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Thermal Design of a Fluidized Bed Steam Boiler Using Refuse Derived Fuel (RDF) in Organic Rankine Cycle

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Abstract

In this study, a water tube type steam boiler has been designed to burn refuse derived fuel (RDF) and coal together. The combustion process was carried out in a water pipe type steam boiler, and the heat energy of the fuel was used to evaporate and superheat the water in the boiler. The superheated water steam has entered the Organic Rankine Cycle (ORC) system, and the system produces superheated N-pentane steam for its turbine to produce 2.0 MWe. The designed water pipe steam boiler has been operated as a fluidized bed combustion system. The properties of water pipe steam boiler system have been explained in detail in this article. Detailed investigations have been done using RDF and coal co-combustion in a water pipe circulating type fluidized bed combustion system. Furthermore, a cost analysis of the designed water pipe steam boiler components has also been performed.

1. INTRODUCTION

The maximum utilization of waste is achieved in integrated waste management systems, at the same time this method is also very often preferred. For this purpose, the material is first used for recycling, and the remaining RDF materials can be used in energy production under suitable conditions. The energy production from the RDF materials, which is left behind from the decomposition process, is the most appropriate method adopted by the whole world. Energy can be produced by burning RDF materials alone or together with coal. Although the use of RDF materials as fuel in steam boilers for energy production is very popular, in fact the burning of RDF in CFB is a very heterogeneous reaction. Therefore, in the event that the RDF is burned alone or burned together with a fuel, the design of the combustion chamber and burner systems must be done very carefully in order to increase the efficiency of the combustion and reduce pollutant emissions. The selection of the technology of combustion systems is as important as its design. Fluidized bed boilers come at the top of all worldwide combustion systems for incineration of heterogeneous and pollutant materials, such as sewage sludge and RDF. In many combustion applications, it is possible to see RDF materials as fuel in the production of energy with a Rankine or Organic Rankine Cycle. In recent years, a large number of companies have used this type of wastes to produce energy, reduce greenhouse gases and take measures against global warming.

Refuse-derived fuel (RDF) systems are incinerator furnaces where the waste is processed prior to combustion with the objective of significantly reducing its level of heterogeneity. The strategic concept of processing heterogeneous solid waste prior to combustion has several potential virtues:

- In the course of processing, portions of the waste can be recovered and recycled. Thus, materials recovery can be an inherent partner in on-going or new resource recovery programs.
- The processing line can be designed to produce a more homogeneous fuel. This should stabilize the combustion process, facilitate more precise combustion control, improve burnout, produce a more stable steaming rate, etc. Since stones, glass, and wet material can be removed by separation

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processes, the mean moisture content of the waste can be reduced and the combustible content enriched, thus increasing the heat recovery potential. Further, one would expect that with better combustion control, excess air levels can be lower, thus reducing the capital cost and many operating expenses for incinerator furnaces, boilers, fans, and air pollution control devices. Improved combustion should reduce air pollution emissions related to unburned or incompletely burned combustibles. In addition, because of the materials recovery steps, emissions related to specific waste components (e.g., PVC) can be reduced.
- Because the processed materials are more regular in physical characteristics (e.g., particle size), materials handling should be easier to automate and should work better.

M. Morris and L. Waldheim aimed gasification of biomass in their study called Energy recovery from solid waste fuels using advanced gasification technology compared to solid waste, and they have reached 50% more efficiency ultimately. Their study has been carried out in a 90 MWth cogeneration plant in Sweden [1]. Shuhn-Shyurng Hou et al. investigated the burning properties of RDF-5 from oil sludge in their study. Thus RFD has been produced from oil sludge. The results showed that the ignition properties have a strong relationship with the oil sludge. When the oil sludge mass ratio increased, it has become more difficult to burn the RDF, and has been found to have a lower rate of burning mass loss [2]. Francisco D. et al. have investigated the combustion properties and the pollutant emissions of RDF in a fluidized bed burner in a study called combustion of refuse-derived fuel in a fluidized bed. A series of combustion tests using three different RDF samples were performed in two fluidized bed burners. They have investigated the properties of temperature profiles, gas composition, and fly ash residues for different RDF fuels and working conditions [3].

Diego Barba et al. have carried out RDF gas-gasification by using GGM (Gibbs Gradient Method) in RDF gasifiers. The synthesis compositions, gasifier temperature and reactions have been determined by GMM. As a result of this study, they have made GMM a tool for the design of industrial gasifiers [4]. Yoshinori Itayaa et al. have studied various types of RDFs in which different chemical compounds in the fluidized bed burner. CO, NOx, HCI and chimney gases emission content have showed combustion behaviour of RDF in a fluidized bed. They have also measured the experimental data of dioxin concentrations using a continuous measurement system [5]. In another study, the author used the most powerful plant in Greve to gasify the RDF in their study titled Chianti Project. As a result, they have demonstrated the economic and technical viability of electricity generation through gasification of RDF [6].

Feng Duan et al. studied combustion behaviour and pollutant emission characteristics of RDF in a vortexing fluidized bed combustor, and investigated their environmental effects. In addition to this, they have demonstrated different combustion properties of RDF [7]. Eduardo Ferrer et al. have optimized the quality of coal burning the RDF together with coal, and studied protection of ash deformation in the combustor in their study. This study has been carried out using a 100 kW and 4 MW CFB [8]. Anita Pettersson et al. have characterized ash and deposit formation in a 20 MWth circulating fluidized bed (CFB) boiler, and residues from different combustion tests in XRD and SEM-EDX. They have investigated whether the lowered bed temperature can alter the alkali and chlorine distribution in the boiler [9].

In their study, Zhi-Min Fua et al. investigated the spontaneous combustion property of a water-free RDF with Thermo gravimetric and Differential Thermal Analysis and Spontaneous Ignition Test device. The experimental results have showed that the heat generation of the RDF having different water contents immediately after addition of water to the RDF [10].

