Performance Assessment of air coolers new tubes layout to achieve optimum design by using finite element model and experimental data: A case study

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Abstract:

Air compressors are located in air generation package unit to prepare the air for instrument devices. In each compressor an air cooler is furnished to reduce the temperature of air and oil. Each air cooler consists of four tube bundles, one stage for oil cooling and three tube bundles for air cooling. According to inspection reports, the air cooling system (three stages of each air cooler) has high corrosion rate. This is because of the violent humidity in site area (Assalouye-Iran) which is always more than 70% by year. Humid air decreases air cooler's efficiency by reducing the heat transfer rate and additionally in contact with carbon steel tubes produces corrosive particles. These particles reduce system efficiency and cause costly damage to compressor blades in downstream. The rate of metal lost in air cooler tubes is considerable so this will make the air cooler unavailable in the future. Several solutions were proposed and finally according to corrosion intensity it was decided to change air cooler materials from carbon steel to stainless steel A213 which prevents the corrosion. Considering thermal loading to be constant, thermal coefficient of new tubes is lower than carbon steel tubes. New expected heat transfer rate has been calculated based on two different methods and results showed that changing CS to SS would cause decrease in overall heat transfer rate about 15% to 20%. So it is necessary to redesign the

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air cooler and its accessories consequently. To prevent mentioned problem since the limited area was available for tubes, it was proposed to add an extra row of tubes. This would increase heat transfer surface which compensates reduction in thermal conductivity coefficient owing to change tube materials. By adding these new tubes there will be an increase in pressure drop which cause channelizing the air flow. In that case air does not flow uniformly over oil and air stage tubes and this result in unsteady temperature distribution which decrease system efficiency. So it is necessary to design an optimum layout for new added tubes to prevent mentioned problem. In this article first the root causes of corrosion in air cooler tubes are analyzed then the combination of effective factors in pressure drop including tube diameters, distances and their layout are investigated using finite element model and experimental data to achieve the best configuration and optimum layout for newly added tube bundles.

Keywords: air cooler, finite volume analysis, pressure drop, tube row number

1- Introduction:

Air cooler heat exchanger is a device for rejecting heat from a fluid or gas directly to ambient air When cooling both liquid and gases. There are two sources readily available, with a relatively low cost, to transfer heat to air and water. The obvious advantage of an air cooler is that it does not require water, which means that equipment requiring cooling does not need to be near a supply of cooling water. In addition, the problem associated with treatment and disposal of water have become more costly with government regulation environmental concerns. The air cooled heat exchanger provides a means of transferring the heat from the fluid or gas into ambient air, without environmental concern, or without great ongoing cost. An air cooled heat exchanger can be as small as your car radiator or large enough to cover several acres of land, as is the case on air coolers for large power plants where water is not available .the application for air cooled heat exchangers cover a wide range of industries and product, however generally they are used to cooler gases and liquids when the outlet temperature required is greater than the surrounding ambient air temperature. The application includes, gas compressor packages, gas transmission facilities, engine cooling, condensing of gases. Air cooler heat exchanger can be built in several configurations, the most common type of air cooler is the horizontal fan and vertical air flow this type is typically driven by an electric motor drive attached to the fan through v-belt to allow for speed reduction between the motor. This model is built in both induced draft and force draft configuration depending on the application, and the installation site, there are advantages and disadvantage to both models. Design of air cooler is 2 category , heat transfer and mechanical strength ,some of the governing factors in the design of the air cooler are ,tube diameter ,tube length ,fin height ,number of tube row ,number of passes ,face area ,horsepower availability ,plot area ,and for mechanical design and construction air cooler governing bodies according ASME code, sec VIII, division 1 API661 standard for air cooled heat exchanger ,TEMA (Tubular Exchanger Manufacturing Association)HTRI (Heat Transfer Research Institute)

This paper issued When vibration observed in high speed air compreesor and decrease compressor polytropic efficency in process air unit in phases 2&3 of south pars gas complax.,compreesor impllers were damaged by impact corrosion particle from piping and air cooler. Compressed air is a important of utility which used for cotrol system supply. maximum time between air commresor shut down and plant shutdown is about 15 min, to protect and prevent further deffect , the air cooler material was changed by stainless steel materials, this material heat conductivity coefficent is less than the carbon steel material and need heat transfer area to be increased ,this increase shall be done only by increase the row tube numberbut adding tube number will measure pressure drop in air cooler , Air compressor is a centrifugal type, with an air cooler between each stage and an after coolers. A stainless steel tube bundle is used to cool the lubrication oil this tube bundle does not need to change and air channelization is unavoidable. If air is channelized several problem may be done such as increase air temperatures in suction and discharge of compressor, decreasing compressor efficiency and unit and plant shutdown.

