

Master's Thesis 2013

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Title: District heating biofuel burner
efficiency and energy balance

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Lower Degree Programmes – M.Sc. Programmes – Ph.D. Programmes

TFver. 0.9



Telemark University College

Faculty of Technology
M.Sc. Programme

MASTER'S THESIS, COURSE CODE FMH606

Student: Oluwashola Okoro

Thesis title: District heating biofuel burner efficiency and energy balance

Signature:

Number of pages: 45

Keywords: District heating, Skien Fjernvarme, energy balance, thermal efficiency, moisture
Contents, woodchips, biomass boilers

Supervisor: Wilhelm Rondeel sign.:

2nd Supervisor: sign.:

Censor: sign.:

External partner: Gaute Finstad sign.:

Availability: Open

Archive approval (supervisor signature): sign.: **Date :**

Abstract:

District heating is an optimal system of distributing heat to residential building in a centralized location through pipeline networks. The district heating of woodchip is cost effective, improve energy efficiency, reduce gas emissions and improve energy security.

The thermal efficiency and energy balance in a boiler is obtained by combustion analysis of the wood (fuel). In this report, the district heating bio fuel burner in Skien Fjernvarme is considered. The capacity of the boiler is 6MW and the operation commenced in December 2012.

The energy balance in a boiler is characterized by the input, output and losses from the boiler. The input components are the woodchip, feed water and combustion air. The losses increases if the woodchip is of high moisture content, more soot in the boiler tubes, woodchip degradation as a result of wood storage etc. The losses gotten from the evaporation of moisture in Skien Fjernvarme boiler is 80.4kWh/m³ from calculation analysis. This loss is a major one from the boiler. The net heat output from calculation is 722kWh/m³ for 1m³ loose woodchip. In the month of December, the woodchip supply was 2350 loose m³; the net heat production was 1698MWh (If all woodchip are utilized). January generate net heat of 2816MWh with a supply of 3900 loose m³. The net heat in February and March are 2238MWh and 2819MWh for supply of 3100 loose m³ and 3905 loose m³ respectively.

The thermal efficiency of Skien Fjernvarme district heater in this report is determined from combustion and analysis of the constituents of the woodchips. The efficiency of a boiler is affected by the wood quality, feed water quality, the moisture content, excess air, density of the woodchip and the operation of the boiler. The thermal efficiency of Skien Fjernvarme district heating system from analysis calculation is 85%. This value indicates that the boiler is in good working state.

Telemark University College accepts no responsibility for results and conclusions presented in this report.

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Preface

District heating business is one with a varying data. This is because the woodchips (fuel) are supplied at different moisture contents, density, sizes, storage rate etc. The data used in this report varies continually. The analysis and results gotten in this report are based on the data from the acceptance test carried out on the plants. The initial task description was to study the energy balance and thermal efficiency of one or more district heater(s) in Skien, Bø or Notodden. With careful observation with my supervisor, we came to a conclusion that this report should be based only on Skien Fjernvarme district heater, since they all have similar working principle. The major difference is their capacities.

This report will not be complete if I fail to appreciate some eminent hands during the course of the project. My appreciation goes to my supervisor, professor Rondeel Wilhelm for his advice and kind help during the project. Special thanks to the two Mortens in Skien Fjernvarme- They are always there when ever I need them. I cannot but appreciate Helgen Hansen in Skien Fjernvarme for his openness during this work.

Lastly, my regards to my parents for the love they shower me this far.

Porsgrunn, 01.06.2013

Oluwashola Okoro.

Nomenclature

ABMA: American boiler manufacturers association on standard radiation loss.

ANSI/ASABE: America national standard/American society of Agricultural and biological engineers.

Btu: british thermal unit

CHP: combine heat and power

Ch: heat lost from combustion of hydrogen

CO₂: carbon dioxide

CP_{ash}: specific heat capacity of ash

CP_{H₂O}: specific heat capacity of water

CP_{N₂}: specific heat capacity of nitrogen

CP_{O₂}: specific heat capacity of oxygen

dg: weight of dry gas

DH: district heating

EU: European union

F: Fahrenheit

GWh: giga watt hour

h_i: enthalpy of water at exhaust temperature

HHV: higher heating value

hw: enthalpy of water at saturated liquid

kg/m³: SI unit of density

lb: pound mass

LHV: lower heating value

lm³: loose volume of woodchip

L_R: radiation loss

M: moisture content

M_{dry}: dry moisture

M_{wet}: wet moisture

MJ: mega joule

MW: mega watt

P1: first boiler in Skien Fjernvarme heating system

P2: second boiler in Skien Fjernvarme heating system

T_{air}: temperature of air

TWh: tera watt hour

X_{ash} : percent mass of ash

X_{C} : percent mass of carbon

X_{H} : percent mass of hydrogen

X_{O} : percent mass of oxygen

X_{S} : percent mass of sulphur

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1 Introduction

Woodchips as a biofuel have been utilized by humans to make heat for some years now. A tremendous growth on woodchips burning has been experienced in the past 20 years. However, with the development of fossil and nuclear fuels, the use of wood declined. Nevertheless, wood is still a major source of energy worldwide. The conversion of wood into electrical and heat energy has been rewarding compare to fossil fuel both economically and environmental wise. (Kevin Healion, 2002). Wood is considered the fuel of civilization catapulting man from other primates; coal is termed the fuel of industrialization while oil and natural gas is considered as the fuel of modern industrialization.

1.1 District heating (DH) of biofuel

District heating is an optimal system whereby heat is distributed to commercial and residential building in a centralized location through pipeline networks. The heat in this case is obtained from burning of fossil fuels and biomass. District heating plants can provide higher efficiencies and less pollution than localized boilers (Alemayehu et al, 2008). In Europe, city wide district heating systems exist in Helsinki, Copenhagen, Stockholm, Munich, Berlin, Paris, Prague, Kiev, Moscow etc. In general, more than 5000 district heating networks in Europe connect citizens to a variety of sustainable heat sources (Andrea et al, 2010). The district heating system can produce heat only from the heat production source. It can also produce heat and electricity simultaneously. This latter heating system is called combined heat and power (CHP) or cogeneration. CHP is illustrated in Figure 1 as shown below:

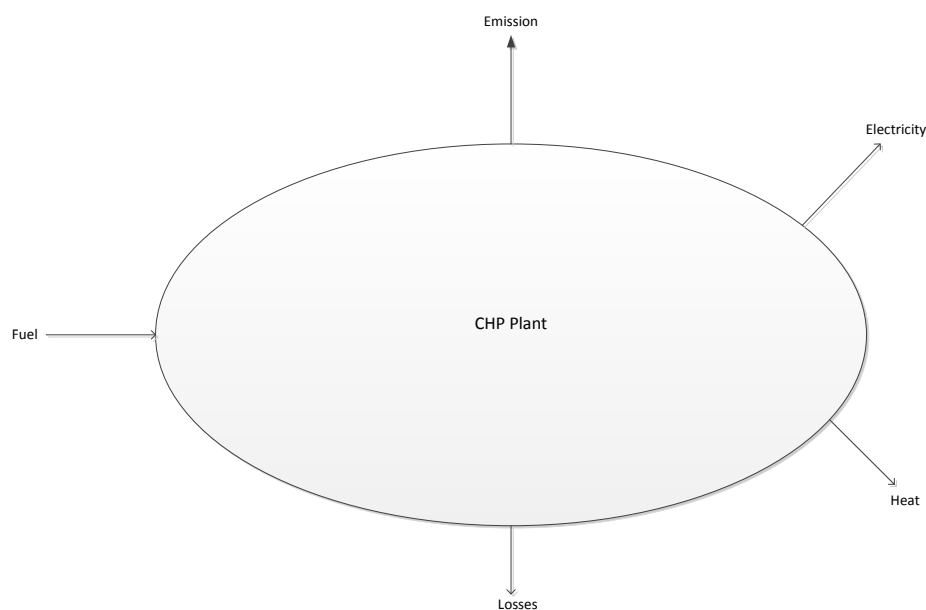


Figure 1: General description of CHP plant.

1.2 District heating in Nordic countries

District heating over the years in all Nordic countries has been a rising carrier except for Norway. Sweden has a supply of more than 50TWh district heating, Denmark and Finland have around 35TWh, Norway has only 3TWh. This supply in Norway has been on the increase over the last decade. Figure 2 shows the production through district heating in Nordic countries in the last three decades.

