International Journal of Information, Engineering & Technology

Volume 11, Issue 5, PP 56-61, ISSN: 2360-9194, August, 2021
Double Blind Peer Reviewed International Research Journal
garcjournalssubmit@gmail.com
Journal Series: Global Academic Research Consortium (garc)

Design Analysis of a Fluidized Bed Combustion Boiler

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Abstract: *The basic criteria required to design a boiler is presented in this paper. The boiler is used to generated steam which will further be used for heating, energy generation or sterilization of medical equipments in hospitals. The design criteria considered include; internal design pressure, stresses in tubes and drums, design of the steam drum and tubes, minimum wall thickness of tubes and drum, change in boiler dimension due to internal design pressure and boiler efficiency.*

Key words: Energy, Boiler, Steam, Pressure, Temperature

INTRODUCTION

A system in which steam is generated is called a boiler or steam generator. Boilers are pressure vessels designed to heat water or produce steam, by combustion of fuel which can then be used to provide space heating and/or service water heating to a building (Odigure *et al*.,2004).

Heating water at any given pressure will eventually cause it to boil and steam will be released. When water is boiling, both water and steam have the same temperature and for each boiling pressure there is only one saturation temperature (Folayan, 2014) as long as water and steam are in contact, temperature will remain at saturation point for that pressure.

Steam is preferred over hot water in some applications, including absorption cooling, kitchens, laundries, sterilizers, and steam driven equipment. Steam is therefore important in engineering and energy studies. According to American Society of Mechanical Engineers (ASME), a steam generating unit is defined as a combination of apparatus for producing, furnishing or recovering heat together with the apparatus for transferring the heat so made available to the fluid being heated and vaporized (Rajput, 2010).

Steam is the technical term for the gaseous phase of water, which is formed when water boils.

Steam is a critical resource in today's industrial world; it is used in the production of goods and foods, the heating and cooling of large buildings, the running of equipment, and the production of electricity (Ohijeagbon *et al*., 2013).

Boilers are classified into different types based on their working pressure and temperature, fuel type, draft method, size and capacity, and whether they condense the water vapour in the combustion gases. Boilers are also sometimes described by their key components, such as heat exchanger materials or tube design. Two primary classifications of boilers are Fire tube and Water tube boilers. In a Fire tube boiler, hot gases of combustion flow through a series of tubes surrounded by water. Alternatively, in a water tube boiler, water flows in the inside of the tubes and the hot gases from combustion flow around the outside of the tubes.

In science and engineering laboratories, there is sometimes the need to utilize steam or hot water to generate power, to carry out tests or for other heating applications. This steam or hot water can be obtained using boilers This paper provides the basic design principles for the constructing a drum boiler for steam generation to be used for the purpose of heat recovery or energy production.

MATERIALS AND METHODS

A boiler should fulfill the following requirement:

- Safety: The boiler should be safe under operating conditions.
- Accessibility: The various parts of the boiler should be accessible for repair and maintenance.
- Capacity: The boiler should be capable of supplying steam according to the requirements.
- Efficiency: To permit efficient operation, the boiler should be able to absorb a maximum amount of heat produced due to burning of fuel in the furnace.
- It should be simple in construction and its maintenance cost should be low.
- Its initial cost should be low.

Boiler Terms

In designing a boiler for any applications, the terms used are as follows (Rajput, 2010).

- Shell: The shell of a boiler consist of one or more steel plates bent into a cylindrical form and riveted or welded together. The shell end is closed with end plate.
- Grate: It is the platform in the furnace upon which fuel is burnt and it is made upon cast iron bars. The bars are arranged that air may pass onto the fuel for combustion. The area of the grate on which the fire rests in a coal or wood boiler is called grate surface.
- Furnace: It is a chamber formed by the space above the grate and below the boiler shell, in which combustion takes place.
- Water space and steam space: The volume of the shell that is occupied by the water is termed water space while the entire shell volume less the water and tubes space is called steam space.
- Mountings: The items such as stop valve, safety valve, water level indicator, pressure gauge, fusible plug, blow-off cock etc., are termed as mountings and a boiler cannot work safely without them.
- Accessories: The items such as superheaters, economisers, feed pumps etc., are termed as the accessories and they form an integral part of the boiler. They increase the efficiency of the boiler.
- Water level: The level at which water stands in the boiler is called water level. The space above the water level called steam space.

- Foaming: Formation of steam bubbles on the surface of the boiler water due to high surface tension of water.
- Scale: A deposit of medium to extreme hardness occurring on water heating surface on boiler because of an undesirable condition in the boiler water.
- Blowing off: The removal of mud and other impurities of water from the lowest part of the boiler (where they usually settle) is termed as blowing off. This is accomplished with the help of a blow cock or valve.
- Lagging: Blocks of asbestos or magnesia insulation wrapped on the outside of the boiler shell or steam piping.

Design analysis

The boiler is a vessel that operates under pressure; hence, the design theories are the basic principles considered to evaluate the various parameters, dimensions and the performance of the boiler under internal pressure.

Operating temperature and pressure

The operating temperature and pressure of a boiler must be determined in order to make other important calculations required for effective functioning of the boiler.