In the present study a water-tube boiler was designed as a combustor to burn RDF and coal together. Firstly, it is necessary to know the analysis of RDF and coal mixture, which will be used for energy production in the steam boiler.

The water-tube steam boiler designed is connected to an ORC system, which provides power from the turbine in this ORC. A heat exchanger is needed to connect the steam boiler to an ORC system. Because water is used as a working fluid in the steam boiler, organic fluids are used instead of water in the ORC system. As said before there is a need for a heat exchanger to connect the two systems. In this study this organic fluid was identified as pentene. In addition, the combustion system of the boiler was designed as a fluidized bed combustion system. Fluidized bed combustion systems are more efficient in terms of emissions than other systems. Fluidized bed burning systems have two types, one of them is bubbling type and the other is the circulation type. In this study, a circulating fluidized bed was chosen. Cross-sectional heat load in the bubbling fluidized bed is less than in the circulating. In addition to this, water pipe boilers are in the big capacity boiler group. The water used as a working fluid is evaporated and energy production is achieved by using the generated steam energy. Water vapours are the ideal working fluid for energy production.

To improve the combustion properties, RDF fuel must be homogenized, dried, and separated from the materials. The relatively simple process may involve separation of large pieces, magnetic extraction of ferrous metals. The processed product is known as densified refuse derived fuel (d-RDF). Selecting equipment to store and retrieve RDF is an essential operation. Transport problems from rags, floes, wires, hard plastics and metals are especially important. Also, RDF is not uniform. Moisture content, particle size changes and unexpected materials appear from time to time. RDF has a high volume, that means that RDF is bulging and relatively uncompressible, while the RDF preparation system is expected to remove most of the non-homogenous materials and minimize [11]. Figure 1 depicts RDF samples.

Figure 1. *RDF samples*

The combustion concepts used in burning RDF are divided into two categories: RDF as primary fuel or as a second fuel together with coal, wood waste or other materials. It is necessary to obtain a homogeneous RDF particle size distribution for highly efficient combustion [12].

1.1. Combustion

The working principle of the main generator of the energy conversion device (converting energy from natural sources to power or electricity) is called fuel combustion. The most common fuels are fossil fuel, coal, gasoline, diesel or natural gas at steam power plants. Moreover, main flammable elements are carbon in fuels and hydrogen. On the other hand Hydrogen as a fuel is more efficient between the two. The fuel selection basically depends on the calorific value and proximate and ultimate analysis. Combustion is defined as a rapid exothermic reaction that can be propagated through a suitable medium, releasing flames as a significant energy heating and burning reaction. As the fuels are burned in pure air, the nitrogen in the air can participate in the combustion process to produce oxides of nitrogen [13].

1.2. Steam boilers

Steam boilers are pressure vessels where the energy is produced by burning fuels in one side of the surface as water and on the other side. One schematic drawing of a CFB boiler furnace is given in Figure 2.

Reasons of Using Steam

- More heat transfer with small diameter pipes
- Environmentally friendly
- Energy saving through recycling
- Reduce the risk of corrosion to the steam system
- Heat losses are low, i.e. an ideal heat carrier
- Thermodynamic properties are good

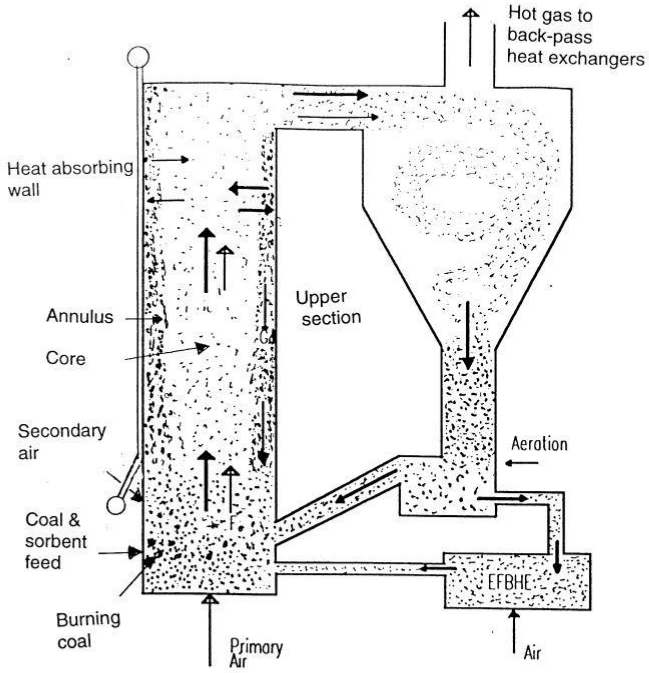

Figure 2. *Schematic drawing of a CFB boiler furnace with lower dense zone, the core and annular regions in the upper fast fluidized bed zone [14].*

2. COMBUSTION SYSTEMS FOR WASTES

Three types of combustion systems are used. These are grate combustion system, fluidized bed combustion system and pulverized combustion system. These three combustion systems have many different properties. These properties are explained and compared below.

2.1. Comparison of the RDF burning systems

Firstly, we can compare grate combustion system, fluidized bed combustion system and pulverized combustion system for combustion characteristics. Fuel burns on the surfaces of the grate combustion system, in the fluidized media for fluidized bed combustion system, and suspended in the combustion chamber for pulverized combustion system. Then, compared in size of grains of fuel; grain size is largest compared to the others for the grate combustion system. Moreover, medium size fuels can be used in fluidized bed boilers. Also that grain sizes are minimum for pulverized combustion system, because these fuel grains are pulverized. After that, we can compare in terms of combustion heat capacity; the heat capacity is lowest compared to the others for grate combustion systems. This capacity is medium or high for fluidized bed combustion systems. This capacity is highest for example in pulverized combustion systems. Then, compared for fuel type; coke, stone coal, biomass, RDF are using grate combustion systems. All coal types and wastes can be used as a fuel for fluidized bed combustors. But the pulverized combustion system uses only pulverized coal. Finally, as compared for emission control requirement, only fluidized bed combustion systems do not require any flue gas purification.

