

Martti Härkönen



WOODBASED FUELS IN SMALL-SCALE REGIONAL HEATING PLANTS

C: CENTRIA TUTKIMUS JA KEHITYS

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FOREWORD

This biomass heating report is compiled as part of the joint Nordic countries EU-Bothnia-Atlantica funded Forest Power project and it explores wood fuels and especially the use of woodchips primarily in the small-scale regional heating plants of Central Ostrobothnia energy cooperatives. The Forest Power project's main coordinator is the Kannus unit of the Finnish Forest Research Institute (METLA). Other partners in Finland are CENTRIA, the research and development unit of the Central Ostrobothnia University of Applied Sciences, the Kannus unit of the Central Ostrobothnia Rural Institute, Central Ostrobothnia Forest Owners Association and, of course, the region's energy cooperatives. The ETPC unit at Umeå University in Sweden also actively participated in this project.

This report is based on field measurements conducted during the project at the Kälviä energy cooperative's woodchip heating plant and is CENTRIA's most visible project outcome. The following individuals participated as researchers in the field measurements: Kari Manninen, project engineer, Anu-Sisko Perttunen, project officer, Martti Härkönen, principal lecturer, Lasse Jansson, director, research and development CENTRIA, Pentti Etelämäki, Central Ostrobothnia Forest Owners Association, Heikki Kykyri and Perttu Suonperä, Kälviä energy cooperative. The following were project members: Dan Boström, Christoffer Boman, Jonathan Fagerström, Markus Broström and Rainer Backman of Umeå University's ETPC unit. Martti Härkönen was responsible for the further analysis of the measurement results and report writing.

Kokkolassa 5.1.2012

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1. INTRODUCTION

1.1 General

This woodchip heating report has been compiled as part of the joint Nordic countries' EU-Bothnia-Atlantica funded Forest Power project (FP project) and examines the use of wood and especially woodchips as a fuel in the small-scale regional heating plants of energy cooperatives in the Central Ostrobothnia region. The main coordinator of the FP project has been the Kannus unit of the Finnish Forest Research Institute (METLA). Other partners in Finland include CENTRIA, the Central Ostrobothnia University of Applied Sciences' research and development unit, the Kannus unit of the Central Ostrobothnia Rural Institute, the Central Ostrobothnia Forest Owners Association and, of course, regional energy cooperatives. The ETPC unit of Umeå University also actively participated in this research. The unit was responsible for ascertaining flue gas particle emission, conducting ash and slag analyses and drawing conclusions.

The report is not merely a wood fuel use manual, but aims to provide forest owners and other users of forest energy or those with an interest in this area information as clearly and diversely as possible to facilitate utilisation of forest energy.

A so-called 20-20-20 commitment exists at EU level. This means, among other things, that by the year 2020 renewable energy will constitute 20% of total energy consumption within the EU. Commitments differ from one country to another, and for example, the goal for Finland is to raise the share of renewable energy in final energy use from 28,5% to 38% by 2020. One of the most important means to achieve this goal is increasing the use of forest processed chips from the current approximately 12 TWh/a level to at least double or treble this to approximately 25–40 TWh/a. One million solid m³ of wood is equivalent to about 2 TWh of energy, thus the goal in 2020 is to burn approximately 13–20 million solid m³ of wood in various heating and power plants.

<http://www.tem.fi/index.phtml?s=2070>.

1.2 Woodchip heating plants of Central Ostrobothnian energy cooperatives

The use of wood as a fuel in small-scale under 2 MW heating plants in the Central Ostrobothnia region is examined in this CENTRIA led sub-project. The examined heating plants are primarily energy cooperative owned or maintained woodchip facilities. Typically, the cooperative is responsible for procurement of fuel (wood), use and maintenance of the heating plant, and heat distribution to consumers. Consumers are typically large properties owned by the municipality, such as office blocks, schools, nursing homes and other public buildings.

Seven energy cooperatives and one woodchip cooperative operate in the Central Ostrobothnia region. The cooperatives are responsible for six woodchip heating plants in total. Additionally, there is one small-scale CHP plant based

on wood gasification. Each heating plant was visited and the staff and cooperative managers were interviewed. The woodchip heating plants examined in this project have a nominal boiler capacity of 0.12–2.0 MW and consume a total of about 27000 loose-m³/a woodchips, generating approximately 17 GWh/a of thermal energy.

Table 1.1 summarises the heating plants. It also gives information on two cooperative form peat heating plants (Kaustinen and Veteli). Separate "data cards", which give a summary of each energy cooperative and the heating plants under their responsibility, have been compiled for each heating plant. For more details, see: <http://www.forestpower.net/Bulletin.aspx?bid=1660&main=1>.



Figure 1.1. Energy and woodchip cooperative heating plants in Central Ostrobothnia.

Laitos	Vuosi	Nimellisteho	Hakkeen ja palaturpeen käyttö	Tuotettu lämpö
Perho	1994	1400 kW	hake 8000 i-m ³ /a turve 1000 i-m ³ /a	5500 MWh/a
Eskola	2001	120 kW	hake 600 i-m ³ /a	420 MWh/a
Lohtaja	2002	300 kW	hake 1200 i-m ³ /a	750 MWh/a
Halsua	2003	700 kW	hake 3500 i-m ³ /a	2600 MWh/a
Kälviä 1	2003	2000 kW	hake 14000 i-m ³ /a	8000 MWh/a
Kälviä 2	2006	2000 kW	(yhteensä)	(yhteensä)
Veteli (osakeyhtiö)	2008	1500 kW	hake + puubriketti yhteensä 1900 i-m ³ /a turve 1000 t/a	3870 MWh/a
Kaustinen 1	1999	2000 kW	turve 15000 i-m ³ /a	16600 MWh/a
Kaustinen 2 (osakeyhtiö)	2004	2000 kW	hake 1000 i-m ³ /a	
YHTEENSÄ		6,52 MW (EOK)	hake 27000 i-m³/a	16-17 GWh/a

Table 1.1. Woodchip heating plants in the Central Ostrobothnian region under the responsibility of energy cooperatives (+ two cooperative form peat plants that also use some woodchips).

The 2.0 MW heating plant (Kälviä 1) managed by the Kälviä energy cooperative was selected for more detailed analysis. The objective was to ascertain the plant's gaseous and solid emissions, the characteristics of the produced ash and slag, and the woodchip boiler's operating efficiency. Measurements were taken in several stages from autumn 2009 to spring 2011 at partial and full loads and with feedstock of various quality and composition.

2. WOOD AND WOODCHIP CHARACTERISTICS

2.1 General

The energy content per unit volume (kWh/i-m³) of wood and woodchips depends on several factors, of which the most important are moisture, tree species, and woodchip pile density. Moisture is the single most significant factor, and its effect is seen in that the moister the wood to be burnt is, the more the bound water in the chips needs to be vaporised in the boiler. This in turn reduces the true heat energy generated by wood as it burns. Woodchip pile density refers to the proportion of wood in a loose cubic metre and depends on, for example, the chipping technique used. The effect of the feedstock is seen, for example, in the dry solid matter's caloric value (MJ/kg ka.) and dry-green density (kg ka./m³). The dry matter caloric value of coniferous trees is slightly higher than that of deciduous trees, and of the most common tree species, birch is the heaviest and spruce the lightest.



Figure 2.1. How much energy is there in a chip pile delivered to a heating plant from the supplier's and chip utiliser's perspective? Photo: Martti Härkönen

2.2 Moisture content of wood

Wood is hygroscopic matter, that is, it can absorb substantial quantities of water, clearly larger amounts than the wood's own dry mass. Moisture content can be defined in two ways: either by comparing water quantity in the tree to the wood's dry mass -> moisture ratio $U = m_{\text{water}}/m_{\text{dm}}$. or by comparing water quantity to the wood's total mass -> moisture content $X = m_{\text{water}}/m_{\text{tot}}$. Often moisture content X expresses water quantity in the wood, but for example in drying calculations the moisture ratio U concept must also be understood.

The interrelation between moisture ratio U and moisture content X is

$$X = \frac{U}{U+1} \quad \text{or} \quad U = \frac{X}{1-X} \quad (1)$$

Moisture content X is always less than 1 (or less than 100%), while moisture ratio U can also be greater than 1. It is important not to mix these two different ways of expressing moisture together.

Example 1: Total mass, i.e. green mass, of wood is 50 kg and moisture content is measured at $X = 40\%$. Therefore the wood contains $m_{\text{water}} = X m_{\text{tot}} = 0.40 \cdot 50 = 20$ kg water and the remainder is dry waterless wood, i.e. $50 - 20 = 30$ kg. Thus the moisture ratio is $U = 20/30 = 0.667$ kg water per kg dry wood. Moisture ratio U is derived using formula (1), i.e. $U = 0.40/(1 - 0.40) = 0.667$ (i.e. 66.7 %)

Example 2: Moisture content of an unseasoned pine log is $X = 55\%$. Its moisture ratio according to formula (1) is $U = 0.55/(1 - 0.55) = 1.22$ (122%). The log contains 1.22 kg water per kg dry wood, i.e. the log contains more water than dry wood. This makes the log very heavy and it may even sink in water (sunken logs).

Drying calculations often require water quantity to be removed from wood or chips when the green wood's initial mass m_1 , initial moisture content X_1 and target final moisture content X_2 are known. The following formula expresses the quantity of water to be removed:

$$\Delta m_{\text{water}} = m_1 \left[X_1 - X_2 \frac{(1 - X_1)}{(1 - X_2)} \right] \quad (2)$$

Example 3: Dry 100 kg of green wood from initial moisture content $X_1 = 40\%$ to final moisture content $X_2 = 15\%$. How much water needs to be removed? Insert directly into formula (2) $\rightarrow \Delta m_{\text{vesi}} = 100[0.40 - 0.15(1-0.40)/(1-0.15)] = 29.4$ kg.

Check: Initially there is $0.40 \cdot 100 = 40$ kg water in the wood and the remaining 60 kg is dry wood. The dry wood mass remains unchanged during drying. So in the final stage there is $40 - 29.4 = 10.6$ kg water in the wood and 60 kg of dry wood still, i.e. total mass is 70.6 kg. Moisture content $X_2 = 10.6/70.6 = 0.15$ i.e. 15% as expected!

2.3 Water bound to wood

2.3.1 Binding methods of water

Water is "attached" to a tree either as bound water and also possibly as free water. Bound water is tightly adsorbed into the cell walls between lumen walls in the wood, while free water is found in the actual lumen. For Finnish wood, the moisture ratio value $U_{\text{FSP}} \approx 0,30$ ("Fibre Saturation Point", FSP) is often used to describe the moisture content of trees with completely water saturated

lumen walls, but no free water present in the lumen. Moisture ratio value $U_{FSP} = 0,30 = 0.30$ is equivalent to moisture content $X_{FSP} = 23\%$ in accordance with formula (1). The moisture content numeric value depends on temperature and the higher the temperature, the lower the numerical value. The above value of $U_{FSP} = 0.30$ is equivalent to a mean value between the temperatures of 0°C -> 60°C , but, for example, at 100°C FSP is only about $U_{FSP} = 0.23$, equivalent to moisture content $X_{FSP} = 19\%$ (see Figure 2.2). If temperature effects are to be taken into account, the formula $U_{FSP} = 0.33 - 0.001T$ can be applied, in which temperature T is given in Celsius.

<http://www.vtt.fi/inf/pdf/julkaisut/1996/J815.pdf>

In practice the most significant difference between bound and free water is that bound water is particularly "tightly" attached to the wood and its removal becomes more difficult the drier the wood becomes. This means that the heat energy per water kilo required to remove water increases as moisture content decreases. Removal of water from lumen, however, equals normal water evaporation.