One of the important point of air cooler design is pressure drop in air side which has effect on selecting to select air cooler fan power ,heat transfer and performance, for this reason ,a number of correlation on pressure drop on circular finned tube bundles have been verified and show that the pressure drop depends on the number of rows except for the result of Gianlio and Guti[1] Jameson [2} Kuntysh et a [3]Nir [4]Robinson and Brigge[5] (Robinson, 1965)Ward and Young [6] Jameson [2] tested the staggered bundles of one to eight rows and varied $\frac{S_t}{d}$ from 1.9 to 3.6 and$\frac{S_l}{d}$ from 1.1 to 2.5 ,how ever ,it should be noted that there is no effect of the fin parameters in this relation ,Weeb [7]cited his recommndation to Robinson and Briggs [5] pressure drop correlation for a staggered tube layout

2: SYSTEM DESCRIPTION

In process air unit in phases 2&3 of south pars gas complex several defect have been occurred in air compressor impellers, which type of defect is erosion. Air compressor is a centrifugal type, with an air cooler between each stage and with an after cooler. A stainless steel tube bundle is used to cool the lubrication oil; According to inspection investigation ,the main cause of this erosion is smash of corroded particles from piping and tube of air cooler to high speed impeller.

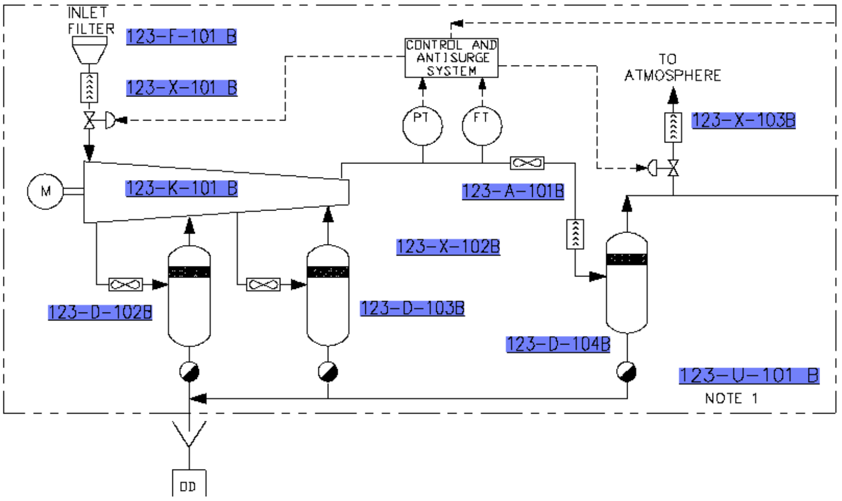


Figure 1. PFD of process air

Figure 2. Air compressor impeller defect

Figure 3. Separation drum corrosion product

Figure 4 Corrosion inside the suction lines of Compressor

Figure 5 Corrosion inside the air cooler

Engineering group suggested changing material for protecting the system against corrosion materials using suitable material is the best proposal. Air cooler and piping materials are from carbon steel which shall be changed by stain steel (type SS316L)

During heat balance calculation new problem was arise, this problem is result of heat conductivity coefficient, carbon steel conduction heat coefficients is about 55 $W/_{m\ K}$ and stainless steel conduction heat coefficients is about 16 $W/_{m\ K}$.

Table 1.Thermal conductivity of materials at room temperature W/m K

Material		Value	Material		Value
Stainless steel	201	16.3	**Hastelloy**	B	10.4
	202	16.3		C	8.8
	301	16.2		D	20.9
	302	16.2		G	10.8
	304	16.3		**X**	9.0
	304L	16.3	Incoloy	800	12.2
	309	13.8		901	13.4
	310	13.8	**Nimonic**	80A	12.2
	316	16.3	Inconel	600	15.0
	318L	16.3		610	15.0
	321	15.8		625	10.8
	330	13.0		700	12.4
	347	15.8		705	15.0
	410	24.9		722	14.7
	414	24.9		**X750**	14.7
	420	24.9	Monel	400	25.1
	430	25.9		401	19.2
	431	20.2		**R405**	25.9
	446	20.9		404	25.0

According to heat balance calculation, heat transfer area shall be increased about 20 percent, and this area must be added only by increasing the number of tube rows, because the lack of enough space, it is not allowed to change width and length of tube bundle, then number of rows increase to 6 instead of 5

Figure 6air cooler arrangement

There are 2 type of tubes bundle new and old on air side of heat exchanger, all tube bundles installed on force draft type structures, lubrication tube bundle does not need to change. which have different pressure drop then canalized is avoidable, pressure drop in air inter cooler and after cooler are different between exist (carbon steel material) and new one (stainless material).then different type of arrangement for fin tube heat exchanger shall be analysis to select the best methods for solved this to achieve to the best solution of this problem

If channelized was happened the heat exchanger does not work on high performance efficiency and outlet temperature of air cooler increase and compressor efficiency will be decrease. And may be occur unit and plant shutdown.

