing analytical and experimental results we can said that design in safe mechanical as well as thermally. Use of ANSYS and HTRI software for validation.

ACKNOWLEDGMENT

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