2.3.2 Equilibrium moisture content of wood

Equilibrium moisture content of wood refers to the level at which moisture sets when it is exposed to a specific humid air temperature for a sufficient period of time. Equilibrium moisture content also depends on relative humidity. The above FSP border $U_{FSP} = 0.30$ (or $X_{FSP} = 0.23$) is equivalent to equilibrium moisture content at a relative humidity of 100%.

Figure 2.2 shows equilibrium moisture content as a function of temperature and ambient relative humidity. If for example wood is stored at 20°C with relative humidity at 60%, the moisture ratio will eventually settle at a value of $U = 11\%$ (0.11), equivalent to a normal moisture content of value $X = 9.9\%$. Moisture equilibrium is, however, exceptionally slow, and therefore the true moisture content of wood rarely corresponds to equilibrium moisture content, which is dependent on ambient temperature and relative humidity. Wood naturally dries from the exterior, in other words, moisture moves from the inner zones of the wood to the outside. This movement of moisture (diffusion) occurs very slowly. Overall of course, the drying process is faster the smaller the wood has been chipped up into. The combustion size of woodchips is normally quite small, so woodchips dry relatively quickly compared to, for example, the drying of an entire tree trunk.

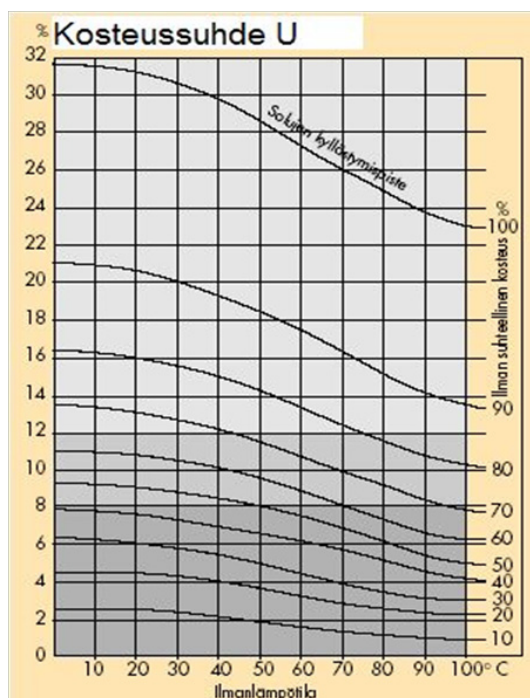


Figure 2.2. Equilibrium moisture ratio (U) of wood as a function of temperature and relative humidity. Temperature shown on the X-axis is also wood temperature. The top line shows FSP as a function of temperature. Figure: www.puuproffa.fi

2.4 Heat energy required to remove water

When green wood is burned, the water in the wood must first be driven off and then vaporised. The heat energy required for this derived from the heat released by combustion of the wood’s dry matter. Often the comparative temperature used in calculations is 25°C instead of the normal boiling point of 100°C. Removing the free water in the wood grain’s lumina and changing it to vapour is equivalent to normal vaporisation of water. If moisture content X is greater than FSP moisture content 23%, removing one water kilo from the wood requires a standard 2.443 MJ/kg of heat energy, i.e. 0.68 kWh/kg water (25°C reference temperature). The numerical value therefore is not dependent on moisture content X .

Bound water, on the other hand, is water tightly adsorbed to the wood grain’s cell walls and its removal requires much more heat than free water which already exists in liquid form. The required heat energy depends on moisture ratio U . As moisture ratio U approaches zero, the required heat energy is considerable, being significantly greater compared to removal of free water (<http://www.vtt.fi/inf/pdf/julkaisut/1996/J815.pdf>). To make further calculations easier, we will assume that the dependency of desorption heat on the moisture ratio U is linear and the desorption heat has a triple value compared to the evaporation heat of water. In this case the heat energy per water kilo as a function of moisture ratio U required to remove bound water and vaporise it

further is calculated using the formula (unit kWh/kg): $q_{des} = 2.036 - 4.524 \cdot U$.

Example 4: Dry 100 kg of wood from initial moisture content of $X_1 = 40\%$ to final moisture content of $X_2 = 23\%$. How much heat energy does this require? The given moisture contents are equivalent to values $U_1 = 0.67$ and $U_2 = 0.30$, i.e. the water to be removed is free water in its entirety. Initially the wood contains 40 kg of water and the remaining 60 kg is dry wood. In the final situation the moisture ratio is 0.30 i.e. the wood still contains $0.30 \cdot 60 = 18$ kg water, therefore 22 kg of water is removed. The required heat energy is thus $22 \text{ kg} \cdot 0.68 \text{ kWh/kg} = 14.96 \text{ kWh}$.

Example 5: Dry 100 kg of wood from initial moisture content of $X_1 = 23\%$ to final moisture content of $X_2 = 6\%$ i.e. moisture content changes the same 17% units as in Example 4. How much heat energy is now required? Equivalent moisture ratios are $U_1 = 0.30$ and $U_2 = 0.064$. Now we are completely in the sphere of bound water. On average the moisture ratio during drying is $(0.30 + 0.064) / 2 = 0.182$. Therefore, the average heat energy required is $2.036 - 4.524 \cdot 0.182 = 1.213 \text{ kWh/kg}$. Calculated as in Example 1, 18.1 kg of water is now removed, so the required heat energy is $18.1 \cdot 1.213 = 21.95 \text{ kWh}$ i.e. 47 % more than in Example 4!

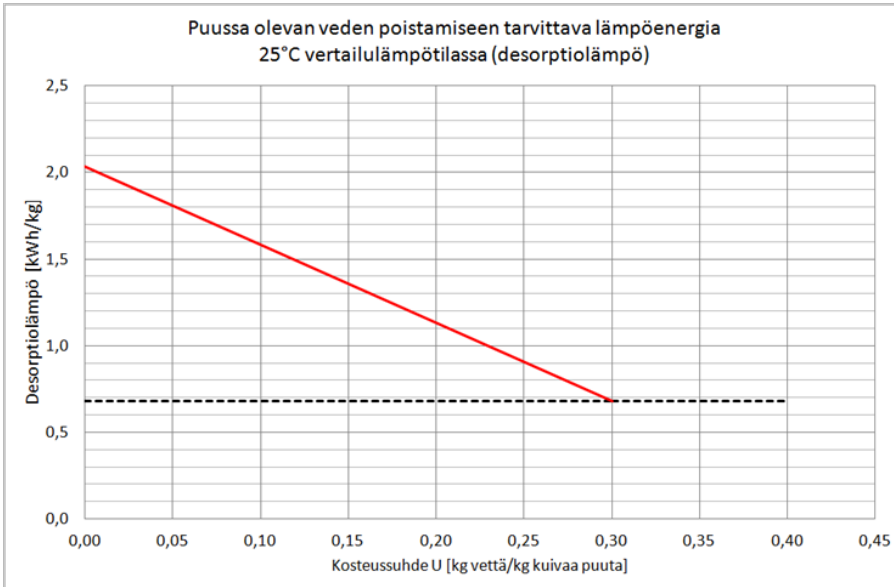


Figure 2.3. Heat energy required to remove water (desorption) as a function of moisture ratio U . Assumed linear dependency (when $U < 0.30$) and $q_{des} = 3 \cdot q_{evap}$, when U approaches zero. Note that moisture content $X = U / (1 + U)$.

2.5 Swelling and shrinkage of wood

When moisture content is in the bound water zone ($X < 23\%$), the volume of the wood changes as moisture content changes. Swelling induced by increases in moisture content and shrinkage resulting from the wood drying are not equally great as expressed in percentages due to the hysteresis phenomenon, but in this context the difference is negligible. In addition to moisture content,

swelling and shrinkage also depend on the wood's dry-green density. The relative volume change in heavier wood is greater. Usually relative swelling is directly comparable to moisture ratio U. The formula applied to calculating relative volume change is: $\Delta V/V=U*\rho_{kT}/1000$, where ρ_{kT} is dry-green density and water density is 1000 kg/m³. <http://puukemia.tkk.fi/fi/opinnot/kurssit/19-1000/luennot/Viitaniemi.pdf>

2.6 True density, i.e. wet density, of green wood

Dry-green density ρ_{kT} of wood is determined by using the wood's dry mass as mass, but the wood's green volume as volume. The volume of completely green wood is, due to swelling, greater than bone-dry wood, so dry density ρ_k is always greater than dry-green density ρ_{kT} . The relationship between dry density and dry-green density is

$$\rho_k = \rho_{kT} (1 + 0,0003\rho_{kT}) \quad (3)$$

Example 6: The dry-green density of birch is 490 kg/m³ and that of pine 405 kg/m³. Equivalent dry densities according to formula (3) are about 490*(1 + 0.0003*490) = 562 kg/m³ for birch and about 454 kg/m³ for pine.

Puulaji	Kuivatuoretiheys	Kuivatiheys
Koivu	490 kg/m ³	562 kg/m ³
Haapa	375 kg/m ³	417 kg/m ³
Leppä	400 kg/m ³	448 kg/m ³
Mänty	405 kg/m ³	454 kg/m ³
Kuusi	395 kg/m ³	442 kg/m ³

Table 2.1. Dry-green and dry densities of various species (considerable variation).

Wet density ρ_m refers to the true density of green wood, that is, the true mass of the wood per true volume. Wet density depends on the wood's dry-green density ρ_{kT} , and moisture content X. When calculating small moisture content levels swelling/shrinkage needs to be taken into account. Because wood only swells to FSP after which volume is constant, wet density needs to be calculated in two ways depending on moisture. The often used term green density is the wet density of a tree at the moment of felling, so depending on the species, moisture content has a value of X = 0.50–0.60. If moisture content is under the FSP i.e. X ≤ 23%, the following formula is used to calculate wet density:

$$\rho_m = \frac{\rho_{kT} (1 + 0,0003\rho_{kT})}{[1 - X(1 - 0,001\rho_{kT})]} \quad (4)$$

If moisture content of the wood is greater than the FSP-moisture content, i.e. $X > 23\%$, wet density is calculated with a simpler formula:

$$\rho_m = \frac{\rho_{kT}}{(1 - X)} \quad (5)$$

Example 7: Moisture content of a green pine log is 55%. What is the log's wet density? According to Table 2.1 dry-green density of pine is 405 kg/m^3 . Applying formula (5), true density of pine is $\rho_m = 900 \text{ kg/m}^3$ i.e. it just manages to float on water. The log will become a sinker when moisture content exceeds 59% (Figure 2.4).

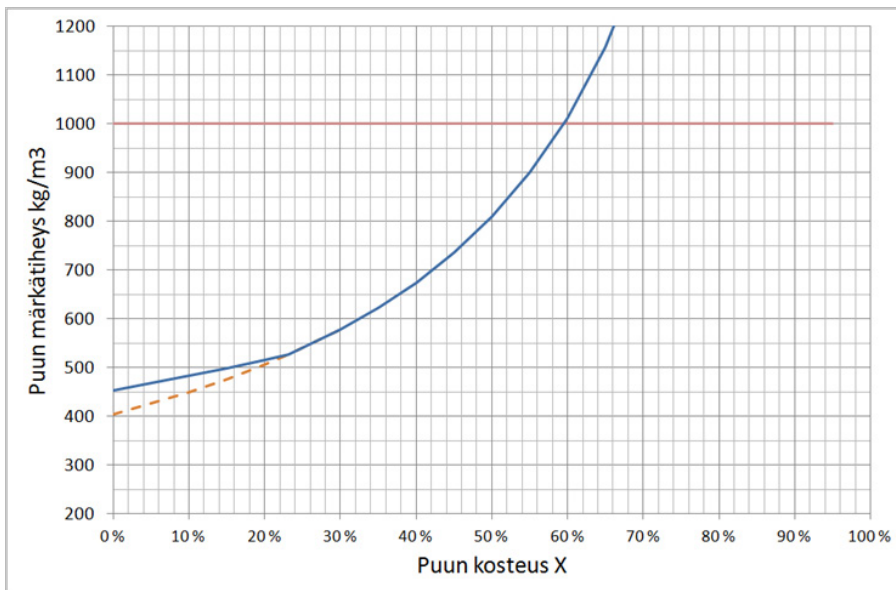


Figure 2.4. True density i.e. wet density of pine as a function of moisture content X . The red horizontal line describes water density and the broken line density if swelling/shrinkage are ignored.