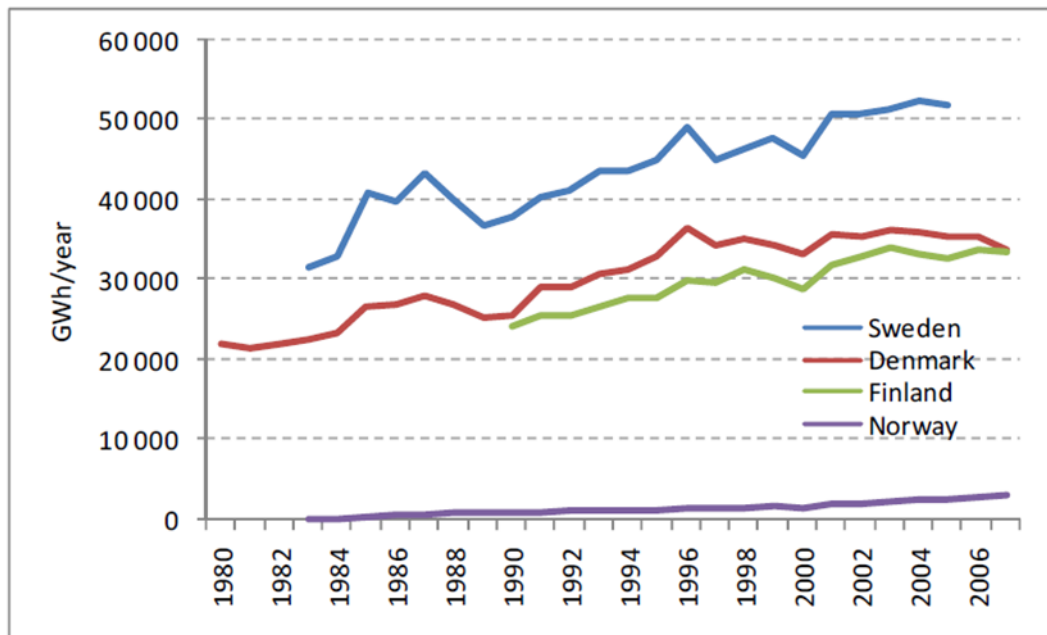


Figure 2: District heating production in Nordic countries

Source: Report on Nordic district heating (Nordic energy perspectives, March 2009).

1.3 Problem description

The task description in this project report is to study the energy balance and thermal efficiency of one (or more) district heating systems in Skien, Bø or Notodden. The boilers in these various heating systems are quite similar. The only major difference is their capacities. This report is streamlined to Skien Fjernvarme district heating system. It describes into details the district heating system, the combustion analysis, the losses and thermal efficiency of the heating system in Skien Fjernvarme AS.

1.4 District heating biofuel burner in Skien Fjernvarme AS

The district heating system in Skien is fully owned by Skagerak energy, AT skog and Løvenskiold Fossum. The district heating system has two boilers P1 and P2 with 6MW

power capacity each. The plant was commissioned by Jernforsen energy system in December 2012 and Operation started in December 2012 with woodchip supply of 2350 loose m³. The plant lay out is shown in figure 3 below.



Figure 3: Skien bio boiler

1.5 Aim

The aim and objectives of this project are to analyze the energy balance and consequently the thermal efficiency of the district heating biofuel (woodchips) burner in skien fjernvarme AS.

Also to discuss the district heating essentials, combustion processes of biofuel, effects of moisture content and the energy content in a biofuel woodchips.

2 Literature Survey

Different topics ranging from the importance of district heating, combustion processes of biofuel, combustion efficiency, calorific values of wood, energy content of biofuel etc. are discussed under this chapter.

2.1 Importance of district heating

In recent decades, there have been increasing demands for energy. This led to global warming, fluctuation in oil prices. These and lots more made the European Union to realize the benefits in a secure and safe supply of energy. Anna Volkova et al, 2012 on methodology for improvement of district heating networks pointed out that a properly operating district heating systems can provide possible improvement on energy efficiency, reduce emissions, and improve energy security, creation of new jobs and cost effectiveness.

One of the main points mentioned in the EU strategy on energy 2020 is to increase the uptake of high efficiency of a district heating systems. It was pointed out that high efficiency district heating system can only be provided when efforts are concentrated on the whole energy chain, from energy production, through distribution to final consumption (Europa the official website of the European union). There are more than 5000 district heating systems in Europe. These supply more than 9% of the total European heat demand. Sweden and Finland main source of energy is the district heating systems which account to 60-75% of energy to various households (Rezaie et al, 2012). District heating systems offer a potential for renewable heat generation technologies (Anna Volkova et al 2012).

The main advantages of district heating are efficiency, reliability and cleanliness. The most used renewable energy source for heat generation is the biomass, which includes agricultural, industrial wastes, forest and manure residues which under a controlled burning condition can generate energy with minimal environmental impacts (Vallios et al, 2009). A well developed and modified district heating systems promote cogeneration development.

Kelly and Pollitt, 2010 pointed out that cogeneration plant with district heating provides an alternative energy production and delivery mechanism that is less resource intensive, more efficient and provide higher energy security.

2.2 Combustion process of biofuel

Nowadays, combustion is mostly applied to obtain the energy from biomass. Biomass combustion is the main technology for bioenergy. It provides over 90% of the global contribution to biological energy (Sjaak et al, 2008). Biofuel can be converted into electricity and heat by thermochemical and biochemical processes. Combustion is the most developed

and frequently used processes. The biofuel combustion process involves chemical and physical mechanisms. The combustion process depends on the fuel properties used. It can be categorized into drying, pyrolysis and gasification. The process of combustion could be batch or continuous phase. Combustion occurs when natural gas, coal or gasoline and fuel oil, biomass react with oxygen in the air to produce water and heat. The heat produced is used for environmental heating and industrial processes. The combustion of fossil fuels produced mainly carbon dioxide (CO₂) and water (H₂O) as the principal chemical products. (combustion analysis basic, 2004). The highest temperature is attained when a fuel is burned with a stoichiometric supply of air and when complete combustion occurs (Sorour, 2009). Combustion could be primary and secondary. Primary combustion is the burning of solid material directly. Secondary combustion is the burning of gas fuels which generates the flames of the fire (Rick, 2011). Complete combustion of wood produces only carbon dioxide (CO₂) and water (H₂O). Incomplete combustion on the other hand, produces carbon monoxide (CO) and other hydrocarbons. Insufficient air during combustion processes leads to incomplete combustion processes and produces soot. To achieve a significant amount of combustion processes, extra air called excess air is introduced. Excess air is the percent air above the theoretical amount needed for complete combustion. It is expressed mathematically as in equation 1.

$$\% \text{ excess air} = \frac{\%O_2 \text{ measured}}{20.9 - \%O_2 \text{ measured}} \times 100 \dots \dots \dots \text{equation 1}$$

In reality, excess air needed for gaseous fuel combustion is around 15% (combustion analysis basic 2004).

2.2.1 Combustion efficiency

Combustion efficiency could be described as the conversion of the effective energy in a biomass to useful energy (heat). Combustion efficiency in percent is expressed as the subtraction of the heat content of the exhaust gases from 100.

$$\% \text{ combustion efficiency} = 1 - \frac{\text{stack heat losses}}{\text{fuel heating value}} \dots \dots \dots \text{equation 2}$$

Stack heat losses are gotten from temperature measurements in combustion analysis and gas concentration. Fuel heating value can be gotten from chemical analysis given by fuel supplier (combustion analysis basic 2004).

Some factors like combustion completeness, amount of excess air, stack temperature, moisture losses determine combustion efficiency (Timothy, 2004).

2.3 Energy content of biofuel

Biofuels have some amount of energy which is used for heating process, production of hot water etc. This energy which is referred to as primary energy could be converted through combustion processes to other forms of energy (Valter francescato et al, 2008).

The energy content also called calorific value is quite consistent on a dry basis for most biomass (Timothy, 2004). Table 1 shows some heating values of various fuels.

Table 1: Calorific values of different fuels

Fuels	mapple	spruce	corn	Fuel oil	Natural gas
Calorific values [Btu/drylb]	8350	8720	8120	19590	22080

Source: woodchip heating systems, Timothy, 2004.

2.3.1 Calorific value based on moisture content

The calorific value also called the heating value is the energy released per unit mass or per unit volume of any fuel or biomass, when the biomass is completely burn. (ANSI/ASABE S593.1, 2011). The units of calorific value are MJ/kg in SI units or Btu/lb in English units. The heating value of fuel is based on the condition of the water molecules in the final combustion products. The higher heating value (HHV) is based on the condition that the water in the combustion products condensed out while the lower heating value (LHV) is when the water in the final combustion products remains as a vapour or steam. (Sara McAllister et al, 2011). The calorific value of biomass is measured experimentally in terms of the high heating value (HHV). The heating value is calculated from the product of mass of fluid multiply by specific heat of fluid and the net temperature rise. The HHV based on dry mass of the biomass can be expressed mathematically as:

$$HHV_{dry\ mass} = \frac{HHV}{1-M} \dots \dots \dots \text{equation 3}$$

M is the moisture content (Bob Boundy, 2011) .

The high heatig value can be expressed from the composition of fuel as

$$HHV_{dry} = 0.35X_c + 1.18X_H + 0.10X_s - 0.02X_N - 0.10X_O - 0.02X_{ash} \dots \dots \dots \text{equation 4}$$

Where X_c is the percent mass of carbon, X_H for hydrogen, X_s is for sulphur, X_N is the percent mass of Nitrogen, X_O for oxygen and X_{ash} is the percent mass for ash.