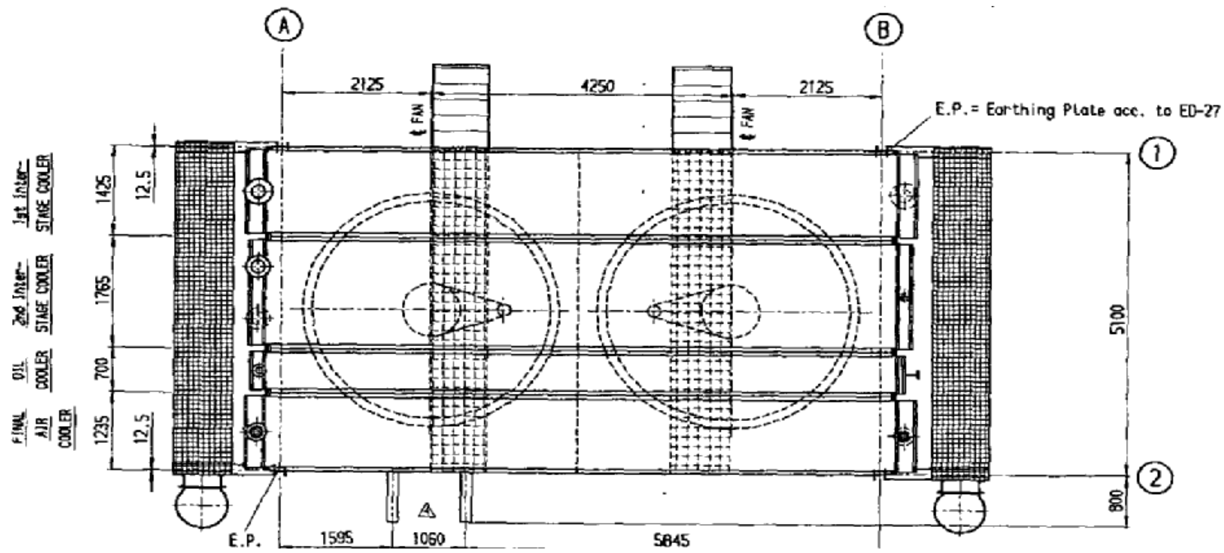


Figure 7.air cooler dimension and arrangement

4-Pressure drop correlation:

The basic design feature of heat exchanger is aimed to synchronize heat transfer rate and pressure drop in the system. minimum fan power to overcome the effect of air friction and to move the air through the tube bundle height is designing the compact heat exchanger .For this reason a number of correlations on pressure drop of circular finned-tube bundles have been verified and showed that the pressure drop depends on the number of rows except for the result of Gianlio and Guti [1] Joneson [2] Kuntysh et al[3] Nir[4]

-the following geometric parameters were considered in this investigation

1-tube diameter

2. Tube spacing

3. Tube arrangement

4. Number of tube row

5. Fin height

6. Fin spacing

7. Fin thickness

For each layout and tube arrangement several formulas are exist, Robinson [--] formula used for this physical geometric and flow condition for staggered tube arrangement

Equation 1

$$Eu = 18.93 R_e^{\ 0.316} \left(\frac{S_t}{d}\right)^{\ -0.927} \left(\frac{S_t}{S_d}\right)^{\ 0.515} . n$$

$$5 \times 10^{\ 4} \geq R_e \geq 2 \times 10^{\ 3}$$

$$40.89mm \geq d \geq 18.64mm$$

$$14.94mm \geq h_{\ f} \geq 10.5mm$$

$$0.6mm \geq \delta \geq 0.4mm$$

$$114.3mm \geq s_{\ t} \geq 42.85mm$$

$$114.3mm \geq s_{\ l} \geq 42.85mm$$

$$n \geq 4$$

Standard deviations 7.8%

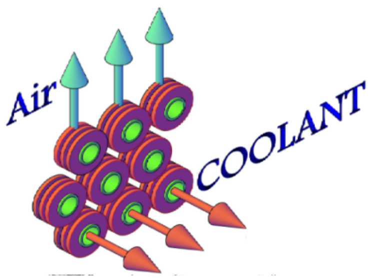


Figure 5 cross- flow circular finned tube heat exchanger

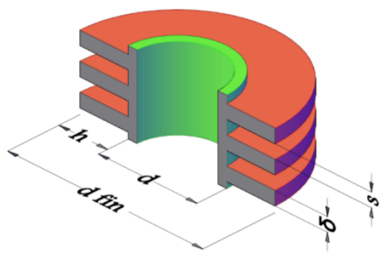


Figure 6 .cross-section of circular fin tube

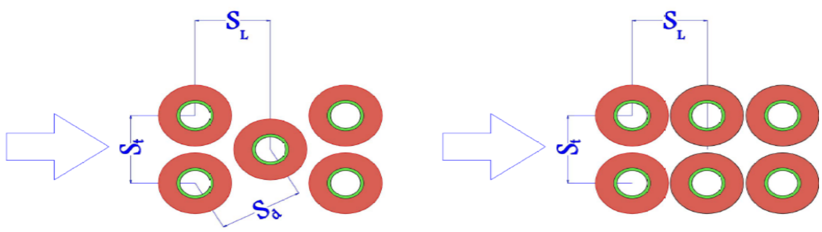


Figure 8.arrangement of tube in bundles a. staggered arrangement b. In-line arrangement