2.7 Energy content of wood

2.7.1 Calorimetric or higher heating value

The calorimetric or higher heating value of wood is approximately 19.0–20.5 MJ/kg dm. (dm. = dry matter). A constant value of 20 MJ/kg dm. or 20.5 MJ/kg dm. is often used, irrespective of species. Using a bomb calorimeter in laboratory measurements is often the only reliable way to ascertain calorimetric energy content of dry matter.

2.7.2 Effective or lower heating value

The average elemental composition of Finnish trees (calculated for anhydric

wood) is: carbon (C) 50–52%, hydrogen (H) 5.9–6.3%, nitrogen (N) 0.2–0.3%, sulphur (S) under 0.01% and the rest oxygen (O) i.e. about 41–43%. In practice, the only elements in wood are carbon, hydrogen and oxygen. Ash content of stemwood is about 0.5–1.0% of the dry matter, so exceptionally small. Ash content of branches, needles, bark and stumps is considerably greater. Hydrogen in wood is a flammable substance and its combustion product is water, which needs to be vapourised in the combustion process. The burning of 1 kg of oven-dry (hydrogen 6.0%) waterless wood generates approximately 0.54 kg water as a combustion product. The heat energy required for vapourisation derived from the tree's dry matter, so the effective or lower heating value of dry wood is slightly lower than the calorimetric or higher heating value. The derived formula (H is hydrogen content of wood expressed as a percentage):

$$q_{lower} = q_{higher} - 0,22H \quad (6)$$

If $q_{higher} = 20.0$ MJ/kg dm. and hydrogen content 6.0%, then $q_{lower} = 20.0 - 0.22 \cdot 6 = 18.68$ MJ/kg dm. and correspondingly, a value of 20.5 MJ/kg dm. gives $q_{lower} = 19.18$ MJ/kg dm. There is considerable variation in the lower heating value of species, and the different parts of a tree also have different energy content. Birch bark, for example, can have a 50% greater energy content than birch stemwood.

Mänty	
Puhdas puu	18,71 - 19,29
Kaarna	18,38 - 20,72
Oksat	19,39 - 20,50
Neulaset	21,05 - 21,07
Latvat	18,84
Kokonainen puu	19,60 - 20,40
Kannot	19,20 - 19,60
Kuusi	
Puhdas puu	17,96 - 19,02
Kaarna	17,83 - 19,83
Oksat	19,80 - 20,00
Latvat	18,63 - 19,80
Kokonainen puu	19,20 - 19,60
Kannot	18,95 - 19,05
Koivu	
Puhdas puu	17,41 - 19,13
Nila	17,12 - 18,42
Tuohi	28,38 - 29,30
Oksat	18,84 - 19,80
Kokonainen puu	19,10 - 19,60
Kannot	

Table 2.2. Lower heating value of the dry matter of various species (MJ/kg).
<http://www.vtt.fi/inf/pdf/tiedotteet/2000/T2045.pdf>

2.7.3 Effect of moisture content on energy content

When burning moist wood, all bound water must first be removed, then heated to boiling point and finally vapourised. Vapourising free water presents no problems, but when moisture content falls below the moisture limit of $X = 23\%$, heat needs to be applied to "detach" water from the wood grain's cell

lumina in. The more green the wood to be burned is, the more its true energy content is lowered compared to dry wood.

True energy content of wood, taking into account moisture content X , is often calculated using the standard formula applied by heating plants:
<http://www.vtt.fi/inf/pdf/tiedotteet/2000/T2045.pdf>

$$q_{STD} = q_{lower} (1 - X) - 0,68X \quad (7)$$

where q_{lower} is expressed in units of kWh/kg (often 5.19 kWh/kg dm.) and 0.68 kWh/kg is evaporation heat of water at 25°C.

Formula (7) can be used to calculate energy content of woodchips on delivery to a heating plant (according to which the woodchip supplier is paid). However, formula (7) does not convey the true combustion situation, as for example it does not take into account the different natures of bound and free water, nor the true initial temperature of wood fed into the boiler. In temperatures well below zero, for example, free water present in wood is frozen (bound water does not freeze) and heat is required to melt this water. More accurate formulae are required for real boiler simulation calculations and efficiency measurement result analysis.

The heat energy (unit kWh/kg) required for heating green wood from an initial temperature T_0 to reference temperature $T_{vert} = 25^\circ\text{C}$ is

$$q_{l\ddot{a}m} = \frac{Q_{l\ddot{a}m}}{m_{tot}} = \frac{[c_{tot} (T_{ref} - T_0) + \alpha (X - X_{FSP}) l_{mel}]}{3600} \quad (8)$$

where m_{tot} = total mass of wood (kg), c_{tot} = effective specific heat of wood and the water it contains (kJ/kgK), T_0 = initial temperature of wood, $T_{ref} = 25^\circ\text{C}$, X = initial moisture content, X_{FSP} = moisture limit (0.23) and l_{mel} = melting heat of ice 333 kJ/kg and coefficient $\alpha = 1$, if initial temperature is less than 0°C and concurrently X is greater than X_{FSP} , otherwise always $\alpha = 0$. Specific heat c_{tot} is calculated with moisture content X as the weighted mean of the specific heat of dry wood and liquid water.

Heat energy q_{des} , required for removing and vapourising all water from wood, must be calculated in one of two ways depending on initial moisture content X . If moisture content exceeds FSP-value 23%, then the heat energy required between $X \rightarrow X_{FSP}$ is equivalent to the evaporation heat of water, i.e. 0.68 kWh/kg water (25°C). Considerably more heat per water kilo is required to remove the remaining water, i.e. on average 1.36 kWh/kg water (25°C). Finally a moisture ratio X weighted mean is calculated

$$q_{des} = \frac{Q_{des}}{m_{tot}} = X \left[\frac{U - 0,30}{U} 0,68 + \frac{0,30}{U} 1,36 \right] \quad (9)$$

where U is moisture ratio equivalent to initial moisture X i.e. $U = X/(1 - X)$.

If moisture ratio is $U < 0.30$, the required energy content is

$$q_{des} = Q_{des}/m_{tot} = X(2.036 - 4.524U/2) \quad (10)$$

The true released energy content of wood is finally derived with the formula:

$$q_{tod} = \frac{Q_{tod}}{m_{tot}} = q_{lower}(1 - X) - q_{l\ddot{a}m} - q_{des} \quad (11)$$

Example 8: Initial moisture content is $X = 40\%$ and initial temperature -10°C . Assume lower heating value of wood is 18.68 MJ/kg dm . i.e. 5.19 kWh/kg dm . What is the true energy content released during combustion in the boiler? Initial temperature is below zero, so all free water is frozen. According to formula (8) heating the wood to reference temperature 25°C requires energy $q_{l\ddot{a}m} = [(1-0.40)*1.5 + 0.40*4.2]*(25 - (-10)) + 1*(0.40-0.23)*333 = 146.91 \text{ kJ/kg}$ i.e. 0.041 kWh/kg . The heat required to remove and vapourise the water, i.e. desorption, according to formula (9) is $q_{des} = 0.40*[(0.667-0.30)/0.667*0.68+0.30/0.667*1.36] = 0.394 \text{ kWh/kg}$. Finally formula (11) gives $q_{tod} = 5.19*(1-0.40)-0.041-0.394 = 2.68 \text{ kWh/kg}$. The result derived at with standard formula (7) is $q_{STD} = 5.19*(1 - 0.40) - 0.68*0.40 = 2.84 \text{ kWh/kg}$. The difference is $1 - 2.68/2.84 = -0.056$ i.e. -5.6% the standard formula giving too great a result.

2.8 Woodchip pile density

Woodchip pile density (v) describes how many solid cubic metres of wood are contained in one loose cubic metre of woodchip.

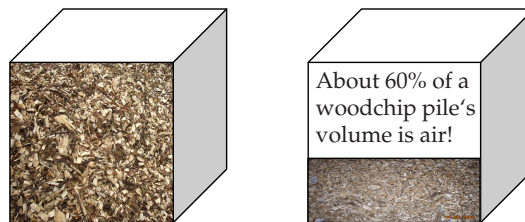


Figure 2.5. Density of a woodchip pile varies between approximately $v = 0.36-0.46$ i.e. one loose cubic metre of woodchip contains about $0.36-0.46$ solid cubic metres (green) wood and the rest is air. An often used value is $v = 0.40 \text{ m}^3/\text{i-m}^3$.

Several factors affect density, such as the size and form of the chips, moisture, species, chip type (forest residue, small round wood (SRW) chip, whole tree chip) and for example transportation. The smaller the chip size, the denser the chip pile usually is. The chipping technology used also affects chip size. Chip piles may become denser during transportation due to vibration. According to

an often used "rule of thumb" one solid cubic metre of wood gives 2.5 loose cubic metres of woodchips, in other words woodchip pile density is $v = 1/2.5 = 0.40 \text{ m}^3/\text{i-m}^3$. This value can be applied if more detailed information on density is lacking.

2.9 Woodchip loose density

Woodchip loose density ρ_{loose} ($\text{kg}/\text{i-m}^3$) is calculated by multiplying the wet density of green wood matter ρ_m by woodchip pile density v :

$$\rho_{\text{loose}} = \rho_m v \quad (12)$$

Example 9: A tractor trailer has a volume of 10 m^3 and its woodchip load has a moisture content of 35%. The load therefore is 10 i-m^3 of woodchips with moisture content 35%. What is the weight of the load, in other words, what is its total mass? Let woodchip pile density be $v = 0.40 \text{ m}^3/\text{i-m}^3$ and dry-green density be $\rho_{\text{kT}} = 405 \text{ kg}/\text{m}^3$ green pine woodchips). Formula (5) gives wet wood density at $\rho_m = 623 \text{ kg}/\text{m}^3$ and formula (12) loose density of woodchips $\rho = 0.40 \times 623 = 249 \text{ kg}/\text{i-m}^3$. Therefore the load contains $249 \times 10 = 2490 \text{ kg}$ green woodchips, of which $0.35 \times 2490 = 872 \text{ kg}$ is water and 1618 kg dry wood.



Figure 2.6. A load of green woodchips arriving at a heating plant. Load volume is 10 i-m^3 . What is the mass of the woodchips in the load? Photo: Martti Härkönen

Figure 2.7 compares loose density of birch and pine woodchips. Chip pile density v and the green-dry density ρ_{kT} of the raw material significantly affect woodchip loose density. Within the moisture content range of $30\% \leq X \leq 50\%$, pine woodchip loose density is about $230\text{--}320 \text{ kg}/\text{i-m}^3$ and birch woodchip density $280\text{--}390 \text{ kg}/\text{i-m}^3$.

