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Design and Analysis of Air Pre-Heater for a Gas Turbine Power Plant using PV Elite Software

Ramonu, O.J
Department of Mechanical Engineering
The Federal Polytechnic
Ilaro, Ogun state, Nigeria
E-mail: john.ramonu@federalpolyilaro.edu.ng,

Mohammed, M.A.
Technology Incubation Centre
, National Board for Technology Incubation
Ilorin, Nigeria
E-mail: engrabayomi@gmail.com

ABSTRACT

This paper presents the design, modeling and analysis of an air pre-heater – fit for safe service at a gas turbine power plant – using PV Elite software. The pre-heater, designed in accordance with ASME Code Section VIII Division 1 – Rules for construction of Pressure Vessels, is made of carbon steel and is capable of exchanging heat energy between flue gas (at 297^0C) and compressed air (at 150^0C), at pressures of 10 bar and 1.5 bar respectively. The design was analyzed by PV Elite design analysis software. It was discovered that the pre-heater's components were within allowable limits for the pre-heater material. However, the software recommends an increase in the tubesheet thickness from the initial 25.4 mm to 38.1 mm. The recommendation was incorporated into the design to minimize possible tubesheet joint failure due to bending or shear stresses induced in the tubesheet.

Keywords: Design, Pre-heater, Tubesheet, PV Elite, Pressure Vessels & Heat exchanger.

Aims Research Journal Reference Format:
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1. INTRODUCTION

Air pre-heater is a heat exchanger; a device built for efficient heat transfer from one medium to another. It could be a recuperative or regenerative type. The recuperative type is a shell and tube heat exchanger; it is the most common type of heat exchanger in oil refineries and other large chemical processes, and it is suitable for higher-pressure applications. As its name implies, this type of heat exchanger consist of a large pressure vessel with bundle of tubes inside it. One fluid runs through the tubes, and another fluid flows over the tubes to transfer heat between the two fluids. The set of tubes is called a tube bundle, and may be composed of several types of tubes; plain, longitudinally finned, etc. In order to realize maximum energy from the fuel burnt in any combustion process, the arrangement must be in a way to aid perfect combustion and maximum heat transfer. This is so because with perfect combustion and maximum heat transfer, combustion gases (flue gases) can be made to leave the plant at near atmospheric temperature, hence, little energy is being wasted. Temperature reduction in the flue gas from the combustion chamber could be achieved by using the flue gas to heat the incoming air, leading to increase in combustion efficiency. Temperature reduction in the flue gas from the combustion chamber could be achieved by using the flue gas to heat the incoming air, leading to increase in combustion efficiency.

Most often, the design of heat exchangers are concerned with the thermal considerations, but this study provides the mechanical design of an air pre-heater (U-tube heat exchanger) with the intent of determining a safe and economical design. In this paper we are concerned about the mechanical design analysis of the pre heater. To do this, we have designed a pre-heater based on the ASME section VIII Division 1 and thereafter PV Elite analysis software was used to vet the analytical design. Yusuf and Ozbilen (2004) studied the design of shell and tube heat exchangers with single phase fluid flow both on shell and tube side using a computer based design model for preliminary. The program was used to determine the overall dimensions of the shell, the tube bundle, and optimum heat transfer surface area required to meet the specified heat transfer duty by calculating allowable shell side pressure drop. They concluded that circulating cold fluid in shell-side has some advantages on hot fluid as shell stream since the former causes lower shell-side pressure drop and requires smaller heat transfer area than the latter and thus it is better to put the stream with lower mass flow rate on the shell side because of the baffled space.