Internal design pressure of a boiler

The design pressure higher than operating pressure with 10% or more will satisfy the requirement. The maximum allowable working pressure is the maximum permissible pressure at the top of the boiler in its normal operating position at specific temperature. This pressure is based on the nominal thickness.

The internal design pressure is given by (Ohijeagbon *et al*., 2013)

$$P_d = \frac{\sigma_u \times t}{R_i \times f_s}$$

where, P_d= Internal design pressure on inside of drum or shell (N/m^2)

σ_u = Ultimate strength of plate (N/m^2)

t = Thickness of plate (m)

R_i = Internal radius of drum (m)

f_s= Factor of safety (ultimate strength divided by allowable working stress)

The boiler code provides that the factor of safety shall be at least 5 and the steel of the plates and welded or rivet joint shall have as a minimum of the following ultimate stresses (Khurmi & Gupta, 2005):

Tensile stress, σ_{ut} = 385 MN/m2

Compressive stress, σ_{uc} = 665 MN/m2

Shear stress, τ = 308 MN/m

Stresses in tubes and drums

Stresses are induced in different parts of an operating boiler by the temperatures and pressures of hot flue gases, feed water and steam respectively. The magnitudes of these stresses must be known so that the boiler will be operated under safe conditions.

Thus the wall of the boiler subjected to internal pressure has to withstand tensile stress of the following types (Khurmi & Gupta, 2005)

- Circumferential or hoop stress
- Longitudinal stress

$$\sigma_{t1} = \frac{P_d \times D_i}{2t}$$

where, P_d = Internal design pressure of the drum or shell (N/m^2)
σ_{t1} = Circumferential or hoops stress (N/m^2)
t = Thickness of plate (m)
D_i = Internal diameter of drum (m)

$$\sigma_{t1} = \frac{P_d \times D_i}{4t}$$

where, σ_{t2} = Longitudinal stress (N/m^2)

Design of the steam drum

The design of this component must be strong enough to contain steam or hot water that is generated and to mechanically hold the boiler tubes as they expand and contract with changes in temperature. Hence, its volume is of importance and is written as:

$$V_{dru} = A_{dru} \times L_{dru}$$

where, A_{dru} = Cross sectional area of the drum (m^2)
L_{dru} = Length of the drum (m)

Design of the steam tube

Materials which can withstand high temperature and resistance to corrosion such as galvanized steel materials was selected to form tubes.

$$V_{st} = A_{st} \times L_{st}$$

where, A_{st} = Cross sectional area of the tube (m2)
L_{st} = Length of the drum (m)

Minimum wall thickness of tubes and drum

The minimum required wall thickness of a boiler is a value beyond which the boiler wall cannot be easily damage by the operation pressure in a boiler.
The formular is given as (Ohijeagbon, 2013)

$$t_w = \frac{P_d \times R_i}{\sigma \times \eta_E - 0.6P_d}$$

where, σ = Allowable working stress of the material (N/m2)
tw = Minimum wall thickness (m)
ηE = Ligament efficiency of the welded joint
Therefore, the minimum wall thickness of the tubes is given as:

$$t_{w\ tubes} = \frac{P_d \times R_i}{2 \times \sigma \times \eta_E + 0.8P_d} + C$$

C = Corrosion allowance
The value of corrosion "C" according to Weiback is given by (Khurmi & Gupta, 2005):

Material	Cast iron	Steel	Zinc and Copper
Corrosion (mm)	9	3	4

Change in boiler dimension due to internal design pressure

The buildup of pressure within the boiler causes slight expansion of the boiler shell thus resulting in change in dimension of the boiler.

The increase in diameter of the shell due to internal pressure is given as (Khurmi & Gupta, 2005)

$$\delta d = \frac{P_d D_i^2}{2Et_w}\left(1 - \frac{\gamma}{2}\right)$$

The increase in length of the shell due to internal pressure is given as (Khurmi & Gupta, 2005):

$$\delta L = \frac{P_d D_i}{2Et_w}\left(\frac{1}{2} - \gamma\right)$$

It may be noted that the increase in diameter and length of the shell will also increase the volume.

The increase in volume of the shell due to internal pressure is given as (Khurmi & Gupta, 2005): $\delta V = Final\ volume - Initial\ volume$

$$\delta V = \frac{\pi}{4}(D_i^2 \delta L + 2D_i L \delta D_i)$$

where, L = Length of the cylindrical shell

E = Young's modulus of the material of the cylindrical shell

γ = Possion ratio

Boiler efficiency

At the heart of any boiler design is overall boiler efficiency. Boiler efficiency varies with different types of fuels, it is important to determine the efficiency so as to know what is expected from the boiler.

$$\eta = \frac{m_s(h_s - h_{fw})}{LCW} \times 100\%$$

where, η= Efficiency of the boiler

hs = Enthalpy of saturated steam at operating pressure (kJ/kg)

hfw= Enthalpy of feed water (kJ/kg)

ms= Mass of steam formed per hour (kg/hr)

CONCLUSION

Boilers are the main technology employed for steam generation which can be used for heating or energy production or for practical demonstration. To have an effective boiler design, the above criteria should be strictly adhered to. The steam generated can solve the problem of energy demand of a small communities so as to reduce dependence on national grid when the energy demand has been calculated.

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