And heat transfer correlation author by, Gianolioan and Cuti [4] for staggered tube arrangement and force draft

Equation 2

$$\boldsymbol{Nu = 0.287 R_e{}^{0.7} Pr^{\ 0.37} \left(\frac{s}{h_f}\right)^{0.37} \left(\frac{s_t}{\delta}\right)^{-0.25} . \left(\frac{n}{6}\right)^{-0.136}}$$

$$2 \times 10^{4} \geq R_e \geq 5 \times 10^{3}$$

$$38.1mm \geq d \geq 25.4mm$$

$$16.4mm \geq h_f \geq 15.15mm$$

$$0.6mm \geq \delta \geq 0.4mm$$

$$114.3mm \geq s_t \geq 42.85mm$$

$$114.3mm \geq s_l \geq 42.85mm$$

$$n \geq 4$$

5-Numerical consideration:

Due to the advances in computational hardware and available numerical methods, CFD is a powerful tools for prediction of the fluid motion various situation

5-1Governing equation and CFD models:

The flow and temperature field in the model geometry is determined by the continuity equation The complete unsteady Navir –stockes and the energy equation for incompressible fluid with temperature dependent properties these three dimensional equation to be solved by numerical calculation method in the Cartesian coordinates, are as follow:

Continuity equations

Equation (3)

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial X_i}(\rho\, u_i) = 0$$

Momentum equation:

Equation (4)

$$\frac{\partial}{\partial t}(\rho\, u_i) + \partial/\partial X_j(\rho\, u_i u_j) = -\frac{\partial \rho}{\partial X_i} + \partial \tau_{ij}/(\partial Xj)$$

Where

Equation 5

$$\tau_{ij} = \boldsymbol{\mu} \langle \frac{\partial \boldsymbol{u}_i}{\partial \boldsymbol{X}_j} + \frac{\partial \boldsymbol{u}_j}{\partial \boldsymbol{X}_i} \rangle - \frac{2}{3} \frac{\boldsymbol{\mu} \partial \boldsymbol{u}_k}{\partial \boldsymbol{X}_k} \boldsymbol{\sigma}_{ij}$$

Energy equation:

Equation 6

$$\frac{\partial}{\partial t}(\rho E) + \partial/\partial X_i\big(u_i(\rho E+\rho)\big) = \frac{\partial}{\partial X_i}(k \frac{\partial T}{\partial X_i})$$

Where K is the thermal conductivity and E is the total energy

5-2Numerical simulation:

A difficulty for application of the CFD method in finned tube and tube bundles is the fact that is a complex geometry of the flow configuration

Fluent software uses a FVM and requires from the user to provide the grid system by software such as GAMBIT and then supply to FLUENT physical properties and the boundary conditions.

5-32Sequence of solving problem by fluent.

Before start the project, collection of information such as the arrangement, dimension of physical properties and material type of analysis (2D, 3D) dynamic of fluid flow and region, such as laminar turbulent flow and method of solving and selection solving method are very important

As described in the objective the purpose of this analysis and the effects of geometric parameter on the flow and the heat transfer characteristics and pressure drop of circular finned tub air cooler

A detail rectangular section circular fin tube scheme is shown in figure 2 the dimensional nomenclatures are the tube outside diameter, fin diameter d ,fin thickness ,δ, fin spacing s , a fin height h

6- Modeling

6-1DESIGN BASIS

Design flow (per machine):6900 Nm3/h (dry basis) with suction air at *48°C, 990 mbar* and 65% RH (ambient conditions for design). Ambient air temperature to design air coolers for non process purposes (such as cooling of machines) is 48°C.

Outside air fouling factor for air coolers: 0.00035 m^2. °C/W .
Inside fouling factor for instrument air: 0.00017 m^2.°C/W

Algorithm

In order to simulate, the following procedures of analysis are performed:

1-start the FLUENT with 2D solver

2-read an existing grid file and feed into FLUENT

3-check the grid

4-choose the suitable type of solver

to investigate heat balance

5-choose the model: To calculate the flow field, select the K-ε model, for coupling heat transfer active the energy equation