In another study, Baghban, et al. (1999) used theoretical and experimental methods to determine the thermal behavior of the shell-side flow of a shell-and-tube heat exchanger. The experimental method provided the effect of the major parameters of the shell-side flow on thermal energy exchange. In the numerical method, besides the effect of the major parameters, they considered the effects of different geometric parameters and Reynolds number (Re) on thermal energy exchange in the shell-side flow while Adelaja, et al (2012) considered both the thermal and mechanical design of the E-type shell and tube heat exchanger with the aid of computer programming. It involves developing a simple user-friendly computer programme for the heat transfer calculations and ensures that the computational time is kept minimal. The algorithm is designed such that after the conditions for the thermal analysis are satisfied, the programme automatically proceeds to the mechanical design.

Pandita et al. (2015) recently studied the CFD analysis of a single shell and single tube heat exchanger and determining the effect of baffle angle on heat transfer, attempts were made to observe the effects of various angles of baffle inclination on fluid flow and the heat transfer characteristics of a shell and tube heat exchanger for three angles of baffles inclination, 0°, 45° and -45°. They compared the simulation results obtained for shell and tube heat exchangers; segmental baffles perpendicular to fluid flow and segmental baffles inclined to the direction of fluid flow for their performance. They concluded that, the steady state heat transfer is found to be more in the case of 45 degrees as compared to the -45 degrees case. In this study, the aim is to design an air pre-heater made of carbon steel which is to pre-heat combustion air (tube side fluid) at 150^0C and 10 bar using flue gas (shell side fluid) whose pressure and temperature are 1.5 bar and 297^0C. The pre-heater is a U-tube heat exchanger that has 2:1 semi-elliptical heads as the end caps fitted to the channel and main shells, and in between the channel shell and main shell flanges is the tube sheet onto which the U-tubes are supported. The design was modeled and analyzed using PV Elite software to determine if the design is safe and reliable.

2. METHODOLOGY

Design of an Air Pre-Heater

The design calculations are based on the ASME Section VIII Division 1. This implies that all equations (formulas) used throughout this design are extracted from the code.

Design Considerations

The design considerations are outlined below:
Ellipsoidal heads are used. The exchanger has two shells – channel and main shells.
Corrosion allowance is chosen to be 3.175mm in the main shell side.
The material used is SA-516-70 with stress value of 13.79 bar.
The main shell side design condition is 1.5 bar at 297^0C.
The channel side design condition is 10 bar at 150^0C.

Determination of the wall thickness and MAWP

The wall thickness and maximum allowable working pressure (MAWP) of the channel, the main shell and the 2:1 elliptical heads will be determined as outlined in the next two subsections. The joint efficiency (E) is 1 for seamless heads otherwise, 0.85 is used.

Thickness and MAWP for shell

Wall thickness for shells:

Channel:

$$t = \frac{PR}{SE-0.6P} = \frac{10 \times 9}{13.79\times1-0.6\times145} = 1.664\text{mm}$$

Hence, the required thickness, t_1 = 1.664mm since no corrosion allowance, hence, the design thickness, t_2 = 1.664mm

Main Shell:

$$t = \frac{PR}{SE-0.6P} = \frac{1.5\times9}{13.51\times1-0.6\times1.5} = 0.256\text{mm}$$

Hence, the required thickness, t_1 =. Adding corrosion allowance, design thickness, t_2 = 0.256+ 3.175 = 3.43mm. For this design we will use a plate of 6.35mm, nominal thickness for the shells.

MAWP for shell

Channel:

$$P = \frac{SEt}{R+0.6t} = \frac{13.79\times1\times6.35}{228.6+0.6\times6.35} = 37.67 \text{ bar}$$

Main Shell:

$$P = \frac{SEt}{R+0.6t} = \frac{13.79\times1\times6.35}{228.6+0.6\times6.35} = 37.67 \text{ bar}$$

This means that both channel and main shell are subjected to the same maximum allowable working pressure at the selected thickness.

Wall thickness for 2:1 elliptical head

Left head:

$$t = \frac{PD}{2SE-0.2P} = \frac{10\times457.2}{2\times13.79\times1-0.2\times10} = 1.659\text{mm}$$

Hence, the required thickness, t_1 = 1.659mm

Since no corrosion allowance is allowed, hence, design thickness, t_2 = 1.659mm.