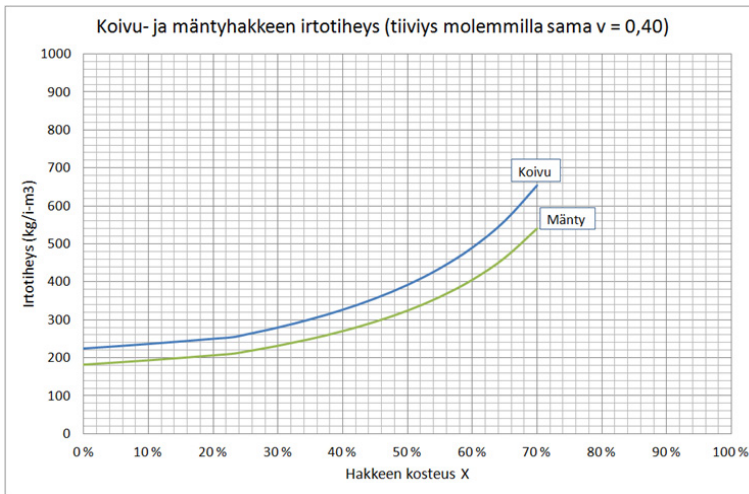


Figure 2.7. The affect of the woodchip raw material's dry-green density on chip loose density. Dry-green density of birch is 490 kg/i-m³ and pine 405 kg/i-m³.

2.10 True energy content of woodchips on the tractor bed (q_{BED})

Multiplying loose density of green woodchips by the term (1 - X) derives the quantity of dry wood matter in a loose cubic metre of woodchips. Multiplying this by the dry wood's lower heating value q_{alempi}, gives the energy content of green woodchips q_{BED} before burning in units of MJ/i-m³ tai kWh/i-m³. Energy content q_{BED} therefore describes the energy content available in principle to the heating plant, for example in a tractor bed of woodchips per loose volume (kWh/i-m³):

$$q_{Bed} = \rho_m v(1 - X)q_{lower} \quad (13)$$

where input $\rho_m v$ is loose density of woodchips and q_{lower} is expressed in units of kWh/kg.



Woodchip volume is V (i-m³)
 Total mass is m_{kok} (kg)
 Moisture content is X (kg water /
 kg green woodchip)



Kuva 2.8. Kostea haketta. Kuva: Martti Härkönen

When wet density of wood matter ρ_m is added to formula (13), we get:

$$(if X \leq 0,23) \quad q_{Bed} = \frac{v\rho_{kT}q_{lower}(1 + 0,0003\rho_{kT})(1 - X)}{[1 - X(1 - 0,001\rho_{kT})]} \quad (14)$$

And if woodchip moisture content is greater than the moisture limit, i.e. moisture content exceeds 23%, then energy content is calculated by the formula

$$(if X > 0,23) \quad q_{Bed} = v\rho_{kT}q_{lower} \quad (15)$$

The results therefore indicate that when woodchip moisture content is greater than the FSP, i.e. when moisture content $X > 23\%$, the energy content contained in the woodchips per loose cubic metre (kWh/i-m³) is in no way dependent on moisture! This means that in a woodchip load delivered on a specific sized bed to the heating plant, from the supplier's point of view there is always the same amount of energy irrespective of moisture content. However, with small moisture content, when $X \leq 23\%$, energy content of the load is dependent on moisture content and is greater the drier the woodchips are. However, the above conclusion is valid only if woodchip pile density (v) is not dependent on moisture.

Example 10: A forest owner delivers to the heating plant 50 l-m³ of pine woodchips with moisture content of a) 20% b) 30% and c) 40%. How much energy does the load contain? Let 18.68 MJ/kg dm. be the energy content of dry matter and 405 kg dm./m³ the dry-green density of pine.

In a) the woodchips are very dry and moisture content is less than the wood's border moisture. If woodchip pile density is a constant 0.40, woodchip energy content is according to formula (13) $q_{Bed} = 856 \text{ kWh/i-m}^3$ i.e. 0.856 MWh/l-m³. Therefore the energy contained in the load is $50 \cdot 0.856 = 42.81 \text{ MWh}$.

In b) the woodchip moisture content exceeds border moisture, and formula (14) is applied. Woodchip energy content is 0.841 MWh/l-m³ and the energy amount of the load $50 \cdot 0.841 = 42.03 \text{ MWh}$.

In c) woodchip moisture content also exceeds border moisture, and applying formula (14) the energy content of the load is equivalent to that of 30% moisture content, i.e. 0.841 MWh/l-m³. Energy content of the load is thus the same as at b), i.e. $50 \cdot 0.841 = 42.03 \text{ MWh}$, irrespective of the greater moisture content.



- a) moisture content 20 % -> in a 50 l-m³ load there is 42.8 MWh of energy.
- b) moisture content 30 % -> in a 50 l-m³ load there is 42.0 MWh of energy.
- c) moisture content 40 % -> in a 50 l-m³ load there is 42.0 MWh of energy.
- When $x > 23\%$, energy content of a load no longer depends on moisture!

Figure 2.9. Woodchips are brought to the heating plant. How does moisture content affect woodchip energy content? Photo: Martti Härkönen

Example 10 and Figure 2.9 show therefore that when woodchip moisture content exceeds FSP, i.e. is over 23%, the energy content of woodchips per loose cubic metre does not depend on moisture. Heating plants and/or energy cooperatives do not, however, pay suppliers according to this principle. A standard formula (formula 16) is used to calculate on arrival energy content, this determining cost.

2.11 True energy content released by woodchips in the boiler (q_{KAT})

The true energy content of green woodchips (from the perspective of the woodchip user) is lower than the above result (q_{Bed}) because the burning of woodchips requires the chips and the water it contains to be heated from initial temperature to a reference temperature, any possible ice within the woodchips to be melted, the water present in the woodchips to be "really detached" from the wood and vapourised, all this requiring energy. The required energy is derived from the heat generated by the burning of the woodchips' dry matter.

Energy content (kWh/l-m³) of woodchips per loose cubic metre derived from the standard formula is

$$q_{STD} = \rho_{loose} [q_{lower} (1 - X) - 0,68X] \quad (16)$$

This result, however, is not accurate enough to account for all factors affecting combustion. More detailed equations need to be applied in the analysis of measurement results and in simulation calculations.

True energy content of woodchips in the boiler q_{BOI} is derived with formula (10) (units kWh/i-m³):

$$q_{BOI} = \rho_{loose} [q_{lower} (1 - X) - q_{lam} - q_{des}] \quad (17)$$

which can be expressed in the following form

$$q_{BOI} = \rho_m v \left[q_{lower} (1 - X) - \frac{c_{tot} (T_{ref} - T_0)}{3600} - \frac{\alpha (X - X_{FSP}) l_{mel}}{3600} - X \left[\frac{U - 0,3}{U} 0,68 + \frac{0,3}{U} 1,36 \right] \right] \quad (18)$$

where input $\rho_m v$ = loose density (kg/i-m³) of green woodchips, ρ_m = wet density of wood, v = density, X = woodchip moisture content, q_{lower} = lower heating value of wood in units kWh/kg dm., c_{tot} = green wood's effective specific heat in units kJ/kgK, $T_{ref} = 25^\circ\text{C}$, T_0 = initial temperature of woodchips, $X_{FSP} = 0.23$, factor $\alpha = 1$, if initial temperature of woodchips is less than 0°C and X is greater than X_{FSP} , otherwise always $\alpha = 0$, melting heat of water $l_{mel} = 333$ kJ/kg and U is moisture ratio equivalent to woodchip moisture content X , i.e. $U = X/(1 - X)$.

Formula (18) is valid when initial moisture content of woodchips is greater than 23%. If initial moisture content is less than 23%, the following formula is applied:

$$q_{BOI} = \rho_m v \left[q_{lower} (1 - X) - \frac{c_{tot} (T_{ref} - T_0)}{3600} - X \left[2,036 - 4,524 \frac{U}{2} \right] \right] \quad (19)$$

The derived formulae (18) and (19) are therefore equivalent to standard formula (16), but better describe the heat energy released by combustion of woodchips taking into account, for example, initial woodchip temperature, possible water present in the form of ice, and the difference between the natures of bound and free water. Figure 2.10 shows that the calculation model presented here results in slightly lower values for woodchip effective heat values (kWh/kg) compared to results derived from the standard formula. If initial woodchip temperature is -15°C (winter), the difference within moisture content zone of 20–60% is about -5.6% on average. If the temperature is $+15^\circ\text{C}$ (summer), the average difference falls to -4.1%.

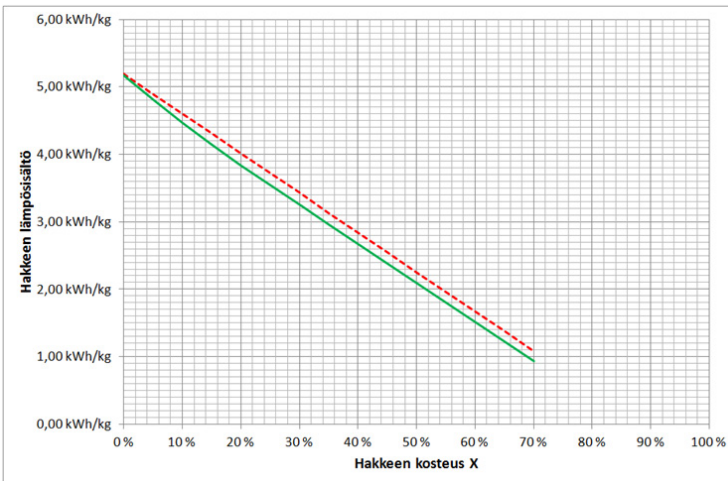


Figure 2.10. Comparison of standard model (formula 16) and more detailed model (formulae 18 and 19). The top broken line represents the standard model. Initial woodchip temperature is -15°C . Lower heating value of dry matter is 18.68 MJ/kg dm. Woodchips are pine.

Figure 2.11 compares the standard model and the model developed here applying kWh/l-m³ as units for woodchip energy content. Base values are the same as above. True energy generated by woodchips in the boiler in summer and winter conditions are compared in Figure 2.12. In the summer when woodchips are warmer (+15°C), the effective heat value is about 2–4% greater than in winter (-15°C). Chip pile density has a considerable effect on the load's energy content, as shown in Figure 2.13. Generally a value of 0.40 m³/l-m³ is used for density, but this is only "a rule of thumb" and does not always reflect reality. According to the graph, energy content of a very dense woodchip load with moisture content of 40% (v = 0.46) is about 28% greater per loose cubic metre than a looser load (v = 0.36).

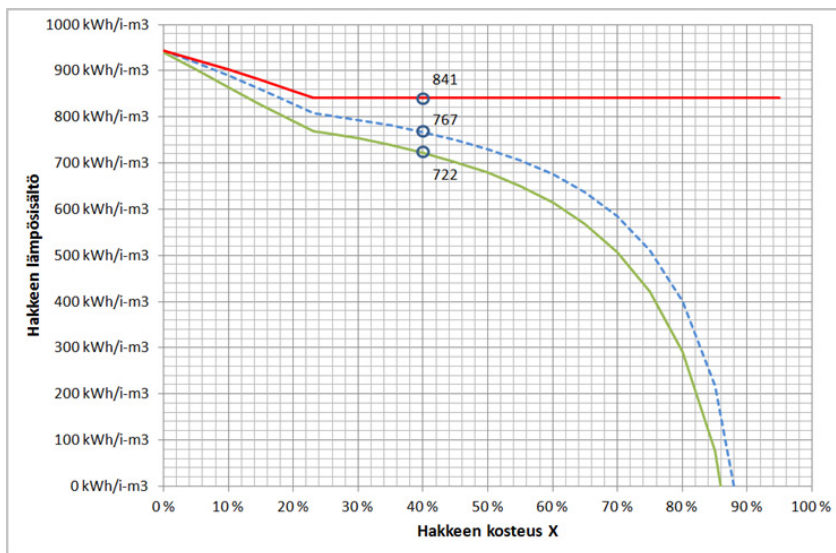


Figure 2.11. Woodchip energy content as a function of moisture expressed in kWh/i-m³. The top curve (broken line) equates to the standard model. A value of 0.40 has been used for woodchip density. Topmost line (red line) depicts the real energy content of woodchip dry matter ($q_{\text{lower}} = 18.68 \text{ MJ/kg dm.}$).