It can be seen that carbon, hydrogen and sulphur increase the heating value while Nitrogen, Oxygen and ash decreases it. (Gaur and Reed, 1995).

The HHV for woody biomass including the bark determined experimentally is around 20MJ/kg (8600Btu/lb) dry mass basis. For herbaceous biomass, it is around 18.8MJ/kg dry mass (Obenberger and Thek, 2010). Moisture content has a great impact on the higher heating value of biomass. Increasing the moisture content decreases the net heat value because most of the heat content of the biomass is used to evaporate the moisture content (Bob Boundy, 2011).

2.4 Combustion process of woodchips

Hardwoods have less resin and burn slower and longer. Softwoods burn quickly. The moisture content of wood will evaporate out if the wood is heated up to 100°C. Wood starts to break down and release energy at about 300°C. The main energy in wood is released at a temperature between (300-600°C) (Bob Boundy, 2011). In this case, the fuel vapours containing 40% to 60% of the energy burns out. The woodchips undergo combustion processes to produce flames that is used to heat water. The hot water is then passed through a pipe to heat home and provide heat. The process that takes place in the wood chip combustion chamber is that woodchip is passed through a conveyor system to a combustion chamber. The woodchips burn through the help of air that is transported from the surrounding through a fan blower. The heat coming out from the chamber is used to heat water in the heat exchanger tube. The hot water is then passed through a pipe as illustrated in figure 4.

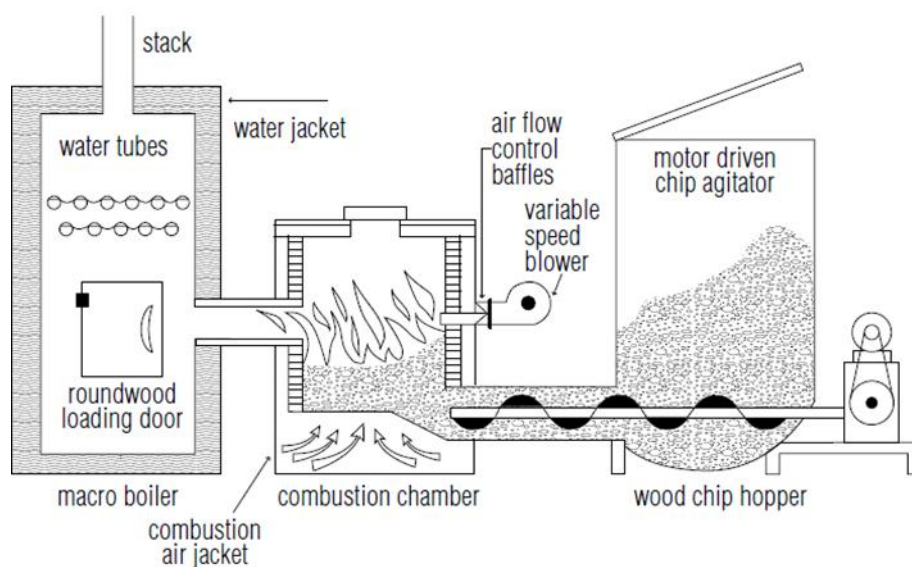


Figure 4: Components of a typical woodchip combustion system.

Source: woodchip combustion system, 1997.

3 Methods of calculating efficiency and energy balance of woodchips burner

3.1 Energy balance of woodchip burner

The heating value of wood fuels depends on the density of the wood, lignin, moisture content and extractives contents. Wood fuel varies by wood species and wood materials. The chemical compositions of wood are of critical important in determining the energy contents of the wood, the physical structure is of less important. Wood consists of three major polymers-cellulose ($C_6H_{11}O_5$), lignin ($C_9H_{10}O_3$) and hemicellulose such as xylan ($C_5H_8O_4$). Wood can also have some extractives and ashes (David Tillman 1978). Hardwoods contain about 43% cellulose, 22% lignin and 35% hemicellulose while soft woods consist of around 43% cellulose, 29% lignin and 28% hemicellulose (Fred Shafizadeh and Williams, 1976).

The energy balance of a woodchip burner could be gotten by analyzing the combustion processes. Wood consists of some organic compounds and when they undergo combustion processes, they produce carbon dioxide, water and heat. The combustion of woodchips has certain species compared to fossil fuels combustion. The elements composition of different woods is very similar. Table 2 shows the various compositions of woods in dry basis.

Table 2: Percentage composition of woods dry basis.

Source: Peter Skok et al, 2012

Wood types	Carbon [%]	Hydrogen [%]	Oxygen [%]	Nitrogen [%]	Ash [%]
Acacia	47.9	6.1	44.6	0.4	1.0
Birch	48.0	6.1	43.3	0.3	2.3
Beech	48.6	6.3	44.5	0.1	0.5
Poplar	49.4	6.0	42.5	0.3	1.8
Willow	49.6	5.9	42.5	0.3	1.7
Pine	49.4	6.4	43.5	0.2	0.5
Spruce	50.1	6.2	43.1	0.1	0.5
Average	49.0	6.1	43.4	0.2	1.3

Wood consist of some constituents which are highlighted in table 3 below

Table 3: Constituents of woods

Source: peter skok et al, 2012

Constituents	Scot pine	Spruce	Eucalyptus	Silver burch
Cellulose [%]	40	39.5	45	41
Hemicellulose [%]	28.5	30.6	19.2	32.4
Lignin [%]	27.7	27.5	31.3	22.0
Total extractives [%]	3.5	2.1	2.8	3.0

The energy balance of woodchip burners can be achieved by considering the total materials into the burner and the total materials out of the burner. Figure 5 shows an illustration of the material and energy balance of a woodchip burner.

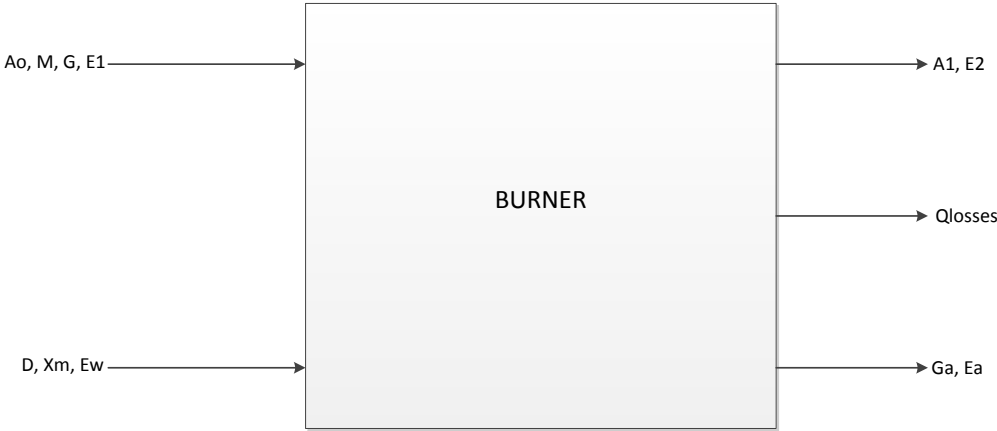


Figure 5: Material and energy balance of district woodchip burner.

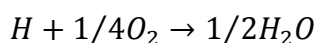
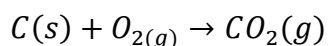
The various terms in the above diagram is explained in table 4.

Table 4: Terms describing the material balance of a woodchip burner

Terms	Meaning
A_o	Inlet air flow rate
M	Mass of moisture/mass of dry air
G	Dry air flow rate
E_1	Enthalpy of inlet air
D	Mass flow rate of woodchip dry basis
X_m	Moisture content of woodchip dry basis
E_w	Enthalpy of woodchip
A_1	Outlet air flow rate out of exhaust
E_2	Enthalpy of exhaust air out
G_a	Ash flow rate out of exhaust
E_a	Enthalpy of ash from exhaust

Assume complete combustion and basis of 1kg of woodchip

Combustion reaction gives:



Energy balance expression shows that:

Total inlet air flow rate + mass flow rate of woodchip (1+ moisture content of woodchip) = outlet air flow rate from the exhaust + ash flow rate from exhaust.

$$A_o + D (1+X_m) = A_1 + G_a \dots \dots \dots \text{equation 5}$$

The energy balance can be written in terms of the enthalpy balance as shown in the expression below:

Dry air flow rate. Enthalpy of air inlet + Mass flow rate of woodchip. Enthalpy of woodchip = flow rate of air in exhaust. Enthalpy of exhaust air + ash flow rate in exhaust. Enthalpy of ash in exhaust + heat lost in the exhaust.

$$G. E_1 + D. E_w = A_1. E_2 + G_a. E_a + Q_{\text{losses}} \dots \dots \dots \text{equation 6.}$$

3.1.1 Calculation of losses in P2 boiler

The acceptance analysis test from Skien Fjernvarme district heating burner for P2 with 6MW boiler shows that carbon has a composition of 51.1% dry basis, hydrogen has 6.2% dry basis, moisture content (X_m) = 48.5%, heat content = 19.539MJ/kg, temperature of moisture = 105°C, ash formation temperature = 550°C.

