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Thermodynamic Design of a Fire-Tube Steam Boiler

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Prepared in response to FABENG-2120 Thermodynamics professor Dr. Shavezipur and the assigned course project. This report seeks to demonstrate and defend calculations to: dimensions of boiler, pipes, and furnace; specifications of burners, volume ratio of fluids, pump power, and volumetric capacity.

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This document is has been written for the purposes of introducing fire-tube steam boilers, demonstrating the application of thermodynamic knowledge, practicing engineering design projects, simulate engineering teamwork and collaboration, and exercise writing technical scientific documents. This document will introduce, derive and defend calculations for:

I. Dimensions of steam boiler body and furnace.
II. Diameter and length of steam boiler pipes.
III. Volume ratio of saturated liquid: saturated vapor.
IV. Specifications of burners.
V. Pump Power.
VI. Volumetric capacity of safety valve.

Introduction

Fire-tube steam boilers are designed for the purpose of industrial scale heat exchange in order to heat saturated liquid entering the control volume to a saturated gas. Exiting gas leaving the control volume may experience a pressure drop when returning to atmospheric pressure. Fire-tube steam boilers are composed of a cylindrical hull filled with thermal insulation in which a series of tubes are contained. Hot air from a burner is passed from a furnace in the 1st pass to a series of tubes in the 2nd pass, then to a series of tubes in the 3rd pass. Finally, the hot air exits through a chimney. The boiler is filled with water up to the top level of the 3rd pass pumped from the base of the boiler. Steam is then pumped from the top of the boiler to wherever heating is needed. The boiler contains a safety valve that, when the pressure becomes too high due to blockage or overheating, releases the excess steam.

Project Description

Our engineering team designed a three-pass fire tube steam boiler with a capacity of 5000 kg of steam per hour and a operating pressure of 10 bar. The Figure below equations shows a standard three pass fire tube steam boiler system used as a template for our engineering team's design.

Conduction through piping to the water is described in the equation

$$Q = A[(Tair - Tw)/(1/hair + ttube/Ktube + 1/hw)]$$

where:

Q = Heat transfer rate in KW

T_{air} = Temperature of the air in K

T_w = Temperature of the water in K

h_{air} = Thermal conductivity of air in KW/m^2*K

t_{tube} = Thickness of tubes in m
K_{tube} = Thermal conductivity of carbon steel in KW/m^2*K
h_w = Thermal conductivity of water in KW/m^2*K

Total heat transfer produced by furnace is modeled by the equation

$$Q = \dot{m}(h3 - h2)$$

where:
Q = Heat transfer rate in KW
$\dot{m}$ = Mass flow rate in kg/s
h_2 = Water entering boiler at 10 bar and 20°C
h_3 = Enthalpy of Steam exiting boiler at 180°C

Power of the pump is modeled by the equation

$$Q = \dot{m}\, v(P2 - P1)$$

where:
Q = Power required by pump in KW
$\dot{m}$ = Mass flow rate in kg/s
v = Specific volume of water entering pump (assumed incompressible) in m^3/kg
P_2 = Pressure exiting pump in Kpa
P_1 = Pressure entering pump in KPa