Example 11: In winter a farmer brings a 10 i-m³ +2°C pine woodchip load to a heating plant. Moisture content is 40%. A sample 100 litre barrel batch of the woodchips is weighed at the heating plant and the derived mass is 27.0 kg. How much of the load will generate heat energy? The measured loose density is 27/0.1 = 270 kg/i-m³ thus the mass of the entire load is 270*10 = 2700 kg. True energy value of woodchips with 40% moisture content is 2.71 kWh/kg of woodchips, i.e. the entire load contains 2700 x 2.71 = 7317 kWh i.e. 7.32 MWh energy. If energy content is estimated without a sample batch, but on the basis of bed volume, then according to Figure 2.13 energy content in 40% moisture content is 680–860 kWh/i-m³ depending on pile density, i.e. for the entire load 6.80–8.60 MWh. The problem is that a visual estimate of pile density is virtually impossible.

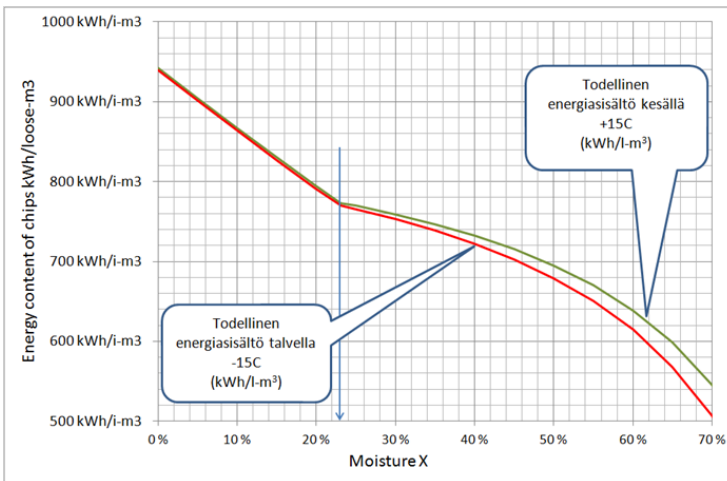


Figure 2.12. True heat energy generated by woodchips in the boiler in summer (+15°C) and in winter (-15°C).

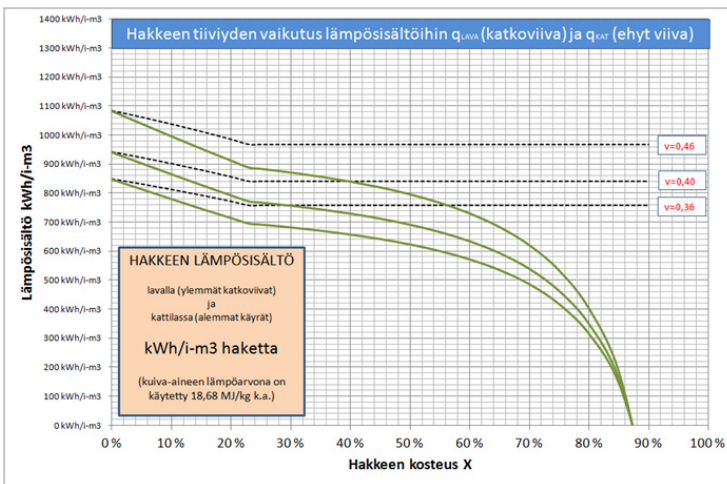


Figure 2.13. Significance of woodchip (+2°C) pile density on woodchip energy content in units (kWh/i-m³).

Example 12: A heating plant burns a) 30% and b) 50% pine woodchips 1000 l-m³. Let 0.40 be woodchip density and -15°C temperature. The farmer is paid 15 €/MWh for the chips if moisture content is less than 35%, otherwise 12 €/MWh. Customers pay 60 €/MWh for the heat produced. Boiler efficiency with drier wood chips is 0.90 and with wetter only 0.70. The drier wood chips' heat energy according to the standard formula is 793 kWh/l-m³ and the greener 731 kWh/l-m³. True energy content generated at the grate for the drier woodchips is about 753 kWh/l-m³, and for the greener only 679 kWh/l-m³. Before the boiler the woodchips' dry matter energy content in both cases is the same 841 kWh/l-m³. The farmer is paid for the woodchips: a) 0.793*1000*15 = 11895 € and b) 0.731*1000*12 = 8772 €. Energy content generated for sale from the woodchips is a) 0.793*1000*0.90 = 713.7 MWh and b) 0.731*1000*0.70 = 511.7 MWh i.e. a) 42882 € and b) 30702 € (see Figure 2.14).

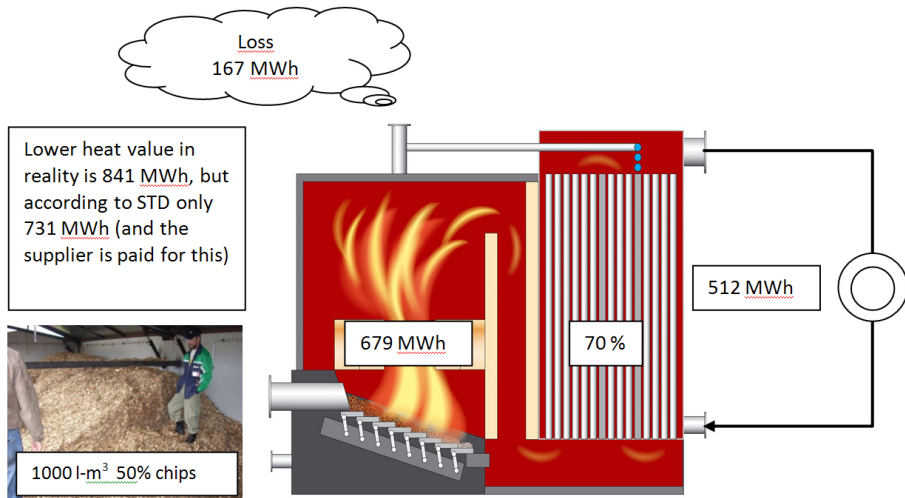


Figure 2.14. Example of the difference in energy quantity between woodchips supplied to the heating plant and heat sold to the customer. The greener the woodchips when burnt, the greater the difference. Photo: Martti Härkönen

3. MEASUREMENTS CONDUCTED AT WOODCHIP HEATING PLANTS

3.1 Woodchip heating plants at Kälviä



Figure 3.1. The two Kälviä 2.0 MW chip heating plants. Photos: Martti Härkönen

The Kälviä energy cooperative is responsible for two almost identical woodchip heating plants, both with a nominal capacity of 2.0 MW. The boilers are Arimax Bio 2000 type boilers equipped with a mechanically moving grate and a wet ash removal system. Wet ash removal means that the entire bottom of the boiler is one water bin into which incombustible fuel and ash fall. Flue gases are able to flow past the bin to heat exchanger surfaces, leaving some of the fly ash in the bin. The ash is removed from the basin as liquid sludge.



Figure 3.2. Woodchip stock and plenum chamber with feed screws in the boiler room. Photos: Martti Härkönen

Energy wood to be burned is chipped in the forest near the place of felling and the ready-made woodchips are delivered to a woodchip storage room next to the boiler room. Rod distributors on the storage room floor move the woodchips to large screws at the sides of the room. The woodchip screw moves the chips from storage to the plenum chamber in the boiler room, where actual feed screws (2 screws) move the woodchips onto the grate in the boiler's combustion chamber for combustion. The required combustion air is supplied to the hearth by primary and secondary air fans. The primary air fan feeds air mainly to under the grate and the secondary air fan to above the grate to ensure efficient combustion of volatile material. Residual oxygen content in the flue gases controls the fans. Woodchips are sourced from fairly good quality SRW and whole trees from the Kälviä energy cooperative members' own forest thinnings. Logging residue is rarely used. Moisture content and loose density of each load is measured on a scale and in an oven. Moisture content has been approximately 20–45%. Very small batches of sod peat have been trialed in amongst woodchips.

Total woodchip consumption in the heating plants in the last several years has been about 14000–15000 l-m³/a and about 8000 MWh/a of heat has been generated. Quantities depend of course on average winter temperatures. Oil boilers are on standby, one of which uses heavy and the other light fuel oil. Oil consumption has been several tens of tonnes annually, primarily restricted to the older Kälviä plant (2003) due to its larger heat load. The newer heating plant (2006) operates mainly at partial capacity due to the small heat load connected to the boiler.

3.2 Description of heat energy production and control processes

Woodchips are fed into the combustion chamber with feed screws and burn on a movable mechanical grate. Before the actual combustion zone, there is a drying zone, where woodchips dry before ignition. Primary and secondary fans blow combustion air above and below the grate. The hot flue gases that are formed flow around the combustion chamber and then past heat exchanger surfaces and warm the district heating water (DH-water) flowing inside the surfaces to an average temperature of about 90–100°C depending on outside air temperature. If the boiler capacity is insufficient for this, a standby oil boiler is used for final heating of the DH-water. The hot DH-water is finally pumped to the consumer, the customer, after which the water, now cooled to about 50°C, returns to the boiler and begins another circuit. The underground DH-pipework at the older plant is several kilometres long and at the newer plant just under a kilometre.

The hot flue gases formed during combustion flow past the boiler's heat exchanger surfaces, cooling and releasing their heat to the DH-water. Flue gas exit temperatures are typically about 90–180°C depending for example on surface cleanliness and boiler load. Flue gases are primarily formed by the combustion air used in the combustion process, as the fuel's (woodchip) mass flow rate is relatively low (about 5-15%) in terms of the required combustion

air quantity. Flue gases are mainly composed of nitrogen and residual oxygen derived from the combustion air, and carbon dioxide and water vapour formed during combustion. Trace quantities of carbon monoxide and other carbon compounds as well as very small solid and partially unburned particles are also present.

Generally speaking there are several different process control methods, depending on boiler type and size, but control can occur as follows: A decrease in customer consumption of district heating energy is evident in a temperature rise in the DH-water returning to the woodchip boiler. Due to insufficient time to make adjustments, the temperature of DH-water leaving the boiler rises. When the control system notices the temperature rise, it begins to reduce the woodchip quantity being fed into the boiler, and the resulting fuel mass flow rate decrease leads to a sudden excess of combustion air. This in turn leads to a rise in residual oxygen content as not all the oxygen is needed for combustion. The increase affects the air fans so that they begin to feed less air into the combustion chamber, reducing the amount of oxygen in the combustion air and flue gases. The situation and fuel quantity is gradually stabilised, and the amount of combustion air and initial DH-water temperature now respond to customer energy load. Another control method might be to maintain outflowing DH-water and the returning water at a constant temperature, with adjustments made to the DH-water mass flow rate when load changes occur. Or the above control methods could work together.