From engineering toolbox, $C_{pH_2O} = 2.3\text{kJ/kgk}$, $C_{pO_2} = 0.95\text{kJ/kgk}$, $C_{pash} = 0.84\text{kJ/kgk}$, $C_{pN_2} = 1.05\text{kJ/kgk}$, $C_{pCO_2} = 1.03\text{kJ/kgk}$.

The mass of carbon per kg of dry woodchip = 0.511kg/kg dry woodchip

Mass of hydrogen per kg of dry woodchip = 0.062kg/kg dry woodchip.

Moles of carbon = $0.511/12 = 0.043\text{kg/kmol}$.

Moles of hydrogen = $0.062/1 = 0.062\text{kg/kmol}$

From the combustion reaction above,

mass of CO_2 produced per kg of woodchip dry basis = $0.511/12*44 = 1.874\text{kg/kg woodchip}$

mass of H_2O produced per kg of dry woodchip = $0.062/2*18 = 0.558\text{kgH}_2\text{O/kg woodchip}$

mass of O_2 required for complete combustion considering reaction with carbon
= $0.511/12*32 = 1.363\text{kg}$

Mass of O_2 required for complete combustion considering reaction with hydrogen
= $0.062/4*32 = 0.496\text{kg}$

Oxygen (theoretical) required for complete combustion of 1kg dry woodchip
= $1.363 + 0.496 = 1.86\text{kg}$.

From the test analysis, mass of oxygen available in 1kg of dry woodchip = 0.42kg.

Oxygen required for complete combustion of 1kg dry woodchip = $1.86-0.42 = 1.44\text{kg}$.

Theoretical air required for complete combustion of 1kg dry woodchip = $1.44*100/21 = 6.86\text{kg}$.

$$\%excess\ air\ (x) = \frac{\%O_2}{20.9-\%O_2} \times 100 \dots\dots\dots\text{equation 7}$$

Where $\%O_2$ = percentage oxygen in flue gas (non-reacted oxygen)

From the analysis test result $\%O_2 = 6\%$

$\%excess\ air\ (x) = 40.3\%$

$$\text{Dry air flow rate (G)} = \frac{(100+x) \times 6.86}{100} = 9.62\text{kg}$$

Water vapour in air at 20°C (room temperature) = 0.01466kgwater/kg air (Engineering tool box).

Total inlet air (Ao) = $(1+0.01466)*(9.62) = 9.76\text{kg}$

Moisture content in flue gas = moisture from air + moisture from wood + moisture in H₂O produced = $G \cdot (0.01466) + D \cdot X_m + 0.558 = 1.18 \text{ kg}$

Oxygen in flue gas (exhaust) = oxygen required for combustion – oxygen consumed
 $9.62(0.21) - 1.44 = 0.58 \text{ kg}$

Nitrogen in flue gas = dry air flow rate . % of nitrogen in air = $9.62(0.78) = 7.5 \text{ kg}$

CO₂ in flue gas = dry air flow rate . % of CO₂ in air + mass of CO₂ produced
 $= 9.62(0.00039) + 1.874 = 1.88 \text{ kg}$

Mass of ash in flue gas = dry air flow rate . % ash in air = $9.62(0.0093) = 0.089 \text{ kg}$

A₁ (outlet air flow rate in exhaust) = H₂O in flue gas + CO₂ in flue gas + O₂ in flue gas + N₂ in flue gas + ash in flue gas = 11.23 kg

From equation 5, the mass of ash in exhaust for 1kg of dry woodchip

$G_a = 0.015 \text{ kg}$

Enthalpy of air (E₁) = 76.9 kJ/kg (Engineering toolbox)

Enthalpy of exhausted ash (E_a) = $C_{p_{\text{ash}}} \cdot \text{temperature of ash}$

$C_{p_{\text{ash}}} = 0.84 \text{ kJ/kgk}$ (Engineering tool box)

$E_a = 691.45 \text{ kJ/kg}$

$E_2 = C_{p_{\text{flue gas}}} \cdot T_{\text{flue gas}}$

$C_{p_{\text{flue gas}}} = \frac{\text{mass of H}_2\text{O} \cdot C_{p_{\text{H}_2\text{O}}} + \text{mass of O}_2 \cdot C_{p_{\text{O}_2}} + \text{mass of ash} \cdot C_{p_{\text{ash}}} + \text{mass of N}_2 \cdot C_{p_{\text{N}_2}} + \text{mass of CO}_2 \cdot C_{p_{\text{CO}_2}} \dots}{\text{mass of H}_2\text{O} + \text{mass of O}_2 + \text{mass of ash} + \text{mass of N}_2 + \text{mass of CO}_2}$

equation 8

$C_{p_{\text{flue gas}}} = 1.17 \text{ kJ/kgk}$

$E_2 = 442.44 \text{ kJ/kg}$

$E_w = 19539 \text{ kJ/kg}$ (gotten from analysis test)

From equation 6 above, Q (heat losses) = 15299.8 kJ

Data for this calculations are gotten from the acceptance test result from Skien Fjernvarme AS, engineering toolbox and from combustion textbook (Sara McAllister, 2011).

3.2 Analysis of combustion process in woodchips

The heating of dried wood chip or peat in inert atmosphere involves the evolution of gases.

The residue produced is called char; the overall reaction process is termed as pyrolysis.

Shafizedeh, 1976 studied the chemistry behind pyrolysis and combustion of wood. His studies show that wood contains cellulose, lignin and hemicellulose. In his studies, hemicellulose decomposes first, cellulose combust in a mild temperature level while lignin decomposes in a

broad temperature and it is the major determinant in char formation. Combustion analysis improves woodchip economy, reduce unwanted exhaust emissions and improve the safety of burning woodchip. It involves the measurement of the concentration of gases, boiler temperature and pressure (combustion analysis, 2004). The major parameters that are considered in analysis of combustion process in woodchip are discussed below:

- **Oxygen:** The combustion of woodchips in a burner involves the reaction of oxygen in air with carbon and hydrogen in the woodchips. If this reaction undergoes complete combustion which is not always the case, the product gives carbon dioxide, water vapor, nitrogen and heat. When more air is applied than needed for combustion, oxygen will be part of the products in the exhaust. These extra air is called excess air (combustion analysis, 2004). The reverse of this case generate carbon monoxide. This is when the air applied is not enough for combustion processes. To save money and more efficient use of woodchip and boiler, carbon dioxide concentration in the exhaust should be maximize as moderate as possible. This is when the oxygen in the air is just enough to combust the woodchip. The air can be stoichiometric or theoretical and excess air. When the air required for combustion falls below the stoichiometric amount, some woodchips are not completely burn and this generate smokes, also produce waste deposits in the burner (Sara McAllister, 2011). Combustion analysis is the primary factor for checking boiler efficiency.

3.3 Estimation of effective heating value of woodchip

The heating value of wood and bark fuels depends on the density, moisture and the wood extractives. Soft wood has a higher heating value than the hard wood. This can be view from the fact that soft wood contain more extractives than the hardwood which contain lesser extractives. The analysis of wood or bark fuel is considered by considering their heating value differences, the moisture content, as well as the density energy of the wood. The effective heating value of woodchip can be estimated by calculating the theoretical maximum thermal value (the higher heating value) of the wood and also calculating the heat losses from furnace combustion. The latter are caused by excess air into the furnace, heat losses in burning hydrogen and heat loss in wood moisture.

3.3.1 Heat loss caused by hydrogen

Wood contains hydrogen, oven dried wood contains about 60g of hydrogen (Peter, 1977). The combustion of wood result in hydrogen combining with oxygen to form water vapor. Water in weight contains 8 parts of oxygen and 1 part of hydrogen. In total, the water vapor formed

from combustion of hydrogen is around 540g. The heat formed in this case is lost in the flue gas chimney.

3.3.2 Heat loss caused by excess air and dry gas

Heat lost in combustion of dry gases is as a result of the high temperature leaving the furnace. Excess air that also enters the furnace and leave through the chimney also contribute to these losses. On an average, dried skien Fjernvarme woodchip contain 50% carbon, 41% oxygen, 6% hydrogen, 0.5% ash and 0.2% nitrogen. Oxygen in air combines with hydrogen to form carbon (IV) oxide and water. Dry gases from combustion of 1kg of oven dried wood chip and theoretical air are approximately 4.64kg nitrogen and 1.83kg carbon (IV) oxide (Peter, 1977).