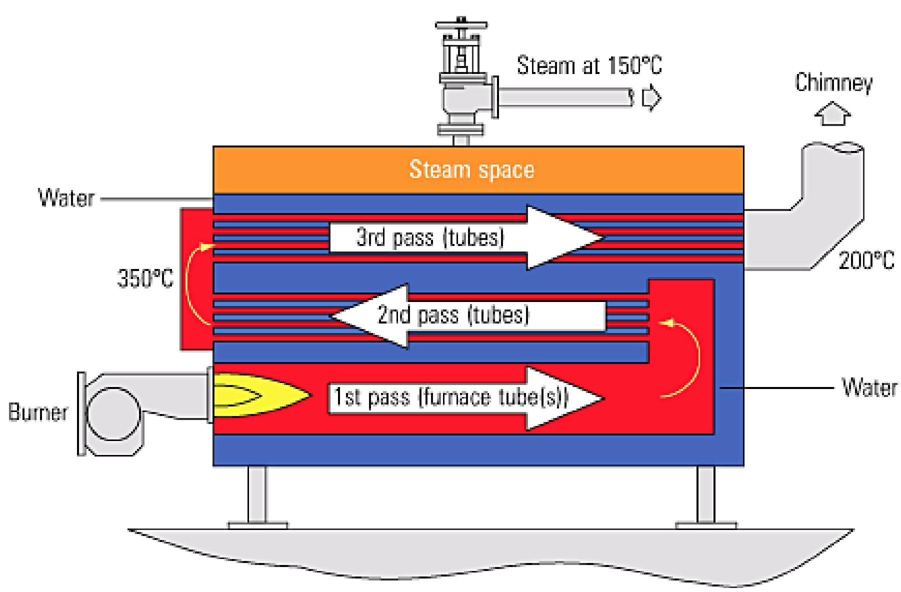

Figure 1: Three-pass fire tube steam boiler system

Engineering Assumptions and Givens

Assignment givens in the prompt of this steam boiler design are:

- Mass Flow Rate : $\dot{m}$ = 5,000 $kg/hour$
- Operating Steam Boiler Pressure : P = 10 bar

Assumptions for the design of this steam boiler are:

- Operating Temperature of Steam boiler: T = 179.9 Celcius *
- Fluid Specific Volume : v_f = 1.1273X10^{-3} m^3/kg *
- Fluid Specific Volume : v_g = 0.1944 m^3/kg *

**All of these assumptions are the consequence of and two-phase mixture heating occurring at 10 bar. Specific volume volumes for saturation fluids and saturation liquids are constant for a fixed pressure. Likewise, a fixed pressure in the two-mixture region imply fixed temperature (T_{sat}).*

- Diameter of Tubes = 0.05 m
- Thickness of Tubes = 0.003 m
- Main Shell Thickness = 0.012 m
- Furnace Plate Thickness = 0.016 m
- Length of Tubes and Boiler = 5.00 m

These assumptions were made as directed in the design project prompt.

- Temperature of Furnace = Temperature 1st Pass = 1200^{o}C
- Temperature 2nd Pass = 740^{o}C
- Temperature 3rd Pass = 280 ^{o}C

Temperature of furnace was given in design project prompt. Second and third passes were based on conductivity constants.

DESIGN OUTCOME

- Maxon-Megafire 15M Natural gas Burner outputs 15,000,000 Btu/hr, or 3949 KW Max. output requiring 0.4 m diameter spacing in furnace.
- The pump requires 1.26 KW of power. The LKH UltraPure-10 Centrifugal Pump was chosen with a motor capacity of 1.5 KW.
- Volume Capacitance of Relief Valve required to accommodate 16200 L/min or 11023.1 lb/h of steam. Apollo Series 119 Section VIII J orifice was chosen with a capacity of 11034 lb/h.
- Number of Pipes for Pass 2 : 68. Number of Pipes for Pass 3 : 70.
- Total diameter: 1.2 m