As far as these properties are concerned, only fluidized-bed steam boilers are suitable for the combustion of RDF fuel. When all three combustion systems are compared, the most advantageous system for RDF burning is the fluidized bed combustion system.

2.2. Fluidized Bed Combustor

Fluidized bed combustion is one of the most effective and reliable technologies for fuel utilization. In spite of its rather long history of utilization in various industrial applications, only in the 1970s this technology was firstly applied in large-scale utilities. The principle of combustion is based on burning fuel in layer of air-suspended mass of particles located at the bottom part of the furnace. It consists of silica sand or other inert materials. The fuel is introduced into this layer and combustion air is supplied from the furnace bottom through the sand layer. In dependence on the velocity of the applied stream of air, the layer acts in different types of fluid-like behaviour.

Fluidization is to gain fluid's behaviours properties to solid particles, or another description is the operation, which is converting the solid particles to fluid like behaviour of particles in a gas or liquid medium [15, 16].

Fluidized bed boilers use a firing technique where the fuel is burnt in a bed or suspension of hot, non-combustible granular solids. This type of firing process has been proved successful in addressing some of the long-standing problems of fossil fuel boilers. As a result, the traditional market for conventional solid fuel firing techniques, like stoker and pulverized fuel firing, is being progressively taken over by fluidized bed boilers [17].

A fluidized bed boiler is a type of steam generator in which fuels burn in a special hydrodynamic condition called the fluidized state, and transfers the heat to boiler surfaces via some non-combustible solid particles. There are two main types of fluidized bed boilers:

l. Bubbling fluidized bed boiler
2. Circulating fluidized bed boiler

The fluidized bed combustion system has been used in this study. So, the combustion system characteristic properties can be explained as,

- Excellent load motion
- High combustion efficiency
- High ash retention efficiency
- Low SO_2 emission
- Low NO_X emissions [18]

This system has low emissions, because of the emission reducing system which is the most important feature in the fluidized bed. For example adding limestone during the combustion into the bed material reduces sulphur dioxide (SO_2) emissions in the flue gases. In addition, the formation of NOx emissions in the combustion chamber is suppressed due to low combustion temperature.

The primary air fan delivers air at high pressure (10 to 20 kPa). This air is preheated in the air preheater of the boiler, and then enters the furnace through the air distributor grate at the bottom of the furnace. The secondary air fan delivers air, which was preheated in the air preheater, at a relatively low pressure (5 to 15 kPa). It is then injected into the bed through a series of ports located around the periphery of the furnace, and at a height above the lower tapered section of the bed. In some boilers, the secondary air provides air to the start-up burner as well as to the tertiary air at a still higher level, if needed. The secondary air fan may also provide air to the fuel feeder to facilitate the smooth flow of fuel into the furnace. Loop-seal blowers deliver the smallest quantity of air but at the highest pressure. This air directly

enters the loop-seals through air distribution grids. Unlike primary and secondary air, the loop-seal air is not heated. Figure 3 shows a general arrangement of a typical circulating fluidized bed boiler.
Comparison of fluidized bed boilers

Fuel amount per cross-sectional area in circulating fluidized beds is higher than the other, because of a high combustion velocity in this bed. Boiler and combustion efficiencies are lower in bubbling fluidized bed than in circulating fluidized bed boilers. And finally, NO_X and SO_2 emissions are lower in a circulating fluidized bed because of low temperature in the combustion chamber and small limestone grain size [19].

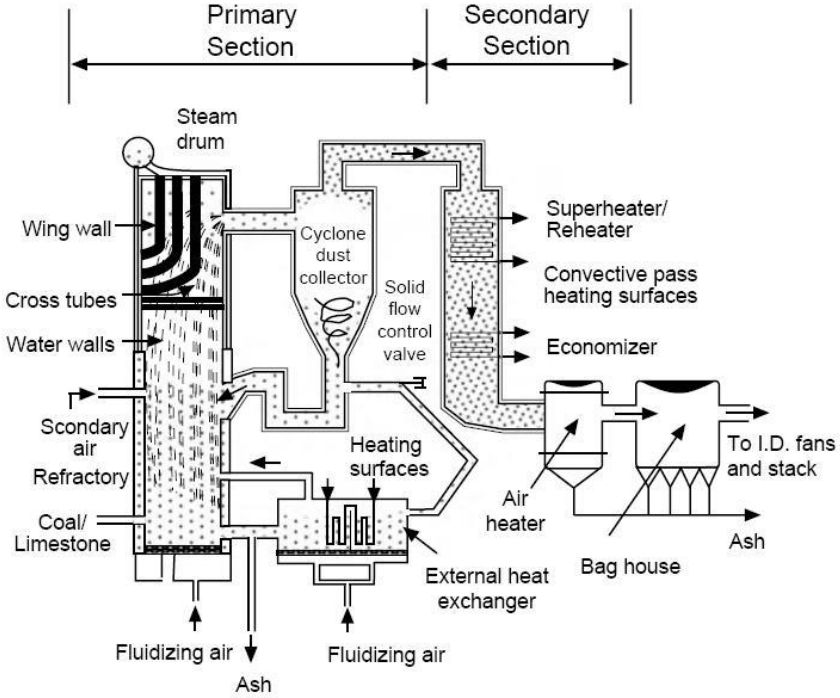

Figure 3. *General arrangement of a typical circulating fluidized bed boiler [16].*

2.3. Organic Rankine Cycle

This system, which is used as an alternative to the steam cycle, provides high efficient electricity generation in a turbine system using organic fluids heated by means of convection heat transfer, such as high thermal oil or direct exhaust gas. This system, which can be used in all plants with continuous waste heat release, is preferred because of high efficiency especially at low temperatures. Despite the use of water vapour as a fluid in a conventional steam turbine, fluid which has higher molecular weight than water is used in the ORC system. Because of this, the turbine runs at a lower speed and the metal parts are exposed to less pressure, so the operating life of the turbine extends. Once the heated organic fluid is evaporated using a suitable heat exchanger system then it enters the turbine. Schematic drawing of the ORC is shown in Figure 4.