3.3.3 Estimation of HHV of Skien Fjernvarme woodchip boiler

The higher heating value is the heat of combustion calculated with the assumption that all the water in the product has been condensed to liquid. The higher heating value of Skien Fjernvarme is determine from the analysis of the acceptance test carried out and the use of equation 4 proposed by Gaur and Reed, 1995. From the acceptance test, the percentage mass of various elements found in the woodchip are given in the appendix 4. The HHV from these values are 20.77MJ/kg for P2 boiler and 20.4MJ/kg for P1 boiler.

3.4 Quality of woodchip

The quality of woodchip shows the durability and efficiency of the woodchip to heat production. There are various categories and factors that determine the qualities of woodchip. The quality of woodchips range from its size, moisture content, the tree species, ash content in the wood, bulk density, energy density ,the level of dust and fungal spores in the woodchips.

3.4.1 The size distribution

This is important parameters in determining the quality of woodchip. The size of woodchips requires depends on the boilers. Sizes of 25-35mm are required for a boiler larger than 1MW. ISCEN standard classifies chips as P16, P45, P63 and P100. Test carried out over time have shown that the classes above do not cover the correct size spectrum. In general, the size of woodchips particles depends greatly on the capacity of the boilers.

3.4.2 Moisture content of woodchip

The moisture content in a woodchip is the percentage of water in the wood. Moisture contents in woodchip are expressed in dry and wet basis. Moisture content in dry basis shows the ratio of mass of water present to the dry oven mass of wood.

$$M_{contentdry\%} = \frac{M_{wet} - M_{dry\ wood}}{M_{dry\ wood}} \times 100 \dots \dots \dots \text{equation 7}$$

$$M_{content\ wet\%} = \frac{M_{wet} - M_{dry\ wood}}{M_w} \times 100 \dots \dots \dots \text{equation 8}$$

(Valter Francescato et al, 2008).

Fresh wood may contain between 22 to 55% water (% wt. of total material basis) and may contain up to 65% moisture. Moisture content influences significantly the heating value of woodchips, the ignition properties, and the efficiency of woodchips (David Tillman, 1978). The moisture content of woodchip used in skien Fjernvarme heating system is between 45-50%. Freshly cut wood has higher moisture content compare to wood that has been cut for long period. Higher moisture content is not so good for wood fuel heating, also lower moisture content can also have negative impact in woodchip burning. If a wood is very dry, it burns faster and gives out heat more than the supply of air into the burner. This can lead to higher emissions and overheating. (Rick 2011). Sylvain Volpe et al, 2011 studied the impact of moisture content on boiler efficiency and came up with a graph showing the efficiency and the moisture content as shown in figure 6 below.

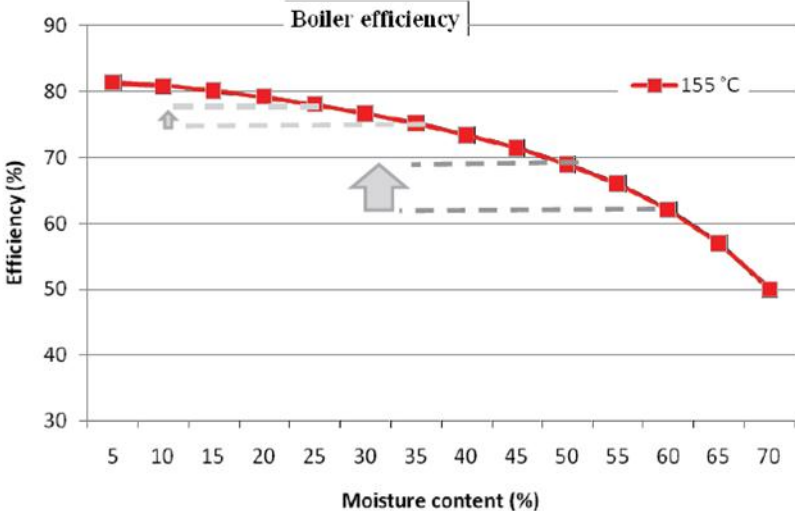


Figure 6: Impact of moisture content on boiler efficiency. Source: Heavy consequences of moisture content on biomass for energy (Sylvain Volpe et al, 2011).

Woodchips with higher moisture content have a great negative impact in producing heat. Higher moisture content has a cooling effect on the combustion gases making it difficult to

burn; micro-organisms could easily penetrate wood with higher moisture content. To maximize heating efficiency and reduce low emissions and combustion, woodchip should be properly dried.

There are different ways to dry woodchip. These could be through moisture sampling checking and splitting, wind- air speed drying, and ventilation drying. Moisture meter is use to determine moisture content in woodchip. A test was carried out to determine the moisture content of Skien Fjervarme pine wood chip using moisture sampling.

- Moisture sampling

Some woodchip samples were taken and the weight of the samples was recorded. The samples were dried in an oven to a temperature of 110°C for 24hrs. The water lost was recorded. This analysis was carried out for different woodchip samples. An average of 46% moisture content was gotten on a dry basis.

3.4.3 Bulk density

There are two major factors that affect the calorific value of a wood chip, the bulk density and the moisture content of the wood. Woods are categories as hard woods and soft woods. Hardwoods (deciduous broadleaved tree species) are denser than softwoods (evergreen, coniferous species). Density of woodchip could be dry fresh density or dry density. Dry fresh density of woodchip is the ratio of dry mass of woodchip to its fresh volume. Dry density of woodchip is greater than fresh density in that volume of fresh wood is higher than the volume of dry wood. Density of woodchip is considered by taking into consideration the swelling and shrinking factor of the woodchip.

Table 5: density of different wood chips

Wood species	Dry fresh density of wood [kg/m ³]	Dry density of woodchip [kg/m ³]
Birch	490	574
Aspen	375	423
Alder	400	455
Pine	405	461
Spruce	395	448

The density of wood varies widely in different species as illustrated in the table above. The greater the proportion of cell walls in plant, the greater the density. Late wood has a higher density than early wood. Klemm, 1958, reported that spruce growing in the northern hemisphere has a density of 415kg/m^3 , while balsam fir has density of around 340 kg/m^3 . Johal et al, 2006 measure the density of black, red and white spruce in the range of 317 to 406kg/m^3 and balsam fir in the range of 298 to 336 kg/m^3 . Many factors like tree age, storage, latitude, altitude, seasonal variation etc. can affect the density of wood. Brill, 1985 found that spruce in northern Norway have a significant lower density than the spruce in the southern part of the country. Difference in basic density of wood could result in variation of woodchip specific energy. Low density woodchip of balsam fir has a considerable less energy than high density of spruces.

3.4.4 Ash content

Ash in wood comes from the minerals present in the trees shrubs and the soil contamination. The properties of wood ash depends on many factors like the type of tree, the bark, leaves, combination with other fuel, type of soil and climate, the combustion condition etc. Ash contained in wood comes primarily from soil and sand absorbed in the bark of the wood. Some proportions come from absorbed salt during the period of growth of the tree. Ash also contains heavy metals. These heavy metals in ash can cause undesirable environmental effect. One main characteristics of ash is its ability to conserve heat (Gary et al, 2013). Wood contains some salt which are important in its combustion processes. These salts are sodium and majorly potassium. These salts result in sticky ashes which are deposited at the furnace. The ash content in wood varies depending on the bark in the wood. Ashes are formed in the process of combustion of woodchip in a burner. Temperature has a great effect in ash formation. The higher the temperature, the lower the yield of ash (Valter Francescato et al, 2008). Ash content in wood burning can be characterize has bottom ash and fly ash. The bottom ash as the name implies are deposited at the boiler grate and can be passed into the storage tank. The ash formed from flue gas is the fly ash. These ashes can be capture with a cyclone, electrostatic precipitator and a bag filter depending on the particles size (Valter Francescato et al, 2008). The device used in capturing ash in a district heater in Skien Fjernvarme is an electrostatic precipitator.

3.5 Effect of soot on woodchip boiler efficiency

Soot is impure carbon particles that result from incomplete combustion of hydrocarbons (Wikipedia, 2013). During incomplete combustion of woodchips, unburn carbon particles are

deposited in the form of soot in the boiler tubes. This deposit is called fouling and it reduces the heat transfer efficiency of a boiler. Tests have shown that soot layer of 0.8mm thick reduces heat transfer by 9.5% and soot thickness of 4.5mm reduces the heat transfer by 69%. (Bhatia, 2009). The stack temperature rises as the layer of soot increases. In fact, the stack temperature rises by about 38°C for 1mm thick layer of soot. This reduces the boiler efficiency greatly. The efficiency of a boiler is reduced by 1% for every 4°C rise in stack temperature (Bhatia, 2009).

3.6 Losses in combustion of woodchip

Losses in combustion of woodchip in a district heating systems are caused by waste heat leaving the chimney, incomplete combustion and losses from the exterior surfaces of the boiler. These losses affect the efficiency of the boiler and account to about 30% of the woodchip input (Bhatia, 2009). There are ways to minimize the stack gas heat losses. These could be through the reduction of the excess air in the combustion chamber, keeping the heat transfer surfaces clean and adding flue gas heat recovery equipment. As a rule of thumb, the boiler efficiency increases with about 1% for each 15% reduction in excess air, 1.3% reduction in oxygen and 4°C reduction in stack gas temperature.

