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ANALYTICAL STUDY OF SUPERHEATERS FOR PROCESS INDUSTRIES

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Abstract

The superheater is an important boiler accessory which is widely used in power generation, sugar factories, and process industries for ensuring good quality of steam for power generation. This increases the efficiency and life of the turbine blades for thermal power plant. In the research work, pendant type convective superheater is designed for 20 Tonnes/hr for power generation in food processing industry with steam outlet pressure of 45 kg/cm^2 and temperature of 450 °C. The superheater was designed considering thermal and mechanical aspects. The process of thermal design involved calculation of overall heat transfer coefficient and surface area for heat transfer. Three-dimensional model of superheater using CATIA V5R20 was created and analysed. The process of mechanical design was used to calculate the working pressure and ensured safe design of superheater.

1. Introduction

A boiler is a device used for generating steam at high pressure by converting chemical energy into heat energy. The boiler is also used for process heating, power generation and air conditioning purposes. The demand is increasing exponentially due to rapid growth in different industries such as electrical, chemical, fertilizers, petrochemicals, etc. due to increase in population. The environmental pollution is created due to unburned chemicals in the boiler [1-3]. Figure 1 shows schematic diagram of boiler power plant with superheater. The important components of the boiler

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power plant are boiler, superheater, economiser, steam turbine, condenser, cooling tower, feed water pump, and air preheater [4]. The boilers are categorised as utility boilers, marine boilers, and industrial boilers. The utility boilers are high pressure steam generators used for generating power from coal though fluidized bed combustion with reheating and cogeneration power plant. The boilers with pressures more than 160 PSIG are categorised as high-pressure boilers. The boilers may be natural circulation or controlled circulation of water through the furnace tubes. The boilers are classified as stoker fired boilers, cyclone furnace fired boilers, fluidized bed combustion boilers, Fixed grate boilers and moving grate boilers depending on the firing method. The boilers are using different types of fuels such as solid fuels, gaseous fuels, liquid fuels, waste fuel or waste heat. The boilers are classified as either fire tube boiler or water tube boilers depending on whether the steam is generated inside or outside the boiler tubes [5].

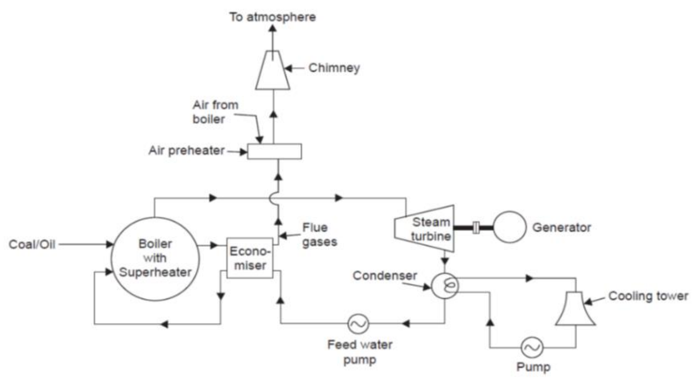

Figure 1. Schematic diagram of working of boiler

1.1 Superheater

The steam generated from boilers is normally wet steam which cannot be directly used in the steam turbine for power production due to corrosion of turbine blades. A superheater is a component which is used in steam boilers to convert wet, saturated steam into dry steam. The superheaters are beneficial part of the steam cycle, because dry steam contains more thermal energy and increases the overall efficiency of the cycle. Also, dry steam is less likely to condense within the cylinder of reciprocating engine or casing of steam turbine. It is studied that the superheating reduces the initial condensation losses in steam engines, enhanced the plant efficiency by reducing 6% to 7% fuel cost, eliminate steam turbine blade erosion problems. The boiler superheaters are categorized as radiant superheaters, convection superheaters, and separately fired superheaters. The degree of superheat can be varied from 700 °F to as low as 50 °F [6-7]. The steam is one of the main process fluids used in refinery, chemical, and petrochemical plants. Since the steam is utilized as process fluid, the conditions at the super-heater coil outlet are different depending upon the final users. The pressure can range from 120 bar for power production down to 2 bar for process applications. The steam temperature can range from 540 °C for power production up to 860 °C required in process plants. Figure 2 shows heating of water from liquid to vapour state at same pressure. Figure 3 shows basic principle of superheater with the boiler. The superheaters are categorized based on mechanical arrangement as horizontal superheaters, vertical superheaters, inverted superheaters pendent superheaters and platen superheaters. The superheaters are also classified as convective superheaters, radiative superheaters and combined superheaters depending upon the heat is supplied [8-9].