Right head:

$$t = \frac{PD}{2SE-0.2P} = \frac{10\times457.2}{2\times13.79\times1-0.2\times10} = 1.659\text{mm}$$

The required thickness, t_1= 0.256mm. Adding corrosion allowance, design thickness, t_2 = 0.256 + 3.175 = 3.431mm. Hence, a plate of 6.35mm nominal thickness was used for the heads.

MAWP for 2:1 elliptical head

Left head:

$$t = \frac{2SEt}{D+0.2t} = \frac{2\times13.791\times6.35}{457.2+0.2\times6.35} = 38.2\text{bar}$$

Right head:

$$t = \frac{2SEt}{D+0.2t} = \frac{2\times13.791\times6.35}{457.2+0.2\times6.35} = 38.2\text{bar}$$

Determination of the height of the 2:1 elliptical head

R = inside radius + head thickness

= 228.6 + 3.431 = 232.03mm

$$H = \frac{\sqrt{R^2+X^2}}{2} = \frac{\sqrt{232.03^2+0^2}}{2} = 115.82\text{mm.}$$

Location of saddles on main shell

A = 0.2L = 0.2*304.8 = 60.96mm.

Estimated weight of the pre-heater and its components.

From the preliminary report generated by PV Elite, the estimated weight is 945.42 kg. Adding miscellaneous weight, the total estimated operating weight = $\frac{110}{100} \times 945.42$= 1043.26 kg.

Determination of optimum web plate thickness

For a contact angle of 1200, k_{11} = 0.204.

Selected web plate thickness = 6.35mm

F = K_{11} × Q = 0.204 $\times$ 628.68= 128.23 kg.

To resist this force, the effective area of web plate = $\frac{R}{3} \times$ selected web thickness.

Effective area, A = 483.87 mm^2

Hence, induce stress = $\frac{F}{A} = \frac{128.23}{483.87}$ =0.26 bar

The allowance stress = $\frac{2}{3} \times$ 20.496 = 13.664 bar.

Since the induced stress is less than the allowable stress then, the selected thickness of the web plate is satisfactory.

Thickness of inlet nozzle
From tables (Pressure Vessel Design Handbook), wall thickness = 3.912mm.
Hence, the channel and shell inlet nozzles, t_{inlet} = 3.912mm

Thickness of outlet nozzle
From tables (Pressure Vessel Design Handbook), wall thickness = 3.378mm.
Hence, the channel and shell inlet nozzles, t_{outlet} = 3.378mm.

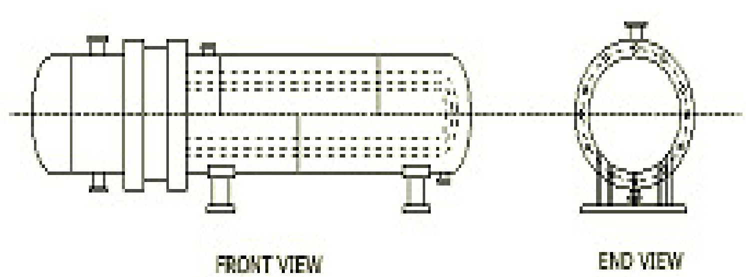

Fig.1: Drawing showing a U-tube heat exchanger.