6-definen material property

7-define the boundary condition

8-define the control parameter

Table 2.Design condition

		Unit	CONTRACTOR DATA				VENDOR DATA				Note	Rev.
594	INTERSTAGE AIR COOLER										18	
595	Duty		Interstage cooling (1st)				Interstage cooling (1st)					
596	Item number						123-A-101 A/B/C					1
597	Supplier						GEA Luftkühler GmbH					1
598	Number of units		1 for each machine				1					
599	OPERATING CONDITIONS		Atm. side		Tube side		Atm. side		Tube side			
600	Fluid		Atm air		Compressed air		Atm air		Compressed air			
601	Total flowrate ratet	kg/h					~550,000 (*)		9.482			1
602					Inlet	Outlet			Inlet	Outlet		
603												
604	Vapor H_2O	kg/h							434	394		
605	Non Condensab	kg/h							9048	9048		1
606	Liquid											
607	H_2O	kg/h							0	40		
608	Specific gravity	kg/m3							2.23			
609	Viscosity	cp							0.0197	0.0247		
610	Operating temperatures		Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet		
611			48 (rated)			55	48	55.6	161,3	55		1
612	Operating pressures	bar g	-				-		1,402	1,32		1
613	Inlet velocity	m/s						3.1	24.17			
614	Pressure drop Allow./Calc.	bar					0.001383		0.082			
615	Design temperature								200			
616	Design pressure	bar g							3,1			1
617	Test pressure	bar g							4,7			1
618	Foul resistance	m2./w	0.00035		0.00017				0,00017			
619	Min corrosion allowance	mm			3				3			
620	Number of passes per bay								1			
621	CONSTRUCTION DETAILS											
622	Total area	m2					1396					
623	LMTD								33.68			
624	Corrected MTD											
625	Code requirements		API 661 +RP5561V 123 0700 001				Yes					
626	Shell diameter	mm					No shell					1
627	Number of tubes per bay								90			
628	Tube diameter	mm							31.8			
629	Tube length	mm							8880			
630	Tube gauge											
631	Tube pitch	mm							70 / 60.5			
632	NOZZLE SIZES		Number	Size	#	Facing	Number	Size	#	Facing		
633	Inlet						1	10	150	RF		1
634	Outlet						1	10	150	RF		1
635	Drain						1	2	150	RF		2
636	Vent						1	2	150	RF		2
637	MATERIALS											

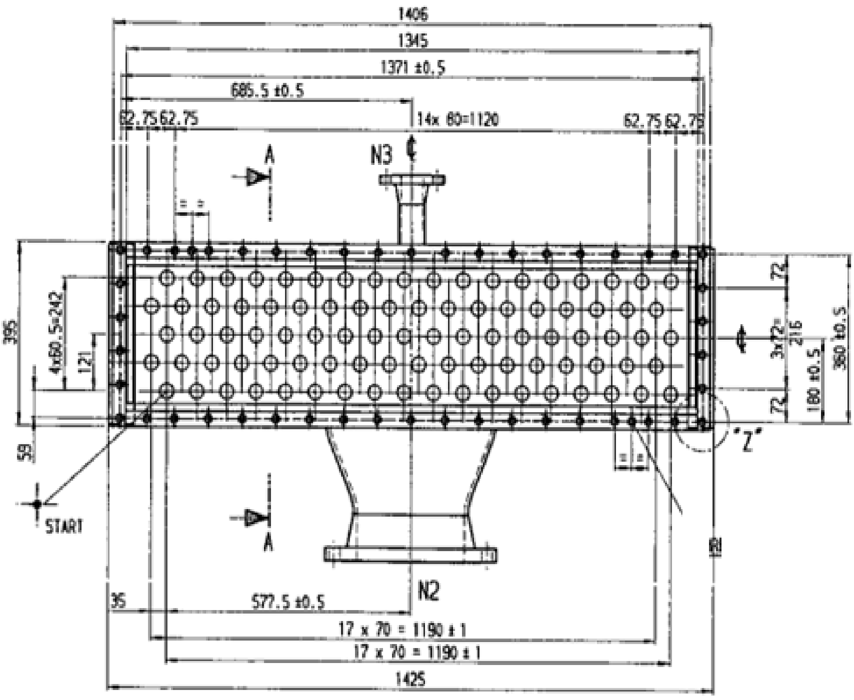


Figure 9 .1st air cooler tube layout

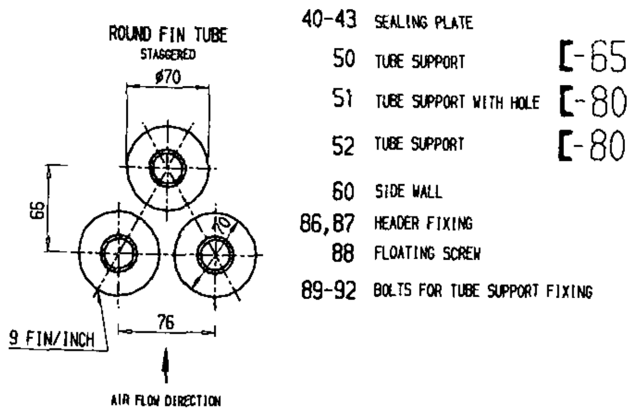


Figure 10fin & tube arrangement and dimension

At the first step of analysis select geometry of air cooler with real dimension and select suitable meshing with boundary condition then supply to FLUENT software .velocity of air in air side is about 3.1 m/s with 48 °c and 1bar absolute pressure.