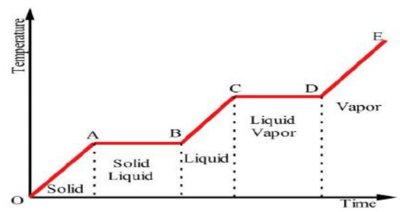

Figure 2. Schematic of heat graph

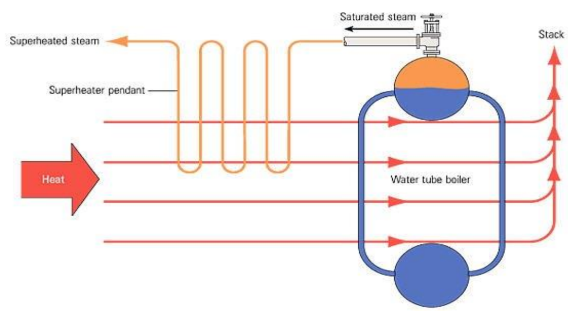

Figure 3. Principle of superheater

1.2 Convective and Radiative Superheaters

The convective superheaters are the primary most widely used superheaters. The convective superheaters operate at 1800–1900 °F in comparison with the 2200–2300 °F for radiant superheaters. The convective superheaters can use low grade material than the radiant superheaters. Figure 4 shows the schematic diagram of convective and radiative superheater. The radiant superheaters are in the furnace exit region which are widely used by boiler manufacturers. The radiant superheaters absorb more heat at lower loads.

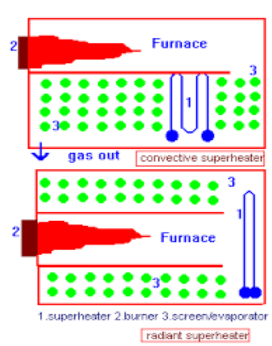

Figure 4. Convective superheaters

1.3 Mechanical Design of Superheater

The superheater material is selected considering high temperature and pressure of steam. The material selected is from ASME and Indian boiler regulations act 1950 (338) [10]. Most steels contain Mn remaining from the deoxidization and desulphurization processes. It increases hardness, strength, and depth of solidity. The phosphorus increases strength and hardness and improves machinability in free-cutting steels. Sulphur improves machinability with 0.05% in steels. Silicon increases strength, toughness, and hardness without lowering ductility [11-13].

1.4 Thermal Design of Superheater

The superheater is designed as per the specifications provided in the Table 1.

Table 1. shows specification of thermal design of superheater

SN	Properties	Values
1	Capacity of boiler	20000 kg/hr (20 tph)
2	Steam outlet pressure	45 kg/sq.cm
3	Steam outlet temperature	450 °C
4	Type of boiler	Fluidized bed combustion boiler
5	Fuel	Rice husk
Convective superheater data		
Tube size		38.1 O. D and 3.66 mm thick
Tube material		SA 210 GR A1
Longitudinal pitch		75 mm
Transverse pitch		120 mm
Space available in depth		1700 mm
Space available in height		3000 mm
Bending radius		75 mm
Front wall width		3240 mm
Front wall tube size		64.5 O/D and 4.06 mm thick
Front wall pitch		120 mm
Average height of loop		2750 mm
Gas data		
Weight of gas		33442 kg/hr (9.289 kg/s)

Gas i/l temp. of con. SH	796 °C
Gas density	1.3007 kg/N m^3
Sp. Heat of gas	0.279 kcal/kg , °C
Gas mass flow rate	5000 -6000 kg/m^2-hr
Steam data	
Weight of steam	20000 kg/hr. (5.55 kg/s)
Steam i/l press. of con.SH	49.3°C
Steam i/l temp. of con. SH	Saturated
Assume press. drop	2 kg/cm^2
Gas density	1.3007 kg/N m^3
Sp. heat of steam	0.279 kcal/kg °C
Steam mass flow rate	2500000 lb/ft^2-hr

Energy balance equation of convective superheater is given by-

$$m_s\,(h_2 - h_1) = m_g C_p \times (T_{fi} - T_{fo}) = UA\theta_m \quad (1)$$

Enthalpy values of steam are observed from steam table as follows.

h_1 = 2793.97 kJ/kg, h_2 = 3017.15 kJ/kg, T_{f0} is calculated as 681. 5 ^{0}C

$$\text{LMTD}, \theta_m = \frac{\theta_1 - \theta_2}{\ln\frac{\theta_1}{\theta_2}} = \frac{346-402}{\ln\frac{346}{402}} = 381.16 \quad (2)$$

$$\text{No of tubes to be inserted} = N_t = \frac{\text{Frontwall width}}{\text{Front wall pitch}} - 2 = \frac{3240}{120} - 2 = 25$$

$$m_s = N_t \times \frac{\pi}{4} \times D^2 \times \frac{V_s}{v_g} \quad (3)$$

$$Re = \frac{\rho \times V_s \times D}{\mu} = \frac{1.3007 \times 14.2956 \times 30.78 \times 10^{-3}}{0.000018003} = 31790 \quad (4)$$

$$\text{Prandtl No Pr.} = \frac{\mu \times C_p}{k} = 0.3894 \quad (5)$$

$$Nu = \frac{hi\,D}{k} = 0.023 \times Re^{0.8} \times Pr^{0.4} \quad (6)$$

$$Nu = \frac{ho\,Do}{k} = 0.33 \times Re^{0.6} \times Pr^{0.33} \quad (6a)$$

$$\frac{1}{U} = \frac{1}{h_i} + \frac{1}{h_o} \tag{7}$$

For hi=111.74 W/m^{2}K and h_o= h_c = 36.1492 W/m^{2}K, U=27.21 W/m^{2}K

$$m_s \times (h_2 - h_1) = U \times A \times \theta_m \tag{8}$$

$$119 = \pi DoLN_t \tag{9}$$

Total length of tubes is L = 41.4236 m. Results obtained from thermal design are summarized in Table 2