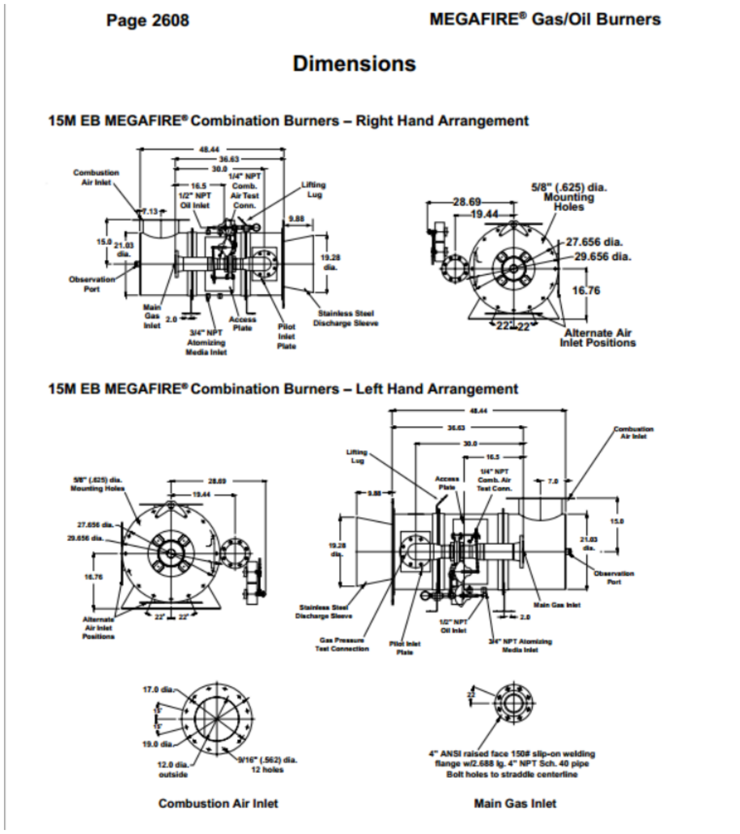

Figure 2: Diagram of Furnace Used

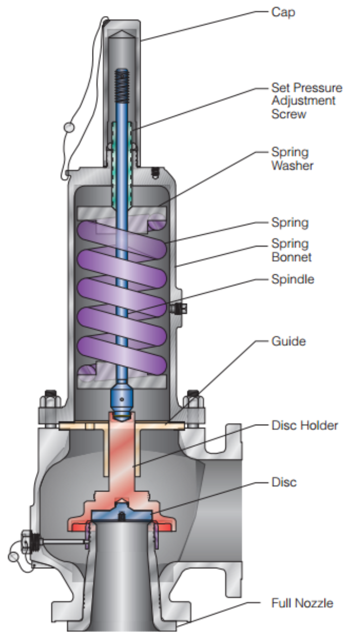

Figure 3: Diagram of Safety Valve

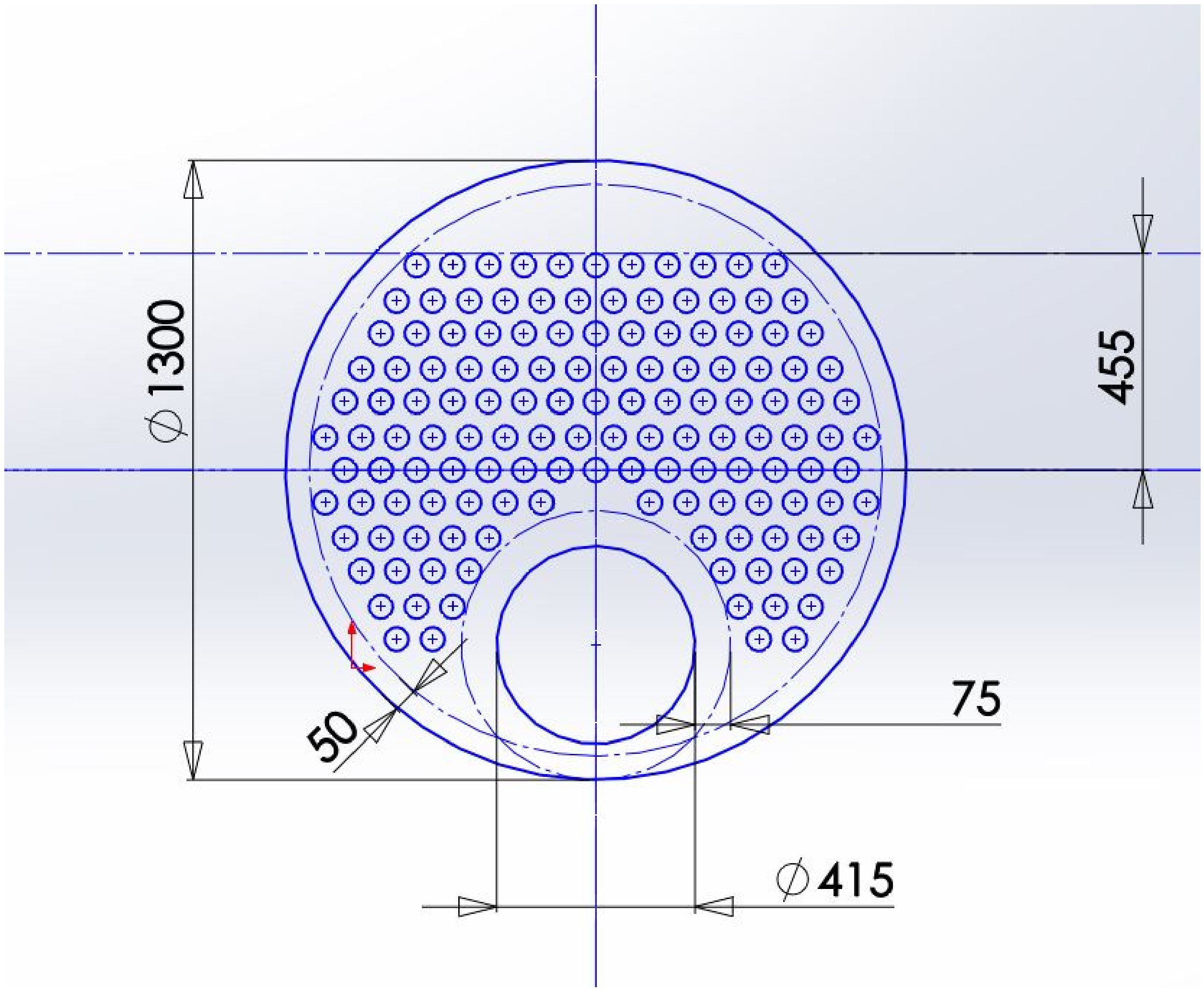

Figure 4: Cross-sectional Diagram

TABLE OF DATA AND CALCULATIONS

Tube diameter (m)	0.05		vg (m3/kg)	0.1944
tube thickness (m)	0.003		m (m3/s)	0.27
main shell thickness (m)	0.012		m (L/min)	16200
furnace plate thickness (m)	0.016			
Flow rate (kg/s)	1.389			
h air (W/m2*K)	69		Rtotal (KW/m2*K)	16.00085251

h water (W/m2*K)	690			
K tube (W/m2*K)	51		Flow rate (kg/h)	5000
h state 1 (kJ/kg)	80		Flow rate (lb/h)	11023.1
h state 2 (kJ/kg)	83.96			
h state 3 (kJ/kg)	2778.1			
Tw (C)	180	Tair2 (C)	970	
T3 (C)	280	Tair3 (C)	510	
T2 (C)	740			
Tf (C)	1200			
Total Q (kW)	3742			
Pass 1				
Q/A	negligible			
Pass 2				
Q/A (kW)	49.372			
Q (kW)	2619.303			
A (m^2)	53.052			
# of Pipes	67.548	Actual # Pipes	68	
Pass 3				
Q/A (kW)	20.624			
Q (kW)	1122.558			
A (m^2)	54.430			

# of Pipes	69.302	Actual # Pipes	70	
Length of Boiler (m)	5			
Surface Area of 1 Pipe (m2)	0.7853981634			
Pump Power (KW)	1.26			
Pump Power (HP)	1.689687833			.

Diameter (m)	1.2
Area (m^2)	1.130973355
distance from center to top of tubes (m)	0.455
area above tubes (m^2)	0.1554989868
CS area of tubes (m^2)	0.2709623664
diameter of pass 1 tube (m)	0.415
area of pass 1 tube (m^2)	0.1352651987
area water (m^2)	0.7045120021
area steam (m^2)	0.1554989868
quality (percent)	0.180810465

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