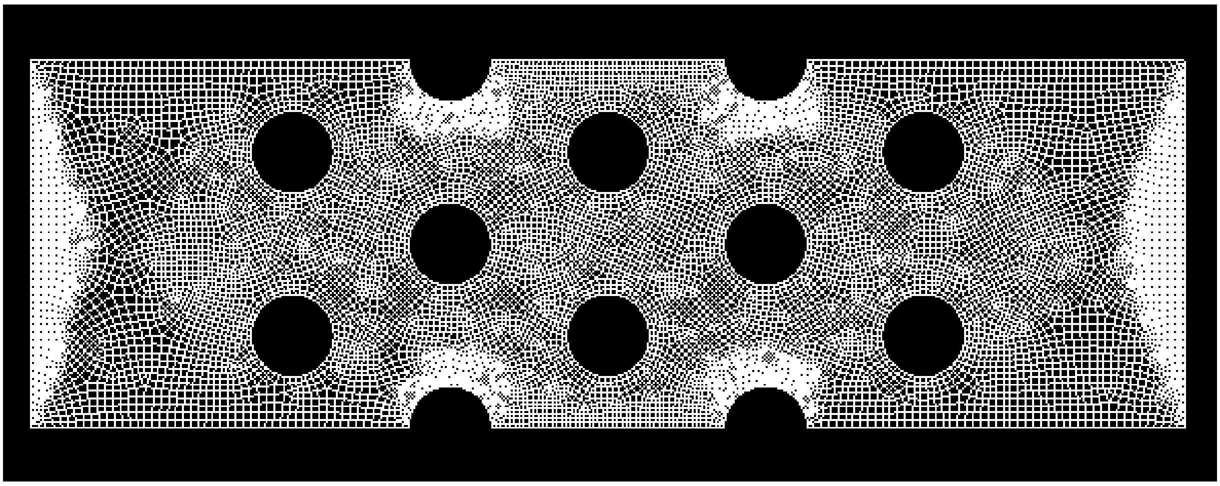


Figure 11.schematic of 5 rows tube heat exchanger

Figure below was shown total pressure at air side stream for 5 row tubes for 1^{st} air cooler

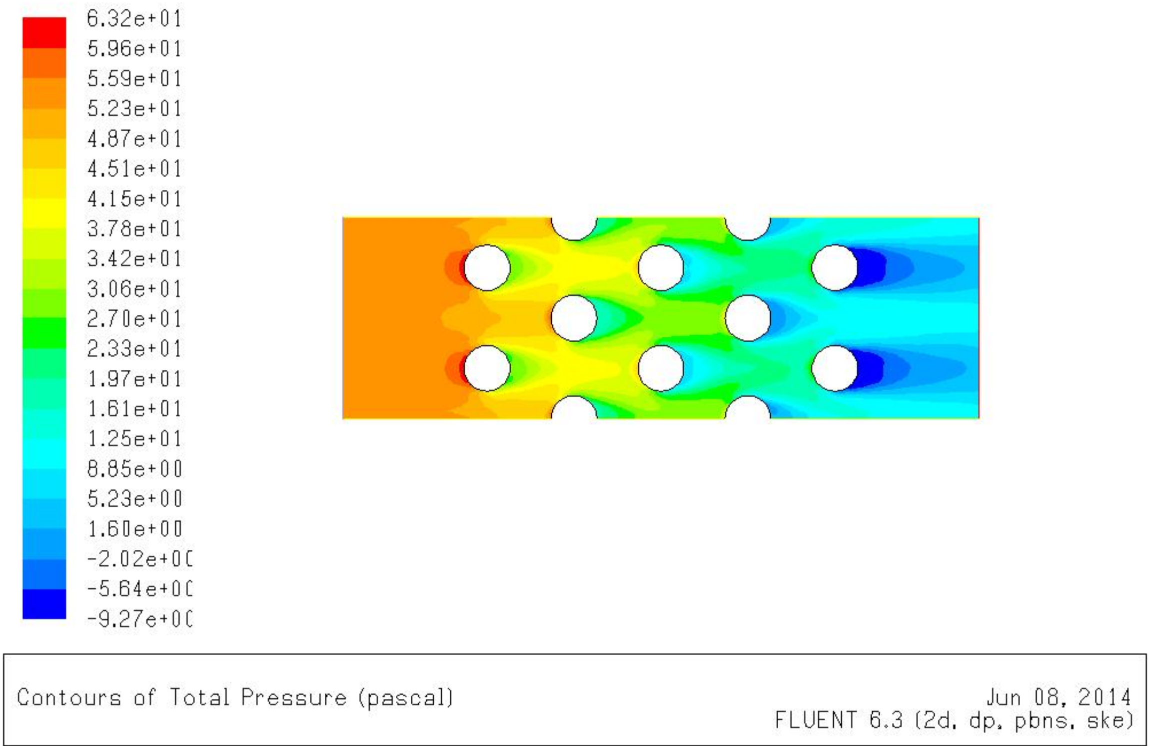
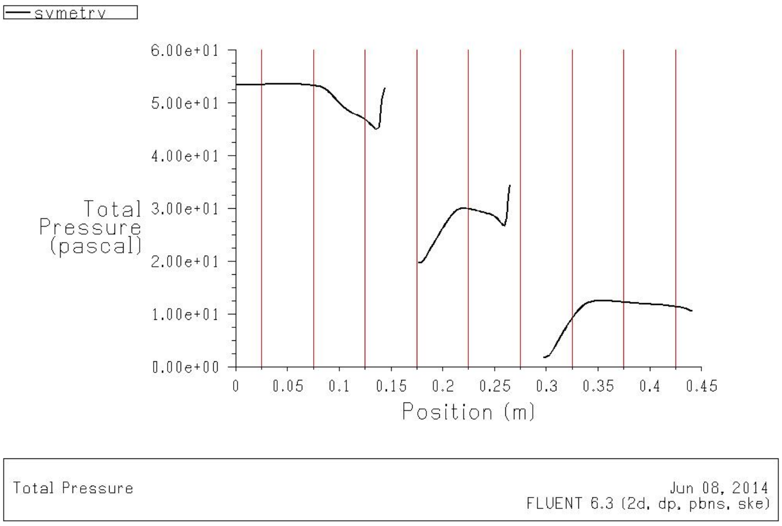