Woodchip combustion losses could also be due to moisture from combustion of hydrogen, losses in the dry flue gas and radiation and convective losses. The air temperature can be increase by preheating the surrounding air. Combustion losses can be minimizing by operating the boiler at a full load.

3.6.1 Losses caused by evaporation of moisture from density and moisture content

The density and moisture content in wood have a significant role in determining the losses due to the evaporation from combustion of the woodchip. The density of woodchip is the ratio of the mass of the woodchip to the volume it contains. Moisture content in wood is the amount of water present in it at a particular point in time. The moisture in woodchip lowers the heating value and decreases the efficiency of the boiler, thereby increasing the gaseous emission. The losses caused by evaporation of moisture from combustion of woodchip in skien fjernvarme district heating system can be analyzed as:

The density of pine woodchip is 384kg/m³ (gotten from density sampling); the moisture content is 46% (moisture sampling). Shrinkage occurs in wood when it begins to lose its water. This shrinking factor is around 11.5 to 12.5% for pine wood (Valter et al, 2008). In reverse, if the saturation water in wood increases, the wood will swell. The compactness

factor of the loose woodchips is between 0.36 to 0.46 (Rondeel Wilhelm, 2013). This factor depends on the size, shape and the species of the wood. The analysis of the losses due to evaporation of moisture from density and moisture is expressed thus:

Wet fresh density of pine chip with no shrinkage is $384(1-12\%) = 338\text{kg/m}^3$

Wet density of pine chip = $338 / (1-46\%) = 626\text{kg/m}^3$, density of wet loose woodchips = $626 * 0.44 = 275.4\text{kg/m}^3$. Evaporation energy for 1kg of water = 0.68kWh/kg (Rondeel Wilhelm, 2013)

Loss by evaporation of moisture = $257\text{kg/m}^3 * 0.68\text{kWh/kg} * 46\% = 80.4\text{kWh/m}^3$.

The energy content of woodchip = 19.539MJ/kg dry basis (from acceptance test) = 5.43kWh/kg ., Assume degradation factor of 1, the net heating value of 1m^3 loose woodchip after storage = $1 * 275.4\text{kg/m}^3 * ((1-0.46) * 5.43\text{kWh/kg} - (275.4\text{kg/m}^3 * 0.68\text{kWh/kg} * 0.46)) = 722\text{kWh/m}^3$.

Wood chip supply for month of December = 2350 loose m^3 (generate 1450MWh of heat). If all these are utilized, the net heating value = $722\text{kWh/m}^3 * 2350\text{m}^3 = 1698\text{MWh}$.

Woodchip supply for month of January = 3900 lm^3 (produce 2730MWh of heat). The net heating value if all the woodchip are utilized = 2816MWh , for month of February, 3100 lm^3 of woodchip was supplied (generate 2182MWh) the net heating value for this month assume all these woodchip are utilized = 2238MWh and for the month of March, 3905 lm^3 (generate 2279MWh of heat) of woodchip was supplied, the net heat produced for this month is 2819MWh .

3.7 Thermal efficiency of Skien Fjernvarme district boiler system

The thermal efficiency of a district heating boiler denotes how well and effective the boiler transfer heat. Combustion efficiency shows the ability of the boiler to undergo a complete combustion without producing carbon monoxide. There are several methods used to determine the efficiency of a district heating burner. In this project, the thermal efficiency of skien fjernvarme district heater (6MW) is evaluated based on some considerations. These factors are:

The heat content of the woodchip: This is termed as the calorific value of the woodchip. This can be the HHV or LHV which was discussed in chapter two. In this case, HHV is used in the efficiency calculation.

Burner stack temperature: The burner stack temperature is the temperature of gases at the chimney of the burner. This temperature indicates the most part of the energy not converted to useful products. This stack temperature is a good efficiency determinant. If the burner stack

temperature is high, the thermal boiler efficiency will be small and it indicates that less energy is transferred to form the products. It is also called the flue gas temperature.

Combustion supply air temperature: This is also the ambient air temperature. It is the surrounding temperature of the boiler. This temperature does not take into account the humidity in the air, the wind and the evaporation of the surrounding water.

Excess air: To ensure complete combustion of the woodchips, the boiler is supplied with excess air. Excess air increases the amount of oxygen. The combustion efficiency will increase with increased excess air. Excess air is the additional air supplied beyond the stoichiometric air needed for combustion (Sara McAllister, 2011).

Fuel specification: The fuel mostly used in skien fjernvarme district heating system is soft pine woodchips, with moisture content between 47%- 50%. The type of fuel specified for combustion process has a significant effect on the efficiency. This is because every fuel has a distinct composition and energy content.

Generally, boiler efficiency is determined by considering the overall input into the boiler and the output into it. Efficiency in this case is expressed as:

$$efficiency (n)\% = \frac{energy\ output}{energy\ input} \times 100 \dots \dots \dots equation\ 7$$

This method of expressing efficiency is the direct method. This method of thermal efficiency takes into account the energy content of the woodchips and the energy out of the burner. Direct method of estimating efficiency requires measuring meters to evaluate steam flow, air flow and woodchips flow rate in the burner. This method is not accurate due to some errors that may be encountered in the parameters measurement (Bhatia, 2009). The other method of calculating the thermal efficiency of a district heating boiler is the indirect method. This method involves the consideration of combustion process of woodchips. Indirect method of estimating thermal efficiency entails the evaluation of the flue gas temperature, ambient temperature, moisture of the woodchips, losses in the burner and from the chimney. Indirect method of estimating thermal efficiency is shown in equation 8 below

$$\%efficiency = 100 - \frac{flue\ heat\ losses}{fuel\ heating\ value} \times 100 \dots \dots \dots equation\ 8$$

(Combustion analysis basic, 2004).

3.7.1 Efficiency calculation of Skien Fjernvarme P2 (6MW) burner

The results of the acceptance test show that:

CO₂ concentration of the woodchip in dry basis = 14.4%

O₂ concentration in the woodchip in dry basis = 6%

N₂ concentration in the woodchip in dry basis = 79.6%

Carbon content in the woodchip dry basis = 51.1%

Sulphur content in the woodchip dry basis = 0.014%

Hydrogen content of woodchip dry basis = 6.2%

Higher heating value (HHV) = 19.539MJ/kg = 8396.65Btu/lb

T_{flue} (flue gas temperature) = 158°C = 316.4F

T_{air} (temperature of supply air) = -5°C = 23F

The heat losses in flue from equation 7 are from- heat lost in dry products of combustion of woodchips, heat lost due to burning hydrogen, heat lost as a result of moisture in fuel, heat lost due to radiation and convection.

- Heat lost in dry woodchip

When a wood undergoes combustion in a chamber, heat is lost in the dry products of combustion. The heat lost due to dry gas is given in equation 9 below:

$$\% \text{ heat lost due to dry gas} = \frac{43.2 \times dg \times (T_{flue} - T_{air})}{HHV} \dots \dots \dots \text{equation 9}$$

Where dg is the weight of dry gas given as:

$$dg = \frac{(11CO_2+8O_2+7N_2)(C+0.375S)}{3CO_2} \dots \dots \dots \text{equation 10 (Bhatia, 2009).}$$

Substituting the values from the acceptance test into the above,

$$dg = 9.03lb$$

$$\% \text{ heat lost due to dry gas} = 7.3\%.$$

- Heat lost due to moisture from combustion of hydrogen

The percentage heat lost due to moisture from combustion of hydrogen can be gotten by considering the enthalpy of water at the exhaust temperature and pressure and also the enthalpy of water at the saturated liquid. The percentage heat lost from combustion of hydrogen can be express as:

$$\% \text{ heat lost } (Ch) = \frac{900 \times H_2 \times (h_l - h_w)}{HHV} \dots \dots \dots \text{equation 11}$$

h_l = enthalpy of water at the exhaust temperature and pressure, h_w = enthalpy of water at saturated liquid.

$$h_l = 1055 + (0.467 \times T_{flue}) \dots \dots \dots \text{equation 12 (Bhatia, 2009)}$$

$$h_w = T_{air} - 32 \dots \dots \dots \text{equation 13.}$$

From these whole expression and considering the losses due to radiation and convection to be 1% (Bhatia, 2009). The thermal efficiency of Skien Fjernvarme district heating burner with capacity of 6MW is 85%.