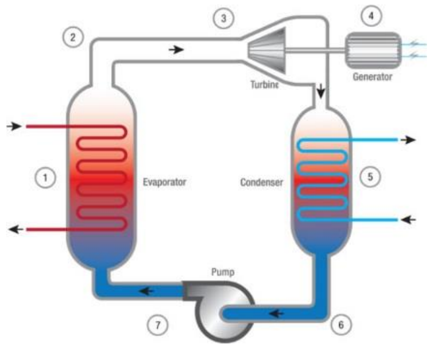

Figure 4. *Schematic drawing of an ORC*

Depending on the low turbine rotation speed, wear in mechanical parts and turbine blades is less than in conventional systems. Because the system can operate at low pressures, the life of the existing equipment in the system becomes longer. It is an environmentally friendly application. There is no need to use hot steam in the system. Low CO_2 emissions are achieved. It can be used and applied easily in different production processes. It has a simple and compact design. There is no need for water treatment. Operation and maintenance costs are low. Fast retrieval and fast output control from the circuit can be performed. Flexible operation and high efficiency are obtained at partial loads. Construction and installation costs are low [20].

3. DESIGN AND CALCULATIONS

In the present analysis RDF and coal co-firing is used in the boiler working under the Organic Rankine Cycle using pentane as the working fluid. This cycle produces 2 MW of electric power.

Circulating fluidized bed (CFB) technology has gained a great progress in coal-firing boilers, since the successful operation of the world's first demonstration of circulating fluidized bed (CFB) boiler in Germany [21]. The largest CFB boiler that has a supercritical unit with a capacity of 460 MWe made by Foster Wheeler Corporation, is under construction in Lagisza, Poland [22]. In China, the number of commercial CFB boilers that have been put into operation is over 800, among which the units with capacity of 100-150MWe are near 30 items. However the first 300MWe CFB boiler (Ahlstrom licensed) is under construction [23].

Typically, the main loop of a CFB boiler is composed of a riser, separators and loop seals. For some small units, single separator and single loop seal might be applied. Nevertheless, the main loop is a typical solid-gas two-phase flow system with chemical reaction. Appropriate understanding of the fluid mechanics inside the furnace is the fundamental importance for designing a CFB boiler.
Theoretically, the regimes of fluidization can be classified into stationary bed (or say fixed bed), particulate fluidization, bubbling bed, slugging bed, turbulent bed, fast bed and pneumatic transport, depending on the gas superficial velocity U_f, bed voidage and physical properties (e.g., size and density) of the solid particles, as shown in Figure 5 [24]. Normally, the fluid mechanics taken place inside the furnace is separately described in two parts: a lower part and upper part. In the lower part, called dense bed, size distribution of particles are rather wide because of many coarse particles, and at the same time bulk density is rather high. Thus, the associated fluidization regime is not necessarily a fast bed, it can be bubbling bed or turbulent bed depending mainly on the U_f.

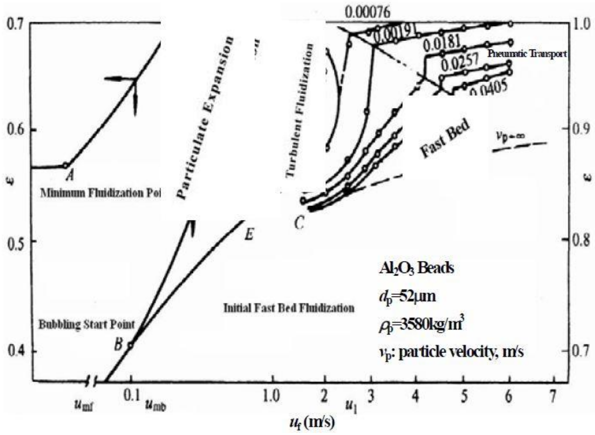

Figure 5. *Fluidization regimes for Al_2O_3 particles - bed voidage vs. superficial velocity [24]*

During the CFB boiler evolution history in China, a CFB boiler was once regarded as nothing else than the traditional bubbling bed boiler with an extended free board unit. However, the fluidization regime inside a bubbling bed boiler is totally different from that inside of a CFB boiler. In a bubbling bed, only a small amount of particles are entrained into the free board so that combustion fraction in the dense bed is about 75-85%, and immersed tubes have to be arranged there. However, in a CFB boiler, much more particles are entrained into the free board unit so that combustion fraction in the dense bed only occupies about 50-60%, and no convective heat transfer surfaces are necessary to be arranged there. It was found that for a bubbling bed boiler retrofitted with fly ash recirculation, if the recirculation flow rate is above a critical amount, the hydrodynamics and thus combustion and heat transfer behaviours inside the bed become CFB-like, and qualitatively different from the bubbling bed. The temperature in the dense bed can be even too low to keep stable combustion.

The upper part of a CFB boiler is a fast bed, shown in Figure 5, for certain particles, flow dynamics of the two-phase flow, or called hydrodynamic state can be defined by two parameters: superficial velocity U_f (m/s) and solid circulating rate G_s (kg/m^2·s). For engineering simplicity, G_s is also assumed to be the solid flux at the separator entrance.