Figure 12.Contours of Total pressure (5 rows)

Figure below was shown X-Y plot total pressure in symmetry axial for 5 rows tube for 1^{st} air cooler



Plot 1.total pressure in air side (5 rows)

Figure below was shown total 6 rows tubes design by GAMBIT

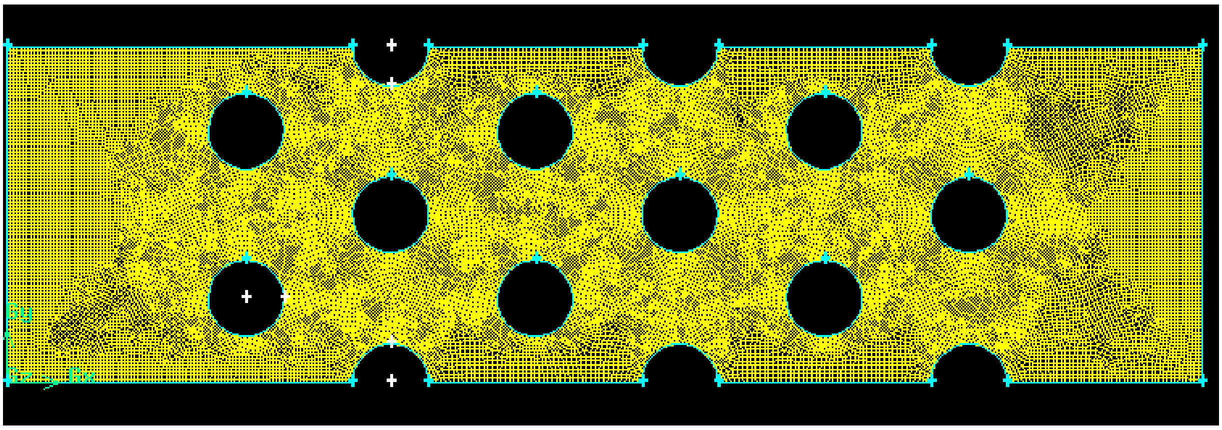


Figure 13 schematic of 6 rows tube heat exchanger

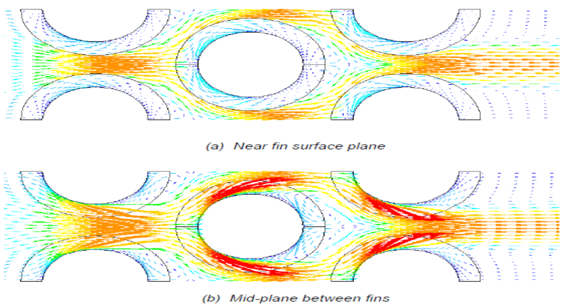


Figure 14.heat transfer calculation

Figure below was shown contour of total pressure at air side stream for 6 row tubes for 1^{st} air cooler