4 Discussion and proposal

4.1 Discussion based on energy balance

Energy balance around a woodchip boiler is a way of accounting for the useful energy and losses in the boiler. The analysis of the energy balance of Skien Fjernvarme boiler was discussed in previous chapters. The energy balance can be summarized in a simple way as the boiler input energy equal to the energy used and the energy losses. The sources of heat into the boiler are woodchips (mostly pine), feed water and combustion air. The energy input from the woodchip is gotten by considering the components of the wood. Wood components vary according to the species of the wood. The most common wood species used in skien fjernvarme district heating system is pine with an energy content of 19MJ/kg to 20MJ/kg dry basis. The variation in the energy content of the woodchips depends mostly on the moisture content (between 45% to 50%) and the energy density of the woodchips. The feed water temperature also serves as energy input in the boiler. The combustion air which is one of the major inputs into the boiler is gotten from within the boiler plant. Energy input from the woodchips will reduce if the combustion air temperature is high.

The boiler uses energy to convert woodchips into a form that is suitable to transport heat energy throughout the network. Energy is lost from the boiler system and discharged through the stack. This energy is lost through flue gas, radiation and incomplete combustion. Heat lost in flue gas is through dry gas heat lost, losses from water vapor in combustion of hydrogen in the woodchips and losses from evaporation of moisture content in the woodchips. Flue gas heat losses are the highest losses in the boiler. Radiation and convection heat losses are due to the difference in temperature between the external surface of the boiler and its surrounding. Accurate measurement of these losses is complex; a convenient means to measure these losses is through the American boiler manufacturer's associations (ABMA) standard radiation loss chart. This can be view in the appendix 3. Insulation of the boiler surfaces reduces heat loss from the boiler. The insulation thickness and quality are determined by the boiler surface temperature. The energy balance analysis of skien fjernvarme district heating system shows that losses in the boiler increases as the total air supply decreased. This leads to incomplete combustion of the woodchips.

4.2 Discussion based on density and moisture content of woodchips

Density and moisture content have an important role to play in the analysis of woodchips, both during the storage process and in the combustion process. Many factors affect the density of wood. Some of the factors could be the wood species, cell wall, variation in seasons, storage, tree age etc. In this section, the storage factors are considered. When a wood is stored in a storage house, two major things happen. The first is that the woods become shrink through the loss of water and the density becomes reduced. Also, the wood can gain water from the condensation of hot air in the room and when this happen the wood get swell. Wood degrades if stored for long period. The degradation could be as a result of microorganism, it could be through wood shrinking or wood swell etc. The analysis in chapter 3.6.1 shows that the degradation factor of woodchip supply for month of December is 0.85 if all the wood chips supply is utilized. In the month of January and February, woodchips degrade by factor of 0.96 and 0.95 respectively during storage. The degradation factor for month of March from the analysis is 0.81. The best way to store wood for long time time is by storing in a whole shoot or by storing in large chunk. Wood chip can also be store in a store room that is airtight.

In the case of moisture, woodchips with higher moisture content has a lower heating value, this also reduce the boiler overall output and the efficiency.

4.3 Suggestion and proposal on future work

The task description in this project report is to study energy balance and thermal efficiency of one (or more) district heating systems in Skien, Bø, or Notodden. The boilers in these various heating systems are quite similar; the only different is their capacities. Therefore, this report is basically streamline on district heating system in Skien Fjernvarme with two boilers (6MW capacity each).

There are some factors which affect and have a greater impact in determining the net energy output and efficiency of a boiler which are not mentioned in the task description and are not well treated in this report. I suggest they are look into in future work. These factors are:

- Storage and degradation of woodchips
- The woodchip size distribution
- Effect of microorganisms on the woodchips
- Insulations of the steam distribution network to avoid excessive heat loss to the surrounding

- The woodchips should be in loose form rather than in compact form. This is in order to avoid convective heat loss from the wood.
- The wood size should be cut in line with the handling equipment in the boiler.

4.4 Control strategies to improve boiler performance

The efficiency of a boiler can be improved on by reducing the energy consumption in the boiler. Most of the boiler efficiency improvements are found after steam generation. Stable maintenance and operation must be the foremost in operating woodchips boilers. Boiler maintenance include making sure the physical components of the boiler are in good performance condition in accordance with the specification design. Boiler systems should be check before tune- ups.

Combustion process of woodchip is also of importance in improving boiler efficiency. A quick analysis is to check any defect in smoke, changes in flame, noise from the exhaust. The temperature of gases from the stack and concentration of the excess air consumed is a good strategy in checking boiler efficiency. Combustion process is essential in woodchip boiler since it is the major process in a boiler. A boiler is in good working condition if it burns the woodchips almost completely, when it uses minimal excess air in the burning process, also if it takes maximum heat energy from the combustion gases to transfer the product to steam. As a rule, the most cost effective and efficient burning of woodchip occur when the carbon dioxide concentration in the exhaust is maximized (Bhatia, 2009). The production of carbon monoxide in the exhaust indicates incomplete combustion and this indicate the consumption or utilization of minimal air in the boiler.

Oxygen generation in flue gas is also a good way to assess the operation of the boiler. Oxygen is present in the flue gas if excess air is utilized but its absence indicates deficient combustion air.

Another way to improve boiler efficiency is the treatment of the feed water in the boiler exchanger. The water could be treated in the boiler or outside the boiler. The purpose of the feed water treatment is to remove hardness in water and unwanted salts. This can be achieved by injecting some chemicals to soften the water. The boiler feed water consists of the condensate generated and the supply water. The condensate water is pure compare to the supply water. The boiler is efficient if the condensate water is more than the supply water. The operation of the boiler should be channel to recover almost all the condensate.

The boiler performs well if the dissolved water in the boiler is regularly removed. The rate of removing this water depends on the feed water and condensate water flow rate. As a rule, the rate of removing this dissolved water is around 8% of the boiler feed water flow rate (Bhatia, 2009).

4.5 Proposal on soot cleaning in boiler

Soot is formed in combustion process as a result of incomplete combustion. The soot generation should be minimized as low as possible to improve the boiler efficiency. The soot deposit at the heating surfaces in a boiler act as heat insulator. The result of this is that less heat is transferred to heat up water and more heat is wasted at the chimney. This leads to lower boiler efficiency, and higher woodchip consumption. Soot blower method is best techniques to remove soot on the heating surface of a boiler. These methods clean the surfaces of the boiler tubes during operation of the boiler. The soot deposits are blown out with the flue gases. In a better operation, they are trapped in a dust collector. Air, water or steam is used as a blowing medium in soot blower.

Other method of soot cleaning is the steam jet cleaner, compressed air soot cleaner and blasting. The steam jet soot cleaner utilized steam to clean the soot in the tube. This method consumes steam and the maintenance cost is expensive. The compressed air soot cleaner use compressed air which is expensive to purchase. The blast method involves the use of small steel ball. In this case, the boiler tubes must be able to withstand abrasion. This method gives a bad cleaning because some of the surfaces are left with soot.

5 Conclusion

Wood energy provides an alternative form of energy to fossil fuels. Combustion of woodchip is economical and cost effective compare to the burning of natural gas, oil and coal. District heating system is an optimal way of providing and selling heat to customers through pipeline networks. Combustion efficiency in woodchip is the conversion of effective energy in woodchip to useful energy. Factors like moisture content of wood, excess air, stack temperature must be considered in analyzing the combustion efficiency of woodchip in a boiler.

The energy balance in a woodchip boiler is determine from the analysis of the input, output and losses in the boiler. The boiler inputs are the woodchips, the feed water and the air from the surrounding. The losses are as a result of incomplete combustion, evaporation of moisture from combustion of woodchip, radiation and convection losses. The degradation of the woodchip during storage also constitute to the losses. The loss caused by moisture evaporation was calculated to be 80.4kWh/m^3 (analytical calculation). This is the major lost in the boiler.

The net heating value for 1m^3 loose woodchip was analyze and calculated to be 722kWh/m^3 . This result shows that the loss from moisture evaporation is around 9% of the overall heating value. The supply of woodchip for month of December when the operation started was 2350 loose m^3 (with generation of 1450MWh). The net heating value for this month from analysis is 1698MWh (degradation factor of 1). This shows that the real degradation ratio of the supplied woodchip for the month of December is 0.85. In the month of January, 3900 loose m^3 of woodchips was supplied (produce 2730MWh). From calculation, the net heat generated was 2816MWh . The woodchip supply in February and March was 3100 lm^3 (2182MWh) and 3905 lm^3 (2279MWh) respectively. The net heat productions in these months are 2238MWh and 2819MWh respectively.

From combustion analysis, the thermal efficiency of the boiler is 85%. This indicates that the boiler is in proper working condition.

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Appendices

Appendix 1 Task description



Telemark University College
Faculty of Technology

FMH606 Master's Thesis

Title: “District heating bio fuel burner efficiency and energy balance”

TUC supervisor: Prof. Wilhelm Rondeel, TUC

External partners: Gaute Finstad, AT Biovarme AS

Task description:

Based on data for a number of relevant parameters, an energy balance and the thermal efficiency for one (or more) district heating bio fuelled heat source(s) shall be estimated. Measurements may be carried out at heat centrals at Thermokraft AS, Notodden (with power capacity 4.7 MW), Skien Fjernvarme AS in Skien (with power capacity 2*6 MW), and possibly also at a smaller installation at Bø (Bø Fjernvarme AS – power capacity 1.5 MW).