Following are the major steps involved in the design of CFB boilers:
1. Stoichiometric calculations
2. Heat and mass balance
3. Furnace design
4. Heat absorption
5. Mechanical component design
6. Design for combustion and emission performance

A a 1-2-3-4 steam boiler cycle, 5-6-7-8 ORC and heat exchanger between the two cyclesare shown in Figure 6.

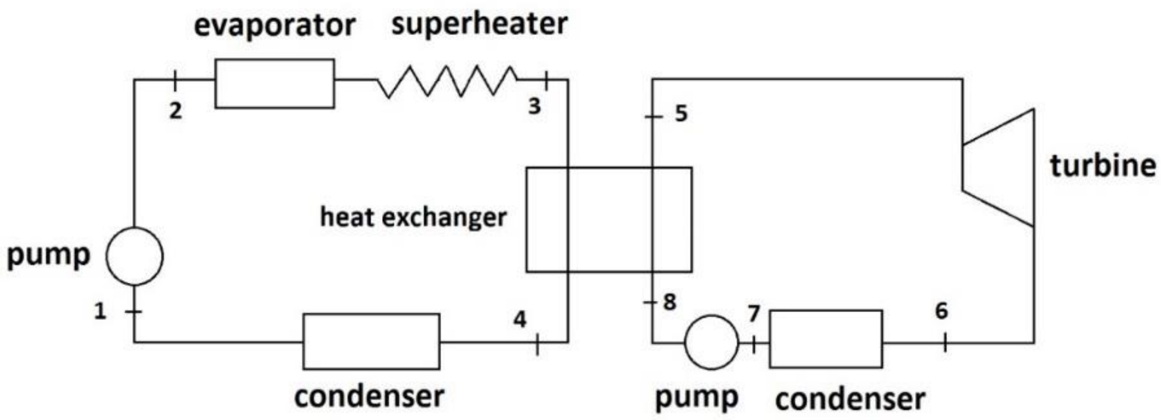

Figure 6. *Power Cycle*

Design parameters [25]; Table 1 and Table 2 show working points for system and working fluid capacities, respectively. Elemental analysis of RDF is shown in Table 3. Then, water and steam circuit of a circulating fluidized bed boiler is given in Figure 7.

Table 1. *Working points for the system*

Cycle Sections		P (bar)	T (ºC)	h (kj/kg)	C_p (kj/kgºC)
2 point	Evaporator inlet	110	315	1450.0	
2a point	Economizer inlet	110	120	501.6	
2’ point	Superheater inlet	110	315	2705.0	
3 point	Exchanger inlet	110	550	3500.0	
4 point	Exchanger outlet	80	380	3100.0	
5 point	Turbine inlet		427		3.157
6 point	Turbine outlet		227		2.662

Table 2. *Working Fluid Capacities*

Water Capacity	M_w	24 tons/h
Pentane Capacity	M_p	20 tons/h

Table 3. *Elemental Analysis of RDF*

Ultimate Analysis	
C	49.65 %
H	5.78 %
N	17.91 %
O	15.11 %
S	0.99 %
W	4.85 %
A	5.72 %
LHV	22345 kj/kg

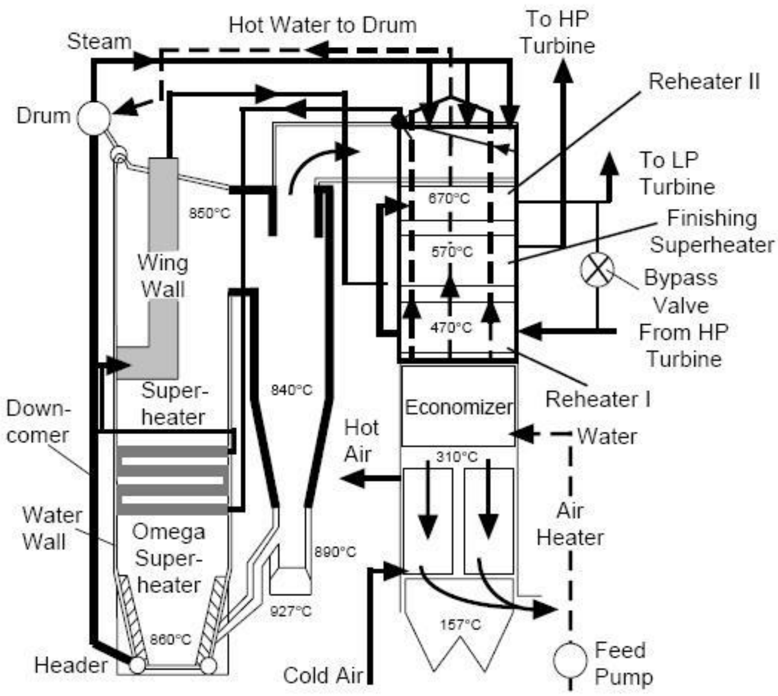

Figure 7. *Water and steam circuit of a circulating fluidized bed boiler without an external heat exchanger [16]*

3.1. Design of Furnace

The main parameters for the furnace sizing are furnace dimensions (height, depth, width and configuration), furnace wall construction and desired furnace outlet temperature. The heat transfer surface area of the furnace consists of three parts: sides, base and beak which is a "L"-formed bending of the evaporator tubes that protect the superheaters from radiation. Most utility and industrial boiler furnaces have a rectangular shape. A large number of package boilers have a cylindrical furnace. Furnace bottom for typical PCF boiler is double inclined or v-form, as shown in Figure 7. Flat bottom is more typical for grate and fluidized bed boilers. The ratio of height and width varies 1-5 for boilers with two-pass layout. The larger the boiler is, the larger the ratio. The largest boilers have a width of 20 m and a height of 100 m. The fuel and vaporization efficiency determines the size of the furnace. To be able to dimension furnaces the overall mass balance, heat balance and heat transfer must be specified.