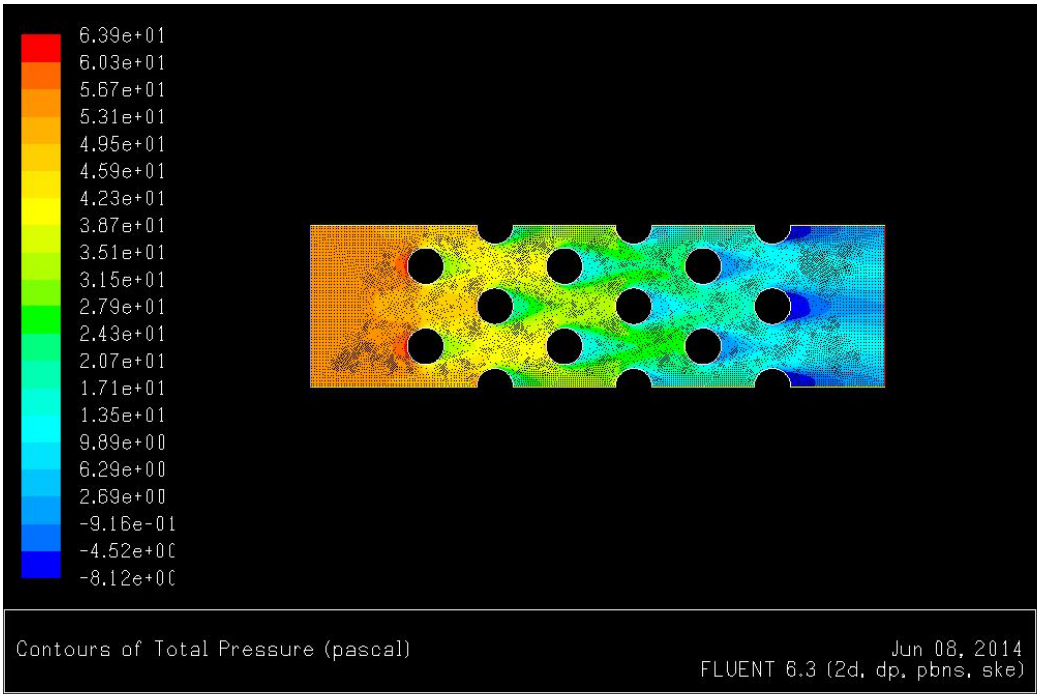


Figure 15. Contours of Total pressure(6 rows)

Figure below was shown X-Y plot total pressure in symmetry axial for 6 rows tube for 1st air cooler

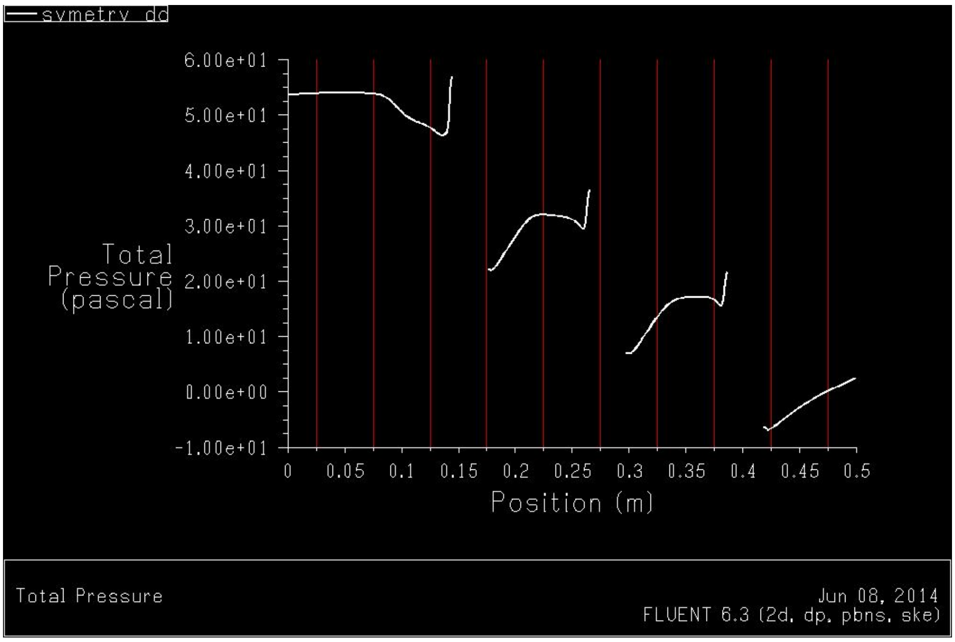


Figure 16. Total pressure in air side (6 rows)

Conclusion: In this research root causes of the air cooler are investigated. Range of possibilities proposed and design for new tubes was considered to overcome the problem based on experimental and analytical studies results are:

1- For refineries which located in high humidity spots it is necessary to use stainless steel for air generation package piping

2- In cases which it is considered to add number of tubes, it is necessary to avoid air canalization using CFD analysis. Based on analysis results other parameters like (number of added tubes, diameter, configuration and pitch) were changed to achieve the minimum pressure drop and optimum flow distribution over tubes

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