Contamination of boiler heat exchanger surfaces results primarily from impurities in the flue gases, which gradually accumulate on the surfaces. Thermal conductivity of the contaminant layer is weak, increasing heat transfer resistance in the flue gases and resulting in a reduction of heat transfer, a so-called total heat transfer coefficient, the U value. Caloric capacity transferred from flue gases to DH-water is $\phi = UA\Delta T$, where ΔT is the mean (logarithmic) difference between flue gas and DH-water temperatures, and A the heat transfer surface area (constant). Now with contamination reducing input UA, temperature difference ΔT does not transfer the same caloric capacity to DH-water. District heating efficiency generated by the boiler thus begins to decrease. This is compensated by increasing woodchip quantity in the combustion chamber, resulting in a rise in combustion air and flue gas quantities and finally also a rise in the final temperature of flue gases and through this a reduction in the boiler's efficiency. For this reason, heat surfaces need to be brushed regularly.

3.3 Measurement of efficiency and emissions

3.3.1 Efficiency measurements

Emission and efficiency measurements were conducted at the older Kälviä heating plant during autumn 2009-spring 2011. Umeå University's ETPC unit had the main responsibility for measurements of flue gas particles, ash and slag. Our Swedish partners carried out measurements three times (11/2009, 2/2010 and 11/2010). Additionally, CENTRIA conducted separate efficiency

measurements twice (3/2010 and 5/2011). Efficiency measurements 3/2010 are examined as an example below.

Good quality stemwood, estimated composition 2% birch and 98% pine (Bi-2Pi98), was used as fuel in the measurements. A few sample chip batches were collected to measure moisture content afterwards in the laboratory. Moisture content was $X = 26.8\%$ i.e. the woodchip batch was especially dry. The chips were delivered to the heating plant on a tractor bed (Figure 4.3). Loose density was determined by weighing several 100 litre batches agitated in different ways. Loose density varied between 213–250 kg/l-m³ depending on agitation method. A measured mean of 222 kg/l-m³ was used in the calculations, which on the basis of a theoretical examination is equivalent to woodchip pile density $\nu = 0.40 \text{ m}^3/\text{l-m}^3$.

A lower heating value of 18.68 MJ/kg dm. was used in the calculations, equivalent to a calorimetric heat value of 20.00 MJ/kg dm. Calculated using the standard formula, energy content of a cubic metre of woodchips was about 803 kWh/l-m³ or calculated per mass about 803 kWh/l-m³/222 kg/l-m³ = 3.62 kWh/kg. Initial woodchip temperature in the boiler room was about +2°C, thus the water in the chips was not frozen. The chips were fed onto a large chip screw in the storage room by shovelling by hand and combustible chip volume was estimated by measuring the tractor load's chip volume before and after the performance measurement period as accurately as possible. The derived combustible chip quantity during the trial was 3.9 l-m³, equivalent to about 866 kg. The performance measurement period was 116 min.



Figure 3.3. Delivery of chips by tractor and loose density calculation. Photo: Martti Härkönen

Near the fan the combustion air fed into the boiler was +10°C and relative humidity was estimated at 70%, outside air temperature being an average of -2°C (air pressure 101.3 kPa). Average temperature in the boiler room was +10°C. Gas composition of the flue gases was measured at the same time with a GAS-MET gas analyser. The measured gases were, among others, carbon monoxide (CO), carbon dioxide (CO₂), sulphur dioxide (SO₂), oxides of nitrogen (NO_x), methane (CH₄) and water vapour (H₂O). Unfortunately it was not possible to measure the residual oxygen content of flue gases 3/2010.

Calculated according to the standard formula, woodchip energy content was $3.9 \cdot 803 = 3131$ kWh and average combustion efficiency 1620 kW. The heating plant's energy meters were continuously monitored during this time and thermal energy delivered to customers during the performance measurement period was 2500 kWh. It must also be noted that during the measurements a few percentage units of the thermal energy generated by the woodchip boiler was used to heat a separate heavy oil container and oil boiler room. It was impossible to calculate this percentage accurately, but calculations assume 4% of the fuel energy fed into the boiler accounts for this. Therefore, during the measurement period the boiler generated $2500 + 0.04 \cdot 3131 = 2625$ kWh of thermal energy.

Using these values, the Kälviä woodchip boiler's calculated efficiency is

$$\eta_{Boiler} = \frac{2625}{3131} = 0,838$$

Efficiency of around 84% is quite good. The boiler's nominal capacity is 2000 kW, so during the measurement the boiler's load factor was $1620/2000 = 0.81$ i.e. 81%.

The measurements contain several sources of error, the most significant being energy meter accuracy, and accuracy in the following measurements: woodchip moisture, loose density, and burned woodchip quantity. Energy meter error can be assumed to be that indicated by the meter supplier $\pm 1.5\%$. Loose density was calculated by shovelling chips into a 100 litre container and then measuring mass. If volume was calculated to within 2 litre accuracy and weight to within 0.2 kg, the error limit for loose density is around $\pm 2.9\%$. Burned woodchip quantity was derived by measuring a load's chip volume before and after the measurement period. If we assume load length, width and height were measured to within 0.5 cm accuracy, chip volume error limit is around $\pm 2.8\%$. Moisture content was measured in laboratory conditions to within $\pm 2\%$ accuracy (estimate). Based on moisture content measurements, the energy content of burned chips can be calculated using the standard formula $Q_{STD} = V\rho_{loose}[q_{lower}(1-X) - 0.68X]$, an error limit of around $\pm 6.3\%$.

Measured calculation values with error limits are therefore:

- a) total thermal energy generated in the boiler $Q_{Boi} = 2625 \pm 45$ kWh
- b) volume of burned woodchips $V = 3.90 \pm 0.11$ i-m³
- c) woodchip moisture content $X = 26.8 \pm 0.5$ %
- d) woodchip loose density $\rho_{loose} = 222 \pm 6$ kg/i-m³
- e) standard model: $Q_{STD} = 3131 \pm 197$ kWh

Boiler efficiency is calculated from the total thermal energy generated by the boiler to which the thermal energy contained in the woodchips as calculated using the standard formula is added. The above error sources impact these fac-

tors. Relative total error of efficiency, taking into account the above error sources is about 8.9%. Therefore, the calculated efficiency including error limits is:

$$\eta_{KAT} = 83,8 \pm 7,5\%$$

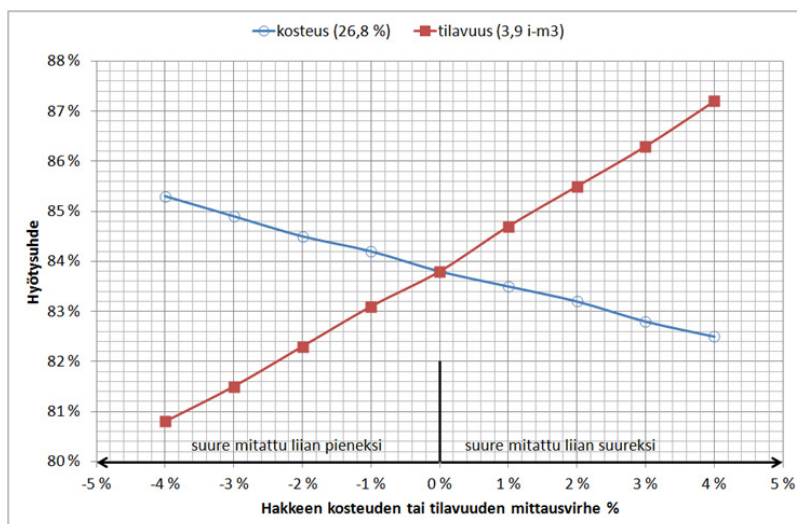


Figure 3.4. Sensitivity analysis of woodchip moisture and burned chip volume measurement errors' impact on calculated efficiency.

The error limits are therefore considerable and more accurate measurements need to be conducted. Figure 3.4 shows sensitivity analysis for two error sources. The graph indicates that if woodchip moisture was in reality greater than the calculated 26.8% (i.e. moisture was calculated too low), its impact on efficiency would need to be increased. Correspondingly if the burned woodchip quantity was in fact lower than the calculated value of 3.9 l-m³, calculated efficiency would have grown. Woodchip volume calculation accuracy seems to have a greater significance on efficiency value than does moisture content. Further calculations should completely avoid estimating volume and endeavour to directly measure the mass of burned chips, which would considerably reduce total error.

3.3.2 Other efficiency measurements

Efficiency measurements were also conducted 5/2011. In May the outside temperature was around 20–25°C, so boiler fuel capacity was very low, being on average around 306 kW i.e. only 15% of nominal capacity. The main fuel was chipped pine and spruce sawmill offcuts received from a small-scale sawmill. Woodchip moisture content was 21.2% i.e. very low. The burned woodchip quantity was, this time, measured by weighing, which avoided measurement errors in loose volume and chip volume. Additionally, the heated water circuit of the backup oil boiler's heavy oil container was closed for the duration of the measurement, so the energy meter reading showed thermal energy generation of the woodchip boiler without dubious error factors. Derived boiler efficiency

with error limits was $83.1 \pm 6.4\%$. The result is in the same order of magnitude as the previous measurement in which boiler load factor was clearly greater (81% vs. 15%). However, the burned woodchips were drier (26.8% vs. 21.2%). In this measurement the combustion air-fuel ratio was noticeably large, being $\lambda = 3.30$. This equated with a flue gas residual oxygen content of 14.6% in dry flue gases. The large combustion air coefficient was caused by the inability of the boiler's control system to decrease the amount of combustion air, but the combustion air fans were driven for the duration of the measurement at the lowest revolution level allowed by the system. This resulted in low unburned gas loss and very low unburned fuel loss.

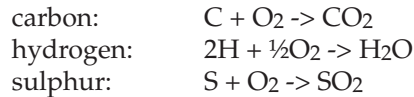
	3/2010	5/2011
Haketyyppi	rankahake Ko2Mä98	sahauspintoja Ku50Mä50
Kosteus	26,8 %	21,2 %
Poltettu määrä	866 kg	415 kg
Tuotettu energia	2625 kWh	1400 kWh
Hake-energia (STD)	3131 kWh 803 kWh/i-m ³	1684 kWh 832 kWh/i-m ³
Kattilakuormitus	81 %	15 %
Hyötysuhde	83,8 %	83,1 %
Virherajat	± 7,5 %	± 6,4 %
Savukaasumäärä	2867 Nm ³ /h	1005 Nm ³ /h
Häkäpäästöt	1361 mg/Nm ³ 10% O ₂ dry	869 mg/Nm ³ 10% O ₂ dry
Polton ilmakerroin	1,58	3,30

Table 3.1. Efficiency measurement summary.

3.3.3 Principle of flue gas analysis

The composition and quantity of flue gases formed in the boiler is theoretically measurable applying a 'flue gas analysis'. The following information is needed for this: the fuel's (in this case woodchips) moisture content, ash content, elemental composition, combustible quantity, and the temperature, relative humidity and amount of combustible air. A flue gas analysis can also indirectly calculate boiler efficiency. In addition to the above details, initial woodchip temperature and effective heat value that takes into account true moisture content and initial temperature are needed. This enables calculation of the thermal capacity and/or energy generated by boiler woodchips and combustion air, i.e. $\phi_{in} = \phi_{BOI} + \phi_{air}$ (see Figure 3.5).

Calculations based on flue gas analyses assume woodchips are completely burned, forming oxygen, nitrogen and water vapour, derived from the combustion air, in the flue gases, and theoretically carbon dioxide, sulphur oxides and additional water vapour. Combustion reactions are:



Oxygen required for combustion is partly supplied by the fuel itself, but oxygen in the combustion air is also required. Air composition is approximately 21 vol-% oxygen, 79 vol-% nitrogen, a trace amount of water vapour and negligible amounts of other elements. The amount of combustion air needed in practice always exceeds the theoretical minimum requirement. This is expressed by an excess air factor λ , which in practice is always greater than one. Example 13 clarifies the method's principle.