When dimensioning a circulating fluidized bed (CFB) furnace the high content of sand has to be taken into consideration. This means that the temperature profile and thus the heat transfer near to the furnace wall differs from other types of furnaces. The furnace of a CFB (circulating fluidized bed) boiler contains a layer of granular solid particles, which have a diameter in the range of 0.1-0.3 mm. It includes sand or gravel, fresh or spent limestone and ash. The operating velocity of the flue gas stream in a CFB boiler is 3-10 m/s. The solids move through the furnace at much lower velocity than the gas velocity; solids residence times in the order of minutes are obtained. The long residence times coupled with the small particle size produce high combustion efficiency, and high SO_2 removal with much lower limestone feed than in conventional furnaces.

After the furnace, flue gas moves through a cyclone, where solids are separated from the gas and the solids are returned to the furnace. Flue gas from the cyclone discharge enters the convection back-pass in which the superheaters, reheaters, economizers and air preheaters are located. A dust collector separates the fly ash before the flue gas exits the plant. The combustion air from the fan transports the solids pneumatically for creating the circulating fluid. The design of the furnace in a CFB boiler depends on:

- required velocity of gas
- time of complete combustion of fuel
- heat required for vaporization.

The design of the furnace of a CFB boiler has three major components:
1. Design of furnace cross section
2. Design of furnace height
3. Design of furnace openings

The furnace cross section is chosen according to the cross sectional specific heat properties. International standards followed by designers vary from manufacturer to manufacturer. The furnace height, on the other hand, is determined from heat transfer in the combustion chamber especially coming from radiation, as well as from the minimum gas/solid residence time. The cyclone dimension and combustion rate may also be related with furnace height. The furnace gaps for various gas-solid flows are also an important criteria, especially for design of the lower section of the furnace.

Water pipe steam boiler has one evaporator, one superheater, one economizer and one air pre-heater in this design. Design parameters with steam boiler thermal capacity and steam boiler section capacities are found as shown below.

$Q_{sb} = Q_e + Q_{sh} + Q_{eco} + Q_{aph}$ ………………………… (Eq. 1)

Where;
Q_{sb} = Steam boiler total heat capacity (MWth)
Q_e = Heat capacity of evaporator (MWth)
Q_{sh} = Heat capacity of superheater (MWth)
Q_{eco} = Heat capacity of economiser (MWth)
Q_{aph} = Heat capacity of air preheater (MWth)
$Q_e = M_b \times \Delta h = 8.366$ MWth ……………………………….. (Eq. 2)

The same formula is used for all sections.
Q_{sh} = 5.3 MW,
Q_{eco} = 6.322 MW,
Q_{aph} = 4.79 MW

Boiler steam capacity is equal to sum of these sections. Q_{sb}= 24.785 $MW_{thermal}$
The boiler efficiency is assumed to be 90 percent. Then fuel capacity formula becomes
$Q_{sb} = M_f \times LHV \times \eta_b$ …………………………………….. (Eq. 3)

Fuel feeding rate is equals to 1,233 kg/s. And then the theoretical air flow rate and the flue gas flow rates are calculated after combustion using the respective formulas as follows.

$O_{2\,min}$ = 1.0316 Nm^3/kg, V_{at}= 4.9102 Nm^3/kg,
If the assumed excess air constant is n = 1.4
V_{air} = 6.8743 Nm^3/kg
V_{CO2} = 0.9267 Nm^3/kg
V_{SO2} = 0.0069 Nm^3/kg
V_{NF} = 0.00608 Nm^3/kg
V_{NA} = 3.8786 Nm^3/kg
V_{H2O} = 0.7078 Nm^3/kg

Wet and theoretical flue gas flow rate = 5.5261 Nm^3/kg and real 7.4902 Nm^3/kg and then temperature should be assumed in these parts of the steam boiler (evaporator, superheater, economizer, air pre-heater). Figure 8 shows temperature lines of both water vapour and flue gases. The top line shows the hot combustion gases. Table 4 shows design temperatures for the boiler sections.

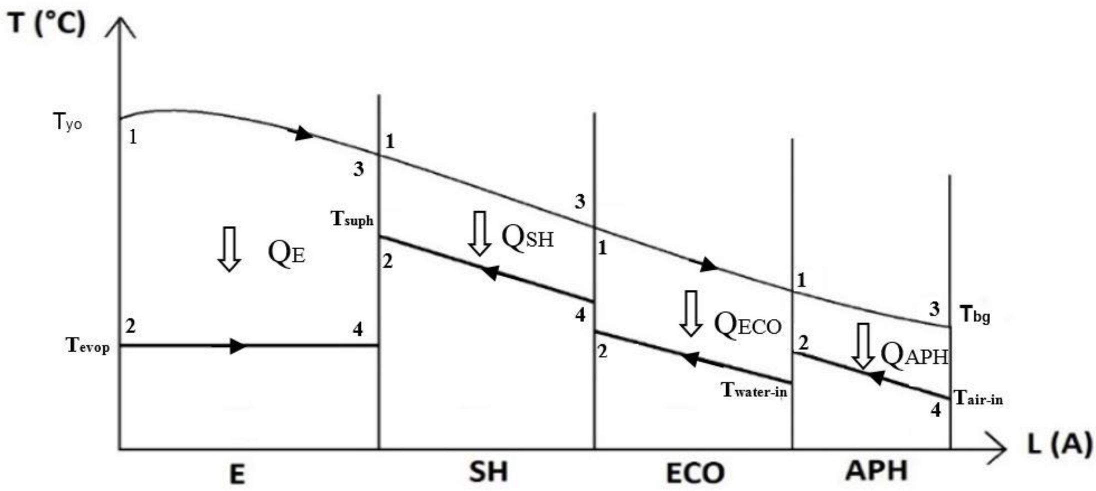

Figure 8. *Temperature Diagram*

Table 4. *Design temperatures for boiler sections*

EVAPORATOR	°C
T_1	950
T_2	315
T_3	840
T_4	315
SUPERHEATER	**°C**
T_1	840
T_2	550
T_3	815
T_4	315
ECONOMIZER	**°C**
T_1	815
T_2	300
T_3	520
T_4	120
AIR PRE-HEATER	**°C**
T_1	520
T_2	123
T_3	200
T_4	20

After that, specific heat values of steam boiler sections are found. The logarithmic mean temperature difference (LMTD) method is used in steam boiler sections and it is given in Table 5. In this case, the steam temperature was 550°C and the pressure was chosen to be 64 bar.