A literature survey in the topic, such as district heating essentials, bio fuel combustions processes, specific energy content of bio fuels depending on quality and moisture content, etc. will be part of the task.

Ingoing fuel volumes, outgoing net energy supply to the heating system (hot water) and heat loss through chimney hot exhaust gases and other heat losses, will have to be measured or estimated.

Exploring the influence on the combustion process from changes in the quality of the fuel (wood chips of different origin and moisture content) and finding optimum control strategies for the burner to improve the performance when relatively large fluctuations in fuel quality is observed, is one of the main tasks.

In the heat exchanger, between the hot combustion gases and the circulating water to be heated, soot will accumulate and influence the efficiency. The effect of this on the heat exchange process shall be evaluated, and indication of optimum cleaning intervals proposed.

Task background:

Thermokraft AS is a district heating system supplying a number of larger customers in central parts of the town Notodden with heat. The annual heat delivery is about 15 GWh, expected to grow to near 20 GWh within some years.

Skien Fjernvarme AS supplies customers in the centre of Skien from a new bio fuel based burner north of the city centre. Expected total annual supply within a few years is expected to be about 50 GWh.

The installation at Bø has been in operation for a number of years, and the heat delivery is about 5 GWh annually.

The commercial transaction involved in the purchase of fuel for the operation of the

aforementioned installations is based on delivered net energy to the distribution system only. Consequently the weight, quality and moisture content of the wood chips will normally NOT be measured or registered. It is therefore of special importance for the commercial partners to have an estimate for the thermal efficiency of the plant. This may change with possible changes in the fuel quality.

Student category:

EET and PT students

Practical arrangements:

The selection of heat central(s) to be included in this study is still to be decided. Data sheets for the installation(s) will be available, as well as access to the installation(s). Much of the necessary instrumentation is permanently available at the installation(s), but extra temporary instrumentation may also prove necessary in order to obtain the necessary data.

As already indicated, finding a practical solution (temporary) for the assessment of fuel supply (relevant energy input) to the combustion process, may be a challenge.

Signatures:

Student (date and signature): Oluwashola Okoro

Supervisor (date and signature): Rondeel Wilhelm.

Appendix 2: Analysis of the energy balance and efficiency of skien fjernvarme district heating system

Data for 1 m ³ of average wood chip input to burner - example Pine			
Moisture content	46%	Calculation of energy content - dry basis	19.54 MJ/kg d.b.
"Oven dry" fresh density of pine	384 kg/m ³	Carbon content - % of dry matter	51.1%
Shrinking factor dry/wet wood	12%	Hydrogen content - % of dry matter	6.2%
"Wet" fresh density of pine - without shrinking	338 kg/m ³	Sulphur content - % dry matter	0.014%
Wet - "solid" - density of chips	626 kg/m ³	Nitrogen content - % dry matter	0.11%
Compactness of the loose wood chips	0.46 ratio	Oxygen content - % dry matter	42%
"Density" of loose wood chips, including moisture	288 kg/m ³	Ash content - % dry matter	0.5%
Evaporation energy of 1 kg water	0.68 kWh/kg	Total matter	99.92%
Degradation factor - due to storage	1-	Vapour volume and losses	
Energy content of DRY solid wood	5.43 kWh/kg	Water volume evaporated pr kg fuel	0.46 kg
Energy content of WET solid wood - <u>before</u> extracting the evaporation heat	2.93 kWh/kg	Losses from heating of water vapor	0.72 kWh/kg
Net energy content of WET solid wood - <u>after</u> extracting the evaporation heat	2.62 kWh/kg	Losses in flue stack and combustion efficiency - pr. unit of fuel	
Net heating value of 1 m³ loose wood chip after storage as chips for ? months	722 kWh/m³	CO2 max	19.1%
Calculation of losses - "Skien Fjernvarme"		O2 flue gas	6.2%
Loss by evaporation of moisture (included above!)	80.4 kWh/m ³	Actual CO2	13%
Flue gas temperature	165 °C	Excess air	42%
Outside temperature	-5 °C	Flue gas weight factor - Wg	9.64 lb
Energy net output	6000 kW	Flue gas weight factor - Wg	4.37 kg
Total flue gas volume - at 6 MW output	11700 m ³ /hour	Specific heat of flue gas - Cp	0.24 Btu/lb*F
Average specific heat - Cp (assuming N2 mostly)	0.23 Wh/m ³ *K	Specific heat of flue gas - Cp	0.28 Wh/kg/K
Fuel burn out factor, - ratio of wood chips totally burned out.	0.985	Flue gas dry losses pr. unit fuel	722 Btu/lb
Approximate energy loss by flue gas emission - at 46% moisture	456 kWh/hour	Flue gas dry losses pr. unit fuel	0.47 kWh/kg
Other losses - surroundings etc. - estimate?	120 kW/hour	Losses from H in DRY fuel - evaporation energy only	0.38 kWh/kg
Total output	6000 kWh	Gross - dry gas and hydrogen - combustion efficiency	0.85%
Combustion efficiency - excluding combustion ratio of chips - first approximation	91%	Degradation of fuel during storage	
Fuel demand with 46% moisture	2548 kg/hour	Degradation pr. year as chips - <u>uncovered</u>	25.00%
		Degradation pr. year as chips - covered	5.00%
		Degradation pr. year <u>uncovered</u> roundwood	2.75%
		Degradation pr. year covered roundwood	1.25%
		Storage period	0.3 years

Appendix 3: America boiler manufacturer association standard radiation loss chart (ABMA).

The lost due to radiation and convection is the heat lost to the surrounding from warm surfaces of the boiler. These lost account for up to 2 to 3% of the heat input. The actual measurement of this loss is complex and time consuming. The ABMA is a convenient way to measure this loss. ABMA works on the principle that the radiation and convection loss (L_R) is proportional to the external surface area of the heat unit. In this case, L_R is larger for small units of load. The actual loss depends on the load range. For full load operation, loss is low. The table below shows ABMA analysis on various percentages of heat input and losses.

*Table 6: Approximate radiation and convection losses L_R , and % heat input
Sources: Radiation and convection losses. Natural resources Canada.*

Max. output [million Btu]	100%	80%	60%	50%	40%	20%
10	1.60	2.00	2.67	3.20	4.00	8.00
20	1.05	1.31	1.75	2.10	2.62	5.25
30	0.84	1.05	1.40	1.68	2.10	4.20
40	0.73	0.91	1.22	1.46	1.82	3.65
50	0.66	0.82	1.10	1.32	1.65	3.30
60	0.62	0.78	1.03	1.24	1.55	3.10
70	0.59	0.74	0.98	1.18	1.48	2.95
80	0.56	0.70	0.93	1.12	1.40	2.80
90	0.54	0.68	0.90	1.08	1.35	2.70
100	0.52	0.65	0.87	1.04	1.30	2.60

Appendix 4a: Constituents of woodchips from Skien Fjernvarme Analysis test.

The following datas are gotten from the analysis test carried out in Skien Fjernvarme district boilers. The boilers are P1 and P2.

Table 7: constituents of P1 boiler

Wood constituents	percentage
Moisture content	45.3
Ash contents	0.7
Carbon dry basis	50.1
Hydrogen dry basis	6.1
Nitrogen dry basis	0.16
Oxygen dry basis	42.9
Sulphur dry basis	0.012

Energy content is 19.233MJ/kg.

Table 8: Constituents of P2 boiler

Wood constituents	percentage
Moisture content	48.5
Ash contents	0.5
Carbon dry basis	51.1
Hydrogen dry basis	6.2
Nitrogen dry basis	0.11
Oxygen dry basis	42.0
Sulphur dry basis	0.014

Energy content is 19.539MJ/kg.

Appendix 4b: Warranty test on Skien Fjernvarme district heater.

The table below shows the test carried out by Tomas Ekstrom KMP AB (19.03.2013) in Vastervik on behalf of Jernforsen energy systems AB. These test was conducted to affirm the warranty conditions on the boilers.

Table 9: Warranty condition on P1 boiler.

Sample point	Power output [kW]	Dust content [mg/m ³ ntg]	O ₂ % tg	CO [mg/m ³ ntg]	NO _x [mg/m ³ ntg]
25% test	2228	0.9	5.5	20	90
50% test	3268	1.5	4.9	4.9	86
100% test	4944	1.8	5.0	5.0	111

Table 10: Warranty condition on P2 boiler

Sample point	Power output [kW]	Dust content [mg/m ³ ntg]	O ₂ % tg	CO [mg/m ³ ntg]	NO _x [mg/m ³ ntg]
25% test	1500	1.1	7.4	<5	127
50% test	3176	1.3	5.5	60	124
100% test	4949	4.8	5.4	23	121