In practice, due to partial combustion, flue gases always contain quantities of combustible gas components, primarily carbon monoxide (CO) and small quantities of different hydrocarbons, for example methane (CH₄). Concentrations of these components cannot be calculated by flue gas analysis, so they must be measured separately. The percentage concentration of carbon monoxide gas and hydrocarbons is, however, negligible. For example, usually carbon monoxide concentration is only 1000–3000 ppm i.e. 0.1–0.3%. Methane concentration is around 10–100 ppm i.e. 0.001–0.01%. Therefore, flue gas analysis as a calculation method for formed flue gas quantities is sufficiently accurate. Carbon monoxide and methane concentrations in flue gases must however be taken into account as different losses in the boiler heat balance, as these gases should have burned in the combustion chamber and their caloric value (carbon monoxide: 10.1 MJ/kg and methane: 51.4 MJ/kg) is considerable. Due to the boiler's wet ash removal system, excess water evaporates from the ash bin into the flue gases, increasing water vapour concentration in the flue gases compared to a theoretical flue gas analysis. If exit temperature of flue gases from the boiler is known, the total caloric capacity lost with flue gases $\phi_{\text{flue gas}}$ (also includes carbon monoxide and methane caloric values) can be calculated.

Example 13: 1 kg of woodchips is burned. Elemental composition of its dry matter is 51.0% carbon, 6.0% hydrogen, 0.005% sulphur, 0.3% nitrogen and 0.7% ash and the remaining 41.995% oxygen. Let excess air factor be $\lambda = 2.0$ and moisture content 40%. Taking moisture into account, woodchip composition (weight %) is: carbon 30.6%, hydrogen 3.6%, sulphur 0.0039%, nitrogen 0.18%, ash 0.42%, oxygen 25.2% and water 40%. Combustion air temperature is 24°C and relative humidity 50%. Nitrogen and moisture (water) contained in the combustion air transfer as is directly to the flue gases. The calculations are best made in table format:

Polton ilmakerroin $\lambda =$		2,00								
Polttoaine		HAKE			Hapen tarve	Savukaasut (mol/kg pa.)				
Aine	M (g/mol)	g/kg pa.	mol/kg pa.	mol/kg pa.	CO ₂	N ₂	SO ₂	O ₂	H ₂ O	
Hiili	12,00	306,0	25,50	25,50	25,50					
Vety	2,00	36,0	18,00	9,00					18,00	
Rikki	32,00	0,0	0,00	0,00			0,00			
Happi	32,00	252,0	7,87	-7,87						
Typpi	28,00	1,8	0,06			0,06				
Vesi	18,00	400,0	22,22						22,22	
Tuhka		4,2								
Summa		1000,0	73,66	26,63	25,50	0,06	0,00	0,00	40,22	
Typeä palamisilmasta						200,93				
Hapetta palamisilmasta								26,63		
Vettä palamisilmasta									3,84	
Summa					25,50	200,99	0,00	26,63	44,07	

The table shows that 1000 g of green woodchips contain 306 g carbon, which requires 25.50 mol i.e. $25.50 \cdot 32 = 816$ g of oxygen to burn completely. Combustion product is 25.50 mol i.e. $25.50 \cdot 44 = 1122$ g carbon dioxide. The woodchips contain 36 g hydrogen, which needs 9.00 mol i.e. 288 g of oxygen to burn, and combustion product is 18.00 mol i.e. 324 g water vapour. The negligible amount of sulphur does not even appear in the table. The oxygen 252 g i.e. 7.87 mol contained in the chips is used in combustion and moisture i.e. water, of which there is 400 g i.e. 22.22 mol, transfers as is directly to flue gases. The final outcome is that 1000 g of chips requires $25.50 + 9.00 = 34.50$ mol i.e. 1104 g oxygen to burn completely. The fuel itself contains 7.87 mol i.e. 252 g oxygen, so the rest must come from the combustion air. However, nitrogen and water vapour are also introduced to the boiler with the combustion air, which transfer directly to flue gases. Now we apply an air-fuel ratio of 2, so there is 100% more air than the required theoretical minimum. Eventually 297.19 mol i.e. about 8395 g flue gases are produced and their composition is: carbon dioxide 8.6%, nitrogen 67.6%, sulphur dioxide 0.00032%, residual oxygen 9.0% and water vapour 14.8%. In total around 7381 g of combustion air with an excess air factor of $\lambda = 2$ is used.

Heat is also lost through the boiler walls. This heat loss ϕ_{wall} can be calculated in two ways. If the surface temperature and surface area of the boiler's outer walls are known, wall radiation loss can be estimated employing heat transfer means that account for convective and radiation heat transfer from the wall surface to the boiler room. The loss can also be estimated on the basis of combustion air quantity, boiler room temperature and outside temperature. Usually the only heat source in a boiler room is the heat leaked from the boiler, so the boiler room temperature is derived from this loss. Radiation heat loss through the walls is typically around 1–2% of boiler fuel capacity.

Heat is also lost from the boiler through ash and any unburned solid matter left in it on the grate. The Kälviä heating plant's boiler has a wet ash removal system in which the ash and unburned matter (mainly wood charcoal) fall into the water basin either through the grate or the end of the basin. Ash content of woodchips is ascertained by an element analysis, but the content of unburned matter removed through the sludge-like ash must be ascertained by measurement. The amount of unburned matter depends on, for example, boiler load and combustion air coefficient, and is around 20–200% of the actual ash quantity. Heat loss ϕ_{ass} not only comprises heat lost in the removal of hot

ash, but also the caloric value of unburned fuel matter (wood charcoal: 32.8 MJ/kg). Furthermore water is also lost from the basin with the ash, which must correspondingly be added from outside. A small amount of water also evaporates from the basin into the flue gases. The thermal energy required for this evaporation comes from the flue gases, so it must also be calculated as dissipation power.

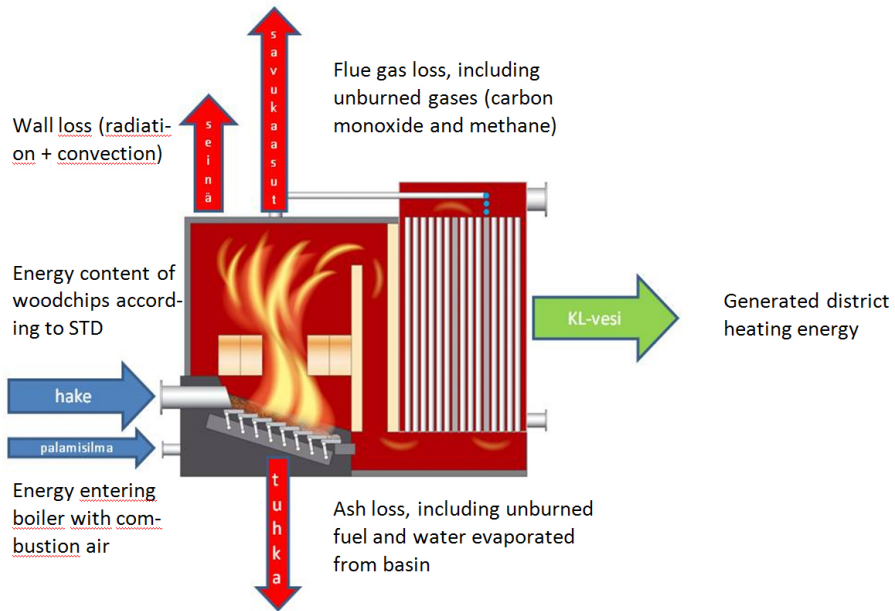


Figure 3.5. Woodchip boiler heat balance.

The remaining caloric capacity generated by combustion of woodchips is transferred to district heating water, so the DH-capacity generated by the boiler is

$$\Phi_{DH} = \Phi_{in} - \Phi_{wall} - \Phi_{ash} - \Phi_{fluegas} \quad (20)$$

where $\phi_{in} = \phi_{BOI} + \phi_{air}$ ja ϕ_{BOI} is the true capacity released on the grate (less than the fuel capacity ϕ_{STD}). as calculated using the standard formula). Boiler efficiency can finally be calculated with the formula

$$\eta_{Boiler} = \frac{\Phi_{DH}}{\Phi_{STD}} \quad (21)$$

where ϕ_{DH} = district heating capacity and ϕ_{STD} = fuel capacity calculated using the standard formula.

3.3.4 Results from the model based on flue gas analysis

Elemental analysis of woodchips used in measurements on 3/2010 was con-

ducted at the Umeå University ETPC unit and is shown as part of Figure 3.7. The carbon content in waterless, completely dry, woodchips was 50.9%, hydrogen content 6.2%, nitrogen 0.2%, sulphur under 0.010%, ash 0.7% and oxygen, 42.0%. Initial moisture content was 26.8%. Exit temperature of flue gases remained constant at an average of 122°C during the measurement period. Surface temperature of boiler walls was around 43°C, so heat loss through walls was convective and taking radiation into account around 20 kW equating to 1.2% of fuel capacity.

<u>Sample batch</u>	<u>Ash content in sample</u>	<u>Amount of unburned in ash sample (kg / kg ash)</u>
1	32.0 %	2.13 kg / kg ash
2	29.6 %	2.38 kg / kg ash
3	31.4 %	2.18 kg / kg ash
4	43.7 %	1.29 kg / kg ash
5	32.6 %	2.07 kg / kg ash
	Mean:	2.01 kg / kg ash

Table 3.2 Ash analysis for measuring unburned concentrations (3/2010)



Figure 3.6. Laboratory analysis of dry matter in ash samples. Photos: Anu-Sisko Perttunen

According to laboratory measurements, unburned matter in the ash sample accounted for an average of 201% of the ash quantity. Ignition residue was measured by drying a wet sample taken from the ash bin augers first to a waterless state in 105°C conditions and then heating the residue to 550°C by gradually increasing temperature. The result means that the "ash sample" collected from the bin auger contained unburned matter 2.01 times more than actual unburned ash (Table 3.2).

Figure 3.7 shows indirect efficiency calculations conducted 3/2010 using an Excel simulation model based on flue gas analysis. Lacking residual oxygen measurements, the combustion air factor has been estimated so that the measured and calculated carbon dioxide concentrations of wet flue gases are

equivalent. Figure 3.8 shows calculations based on flue gas analysis for measurements on 5/2011.

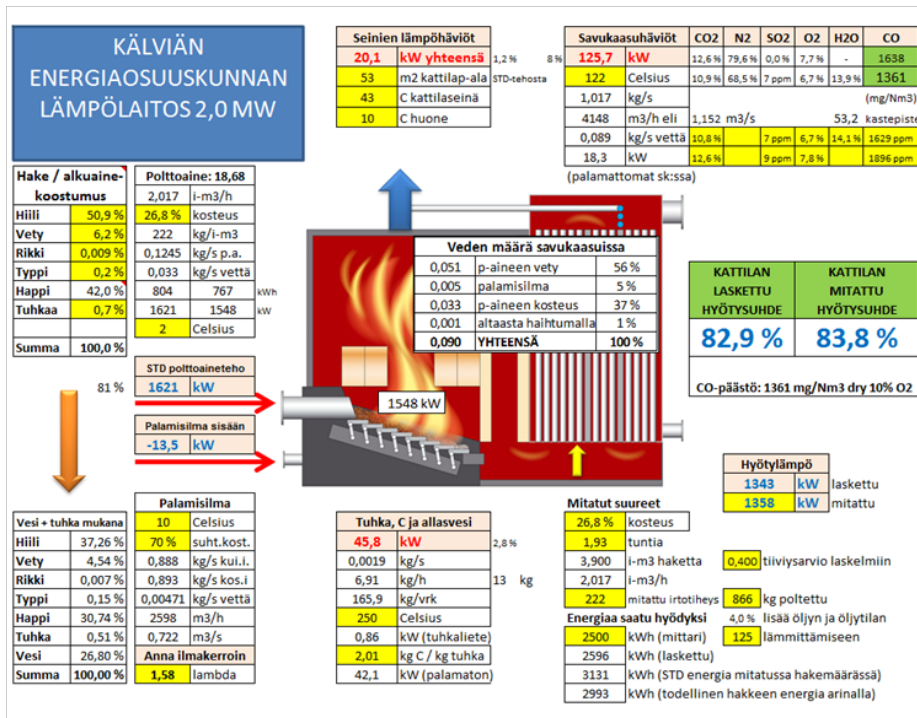


Figure 3.7. Flue gas analysis based calculations for measurements on 3/2010.