Table 5. *Thermal capacities of boiler sections*

Boiler Sections	V_{fg} (Nm^3/s)	C_{pfg} (kj/Nm^3K)	LMDT	Q (MW)
Evaporator	9.2313	1.566	578.257	8.359
Superheater	9.2313	1.481	385.514	5.270
Economiser	9.2313	1.515	456.181	6.378
Air Pre-Heater	9.2313	1.429	280.171	3.695

Here, the thermal capacities of the evaporator, superheater and economizer are determined, and in the meantime flue gas is very close to the thermal capacities of the working fluids. However, the combustion air is heated using the flue gas in the air preheater unit. The thermal efficiency of this steam boiler is assumed as 90 percent, depending on the combustion technology.

At the beginning of the design, combustion chamber has been sized. The combustion efficiency is calculated as 98 percent for this combustion system, and the heat load is calculated per unit bed area as shown below.

q_a=1.3 MW/m^2

$Q_{cc} = M_f \times LHV \times \eta_c$ …………………………………… (Eq. 4)

The combustion chamber heat load was calculated as 27 MW_{th}. Then,

$A_{cc} = \frac{Q_{cc}}{q_a}$ ……………………….………………………….. (Eq. 5)

And area of the combustion chamber is found as 20.75 m^2 (3.5 x 6 dimension assignation). After, using

$Q_i = U \times A \times LMTD$ ………………………………………. (Eq. 6)

formula and calculating areas for this steam boiler sections.

A_e = 327.131 m^2, A_{sh} = 185.69 m^2, A_{eco} = 290.199 m^2, A_{aph} = 417.239 m^2

These areas are water pipe outer surface areas in the steam boiler sections.
Boiler sections are designed consecutively for the combustion chamber. When designed in this manner, the combustion chamber has 20.75 m^2 (3.5 x 6), evaporator 20.75 m^2 (3.5 x 6), superheater 18 m^2 (3.5 x 5.5), economizer 15 m^2 (3 x 5), air preheater 9 m^2 (2.5 x 3.6) dimensions. The pipe lengths that will be used in boiler sections are given in Table 6 below.

Table 6. *Pipe diameters and lengths of the boiler sections*

Boiler Sections	**Diameter (m)**	**Length (m)**
Evaporator	0.080	1303
Superheater	0.036	1642
Economiser	0.044	2100
Air Pre-Heater	0.068	950

This boiler is a circulating fluidized bed boiler. Evaporator section is constituted from the four walls of the combustion chamber this membrane walls, beginning at 5 meter altitude from the bed surface. The secondary and tertiary combustion air should be fed to the boiler at the optimum level to ensure efficient combustion. Membrane wall length has been found 12 meter by calculations. However, this circulating fluidized bed boiler is 17 meter high. Then, superheater, economizer and air pre-heater have not any membrane wall. The superheater, economizer and air pre-heater sections are connected with one set of collectors. Pipes are placed at the inlet of the steam boiler and the steam boiler section lengths are calculated. The lengths of the superheater, economizer and air pre-heater are 3.3m; 7.8m and, 12.0m, respectively. Solid model drawing of the RDF fired boiler is given in Figure 9.

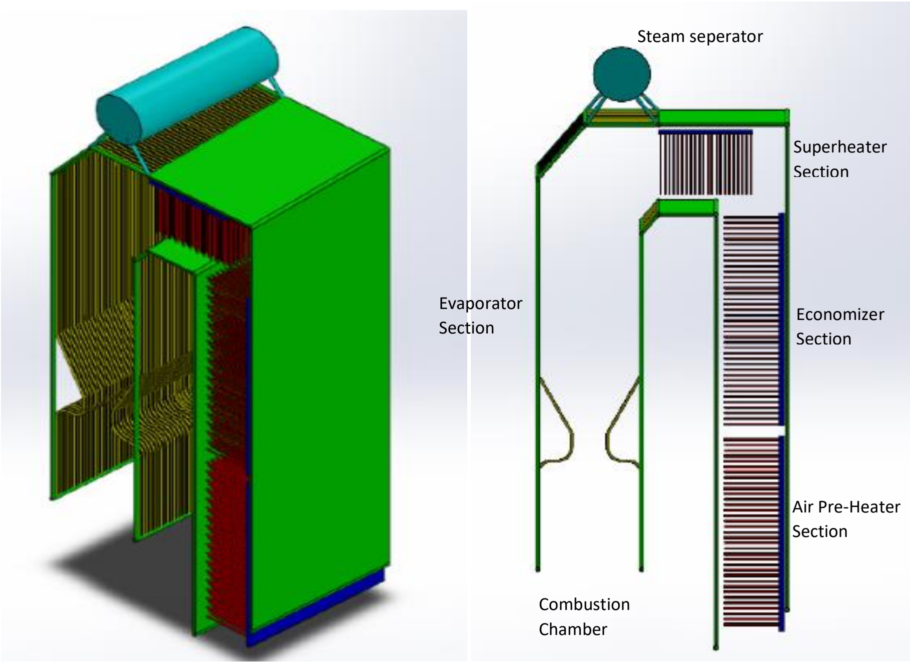

Figure 9. *Solid model drawing of the RDF fired boiler*

3.2. Cost Analysis of Design

The cost of pipe, steel construction, insulation and control safety equipment are taken into consideration when calculating the cost analysis. In an approximate calculation, half of the pipe cost for steel construction is added to the cost account as one fourth of pipe cost for insulation and one fifth of pipe cost for control and safety equipment's. The results of boiler cost analysis are given in Table 7 below. However the chimney, emission control equipment and fans of the steam boiler and the automatic control systems should be specially priced.