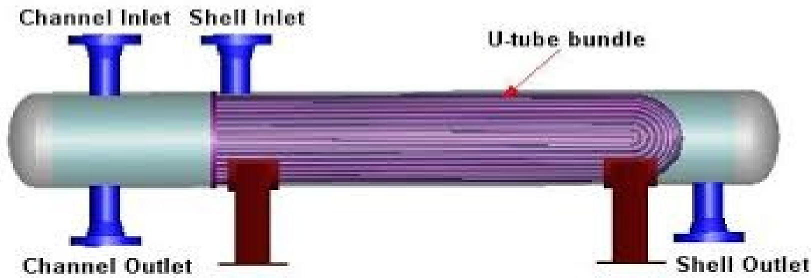

Fig. 2: Model of a U-tube heat exchanger. (COADE)

3. COMPONENT ANALYSIS USING PV ELITE SOFTWARE

PV Elite is a PC-based pressure vessel design and analysis software program developed by COADE Engineering Software. The software is a package of nineteen applications for the design of pressure vessels and heat exchangers, and fitness for service assessments in accordance to codes from ASME Section VIII (Div. 1 and Div. 2), PD 5500 and EN 13445.

Although an air pre-heater is designed in compliance with a design code, it does not follow that it is safe. The safety and reliability of the design, however, can be improved by using a design and analysis software to vet the analytical design. This is done by using PV Elite software. The analysis modules in PV Elite use all the design data entered into the software to analyze the air pre-heater. The software then produces an analysis report for each component of the air pre-heater. These reports highlight the errors and omissions in the analytical design and give recommendations as to how these can be corrected.

In the first report generated, PV Elite warned against the selected tubesheet (i.e. 25.4mm) being less than the expanded length of tube 35.69mm and it recommended a tubesheet thickness greater than the 35.69mm. A thickness of 38.1 mm was thus selected. Also, from the new report generated, it is clear that the bending and shear stresses 11.75 bar and 1.43 bar respectively are well below the allowable stress of 27.58 bar. Hence, it has been established that the tubesheet is not prone to failure due to bending or shear stresses induced in the tubesheet.

According to the PV Elite report, the maximum allowable working pressure (MAWP) as calculated in the report for the shells and heads (i.e. left head, channel, main shell, right head) respectively are: 38.19 bar, 37.67 bar, 18.36 bar and 18.48 bar. Since the MAWP is limited by the lower value (between the MAWP for the heads and for the shells), the MAWP for this air pre-heater is therefore 18.36 bar (limited by the main shell).

The report also shows that the required thickness of both inlet and outlet nozzles of the channel and main shell are less than the actual thickness. And for the fact that the nozzles are small in size as shown in paragraph UG-36(c)(3)(a) of the ASME code, hence, there is no need for reinforcement.

Similarly, the report shows that stresses induced in the air pre-heater due to the saddle supports are well below the allowable stress (13.51 bar) with the highest induced stress for the left saddle being (0.91 bar – longitudinal stress at top of the saddle). It is obvious from the geometry of the air pre-heater that the loads on the saddles are not the same, hence that accounts for the need to analyze both saddles. Although, loads on both saddles are not same (453.865 kg for left saddle and 184.807 kg for the right saddle)

4. CONCLUSION

An air pre-heater capable of heating air at temperature of 150^{o}C and pressure of 10 bar with the aid of flue gas at 1.5 bar and 297^{o}C has been designed. This design was analyzed and modeled using PV Elite software and thereafter revised to incorporate the corrections and additions (to the design) given by the design and analysis software. These are to be referenced when fabricating the air pre-heater to ensure that the fabrication is in compliance with the design calculations. From the analysis carried out using PV Elite software, we can conclude that the stresses induced in the air pre-heater are well within the allowable limits of the material of construction (carbon steel). Also, the selected nozzle sizes need no reinforcement and are suitable for this design.

Finally, the thickness previously selected for the tubesheet have been revised to a more suitable thickness as recommended by the PV Elite software to ensure that the pre-heater is fit for extended service life. Also, the selected thickness of the shell and elliptical heads are in compliance with the minimal thickness recommended by the software. We can therefore conclude that the design is suitable for the internal operating pressures. This study focus majorly on the mechanical design aspect of an air pre-heater, it is thereby recommended that other aspects such as hydraulic design, thermal design, and process design be given due considerations as well in the future.

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