Table 2. Result table for thermal design

S N	Parameters	Symbol	Value	Unit
1	Outlet flue gas temperature	T_{fo}	681.5	°C
2	LMTD	θm	381.195	°C
3	No of tubes to be inserted	N_t	25	-
4	No of loops	-	23	-
5	Average steam velocity	V_s	12.2956	m/sec
6	Flue gas velocity	V_g	4.2075	m/sec
7	Inner heat transfer coefficient	h_i	111.7462	W/m^{2}K
8	Outer heat transfer coefficient	h_o	36.1492	W/m^{2}K
9	Overall heat transfer coefficient	U	27.2172	W/m^{2}K
10	Heating Surface Area	A	118.9930	m^2
11	Overall Length	L	41.4236	m

1.5 Mechanical Design of Superheater

Following are the specifications for mechanical design of superheater. Table 5 shows allowable stress for plates, pipes, and tubes

1. Type of superheater : Pendant type convective superheater
2. Design : IBR-1950 and ASME Code
3. Design temperature : 450 °C
4. Design pressure: 49.3 kg/cm^2
5. Actual pressure: 1.1 x Design Pressure = 1.10 x 49.3 = 54.23 kg/cm^2
6. Hydro test pressure: 1.5 x Design Pressure = 1.5 x 49.3= 73.95 kg/cm^2
7. Outside diameter : 38.1 mm
8. Thickness (t) : 3.66 mm

Table 3. Stresses for plates, pipes, and tubes

Part	Design metal temp in ^0C	Material	Tensile strength kg/mm^2	Allowable Stress kg/mm^2
Tubes	450	SA210-GrA1	42.2	10.13
Pipes	450	ASTMA106GrBOREQ	42.2	12.03

1.6 Working pressure

For SA210GrA1 working pressure (P) in kg/cm^2 is calculated using below equation [14-15].

$$P = \frac{2f(t-C)}{(D-t+C)} = \frac{2 \times 1012\ (3.66-0.75)}{(38.1\ -3.66+0.75)} = 167.37 \tag{10}$$

Where- f is allowable stress kgf/cm^2, t is minimum thickness of tubes, C= 0.75 mm for working pressure up to 70 kg/cm^2 and D is outer diameter of tube. As the actual pressure is 54.23 kg/cm^2 is less than 167.37 kg/cm^2, design is safe.

1.7 Allowable stress for top main-sub header pipe for material ASTMA106GrB

Allowable Stress =12.03 kg/cm^2 from ASME data book. For top main header pipe 200NB SCH80 pipe with material ASTM A 106 Gr B. The working pressure (P) in kg/cm^2 for the pipe is determined by the following formula.

$$P = \frac{2 \times f \times e \times (t-C)}{(D-t+C)} = \frac{2\ \times 1203\ \times 0.67(8.6-0.75)}{(114.3-8.6+0.75)} = 118.28 \tag{11}$$

Thus, the design is safe as the working pressure 118.28 kg/cm^2 is more than actual pressure 54.23 kg/cm^2. While designing the superheater, environmental impact and degradation are considered [16-20]. Figure 5 shows 3D modeling of superheater in CATIA V5 R20.

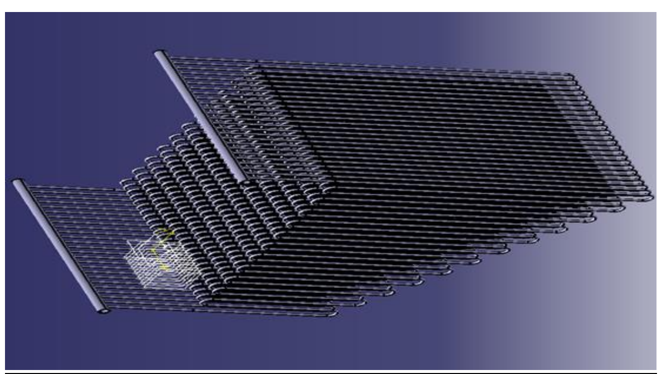

Figure 5. 3D view of superheater

Conclusions

It is found that the range of value for overall heat transfer coefficient is from 25 to 40 W/m^2K. The value obtained from thermal design is 27.22 W/m^2K. The area requirement as per the plan is 180 m^2 whereas the area obtained by thermal design is 118.99 m^2. The actual pressure is 54.23 kg/cm^2 which is less than working pressure of 167 kg/cm^2 for the material selected, the design is safe. The convective superheater is designed as per the requirement of process industry and the area available. For the material selected for tubes and pipe, actual pressure is less than working pressure, thus the design is safe.

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