In addition to some direct costs, there are some indirect costs in the boiler cost analysis. Depending on the boiler technology, the cost of the combustion and emission control systems must be added to the whole boiler construction cost. In this study, some indirect costs have been foreseen but some of them have been neglected. Cost of the boiler is also given in Table 7.

Table 7. *Cost of the Boiler (Based on June 2018 prices)*

Boiler Section's	Diameter (m)	Length (m)	Unit Price (TL/m)	Cost (TL)
Evaporator	0.076	1303	44.50	57983.00
Superheater	0.036	1642	55.00	90310.00
Economizer	0.044	2100	38.20	80220.00
Air Pre-Heater	0.068	950	40.00	38000.00
Total Pipe Cost				266513.00
Steel construction cost				133256.50
Cost of insulation				66628.25
Coal and adsorbent feeding system				180000.00
Cost of control and safety equipment's				53302.60
Workmanship				250000.00
Installation				100000.00
Steam boiler auxiliary systems (pump, water treatment, control systems, etc)				330000.00
Total Cost				**1379700.35**

4. RESULTS AND CONCLUSIONS

RDF is derived from a variety of wastes, especially occurring in municipal wastes. In order to dispose RDF, it is better to burn RDF, which is both environmentally beneficial and more efficient than other fuels. RDF is generally burned as a secondary fuel with coal, wood waste or other materials. Combustion is the reaction of any fuel that is a combustible material with oxygen. The burning process is usually carried out in combustion chambers or burners. RDF-coal mixture was considered using it as fuel in a water pipe steam boiler design in the scope of this study. This fuel, which contains about 5% moisture, has a heat value of 22350kJ/kg. As a result of the calculations 24.75MWth is determined as boiler thermal capacity. And the superheated water steam has entered the Organic Rankine Cycle (ORC) system, and the system produces superheated N-pentane steam for its turbine to produce 2.0 MWe.

A classical steam boiler system consists of the evaporator, superheater, economizer and the air preheater sections. The heat load and heat transfer coefficients of each section were determined and required surface areas were calculated. In the design, the cross-sectional area of each zone is determined and the numbers of pipes are calculated.

The geometry and external dimensions of the boiler emerged as a result of calculations and acceptances. Circulating type fluidized bed combustion system was chosen as a solid fuel combustor for clean and efficient firing in the steam boiler.

The major gaseous effluents that affect the ecosystem are sulphur dioxide, nitrogen oxide, and the greenhouse gases. The combustion of fossil fuels in stationary and transportation systems is the main source of air pollution. Various boilers, furnaces, and engines that use fossil fuels emit gaseous pollutants, such as SO_2, NO_x, CO and volatile organic compounds (H_mC_n). Using renewable energy sources as fuels in energy production in the steam boilers reduces these emissions.

On account of fluidized bed combustion used (FBC) to burn wide variety of fuels, including low-quality fuels in conventional burning systems, power engineering design becomes versatile. Fuels which contain high concentrations of ash, sulphur, and nitrogen can be burned within the combustion chamber of a fluidized bed boiler, the processes of fuel burning, sulphur dioxide adsorption, and NO reduction takes place concurrently with sulphur dioxide adsorption. For example; the nitrogen oxide emission level is low due to the low combustion temperatures. Meanwhile SO_2 emission control mechanism is provided while burning process in the fluidized media by using adsorbents such as limestone.
Fluidized bed combustion systems are considered to be the most suitable steam boiler application to burn Turkish lignite alone or to burn biomass or waste together with lignite coal. Today, low thermal capacity bubbling fluidized bed boilers are manufactured by some companies in Turkey. The domestic production of circulating type fluidized bed boilers with proper combustion systems especially for power plants using different fuels are important in terms of the national economy.

SYMBOLS

C	: Carbon
C_S	: Fixed carbon
Ca	: Calcium
CaO	: Calcium oxide
$CaCO_3$	: Calcium carbonate
$CaSO_4$	: Calcium Sulphate
C_mH_n	: Total hydrocarbons, ppm
CO	: Carbon monoxide
CO_2	: Carbon dioxide
dP	: Particule diameter, μm
dP, ΔP	: Pressure drop, mbar, Pa
g	: Gravitational acceleration, m/s^2
L	: Height of riser, m

N_2	: Nitrogen
NO	: Nitrogen oxide
NO_2	: Nitrogen dioxide
NO_X	: Total nitrogen oxides
L	: Lenght of the boiler sections, m
O_2	: Oxygen
P	: Pressure, bar, mbar, Pa
ρ_S	: Solid particle density, kg/m^3
ρ_g	: Gas density, kg/m^3
ρ_b	: Bulk density, kg/m^3
Re	: Reynolds number
S	: Sulphur
SO_2	: Sulphur dioxide
SO_3	: Sulphite
SO_X	: Total sulphur compounds
U_f	: Superficial velocity, m/s
η	: Efficiency
FBCCS	: Fluidized Bed Coal Combustion System
CFB	: Circulating Fluidized Bed
CFBC	: Circulating Fluidized Bed Combustion
BFB	: Bubbling Fluidized Bed
ORC	: Organic Rankine Cycle
RDF	: Refuse Derived Fuel

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CONFLICT OF INTEREST

No conflict of interest was declared by the authors

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