The calculated and measured efficiencies are very similar and the difference clearly fits within efficiency measurement error limits. An interesting detail is the origin of the water vapour in the flue gases. Over half i.e. 56% of water vapour in the flue gases comes from hydrogen contained in the woodchips and only just over a third from the actual chips. Excess air factor $\lambda = 1.58$ equated to residual oxygen content 7.7% in dry flue gases. The second measurement results on 5/2011 corresponded with Figure 3.8. An interesting feature of this measurement was the large excess air factor $\lambda = 3.30$, resulting from a very small boiler heat load. The combustion air fans were modulated so that they were unable to supply a smaller amount of draft. More draft reduced carbon monoxide emissions in the flue gases, and the quantity of unburned carbon in the ash sludge was very low.

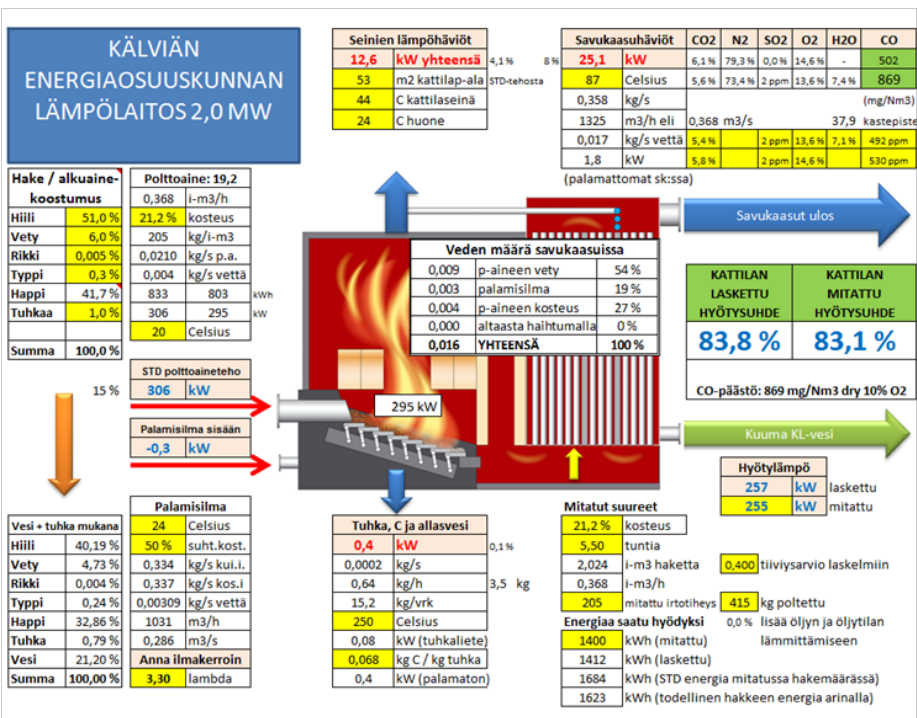


Figure 3.8. Calculations based on flue gas analysis for measurements on 5/2011.

Figures 3.9 - 3.11 show the results for all five measurements. Actual efficiency measurements were only conducted 3/2010 and 5/2011. Efficiency in the other three measurements was indirectly calculated using the flue gas based model. The results show efficiency between 82 – 84% in all measurements. It must be noted that the results are not necessarily comparable, as woodchip moisture in each case was different, and combustion excess air factor and boiler load also varied.

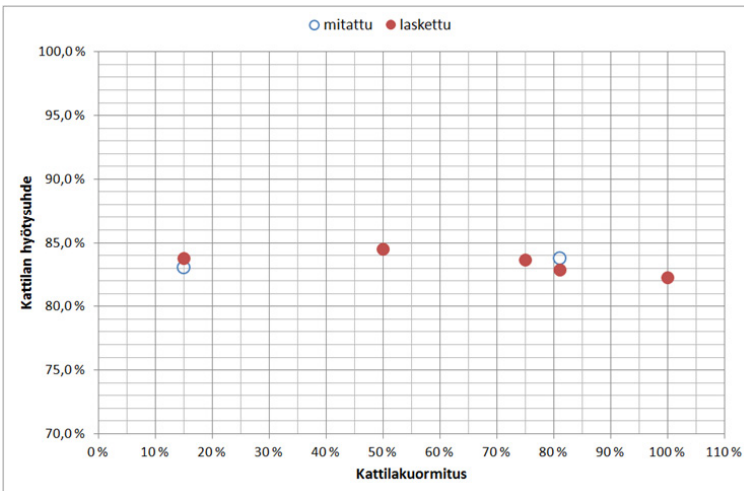


Figure 3.9. Efficiency of the Kälviä boiler as a function of boiler load.

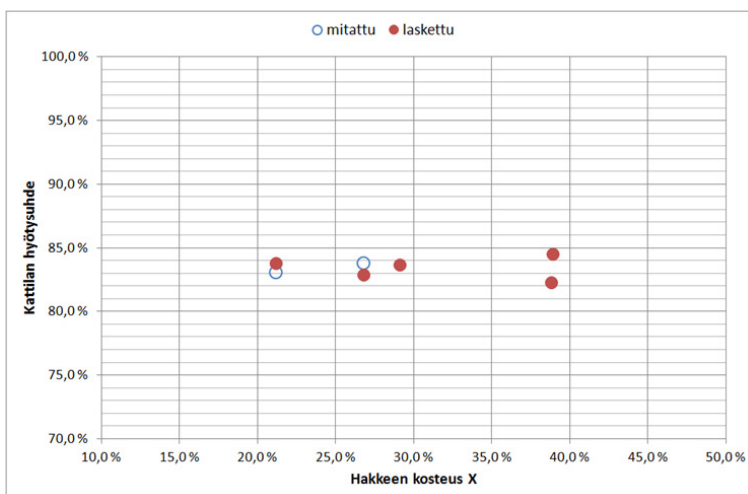


Figure 3.10. Efficiency of the Kälviä boiler as a function of woodchip moisture.

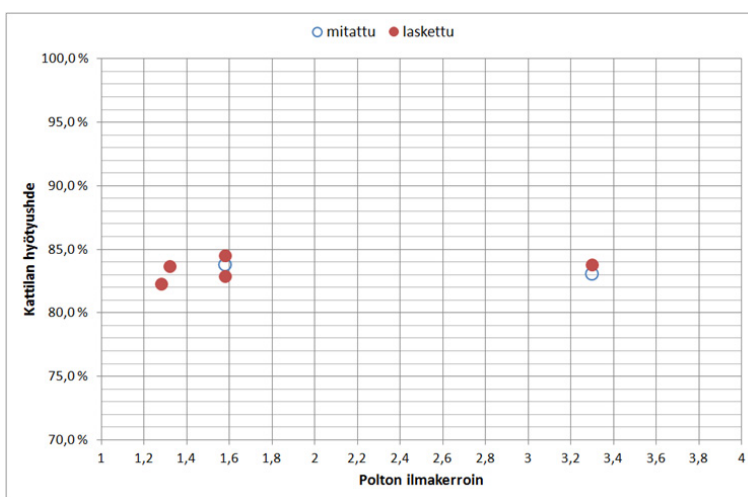


Figure 3.11. Efficiency of the Kälviä boiler as a function of excess air factor λ .

3.3.5 Gaseous emissions of flue gases

Gaseous emissions in flue gases were measured using the GASMET gas analyser. The most significant volatile gases were mainly only carbon monoxide (CO) and methane (CH₄). The results are shown in Figures 3.12 – 3.15 normalised to 10% residual oxygen content in dry flue gases. Concentration of carbon monoxide in flue gases varied between 1000–2000 ppm. There were only negligible amounts of sulphur oxides or hydrogen sulphur in the flue gases. Concentrations were typically 2–8 ppm. This was due of course to the exceptionally low sulphur concentration in the wood used as fuel. Of the other volatile gases, methane concentration was 10–100 ppm. The total amount of nitrogen oxides (NO_x) was clearly under 100 ppm. The results are also expressed in units of mg/Nm³.

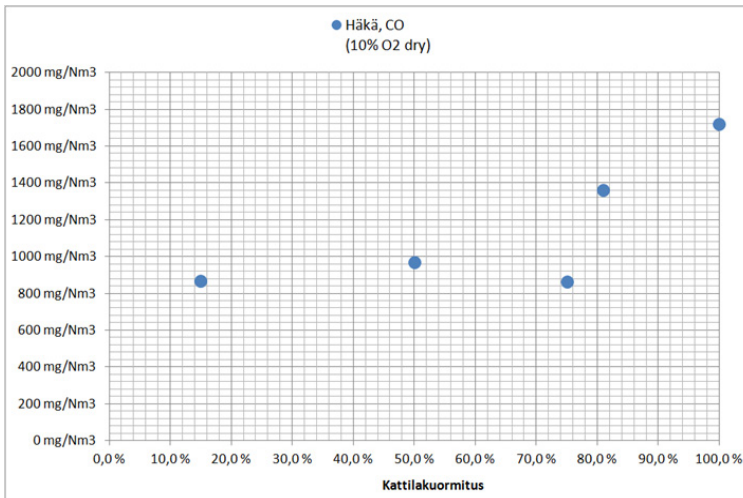


Figure 3.12. Carbon monoxide concentrations in flue gases as a function of boiler load in units of mg/Nm³ (normalised 10% O₂ concentration in dry flue gases).

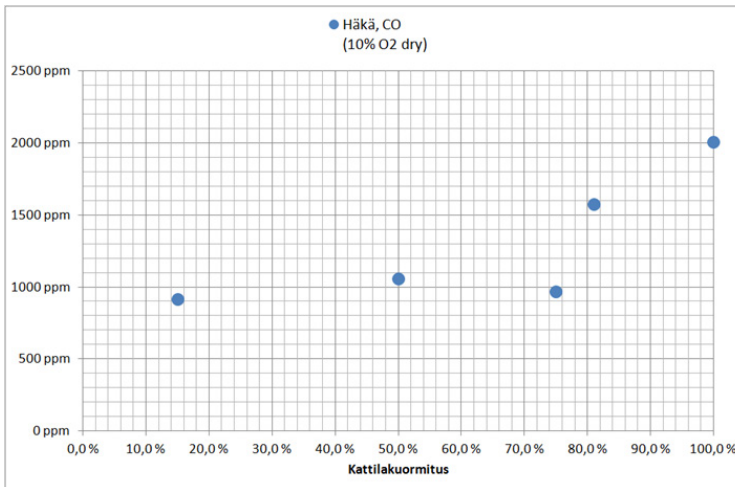


Figure 3.13. Carbon monoxide concentrations in flue gases as a function of boiler load in units of ppm (normalised 10% O₂ concentration in dry flue gases).

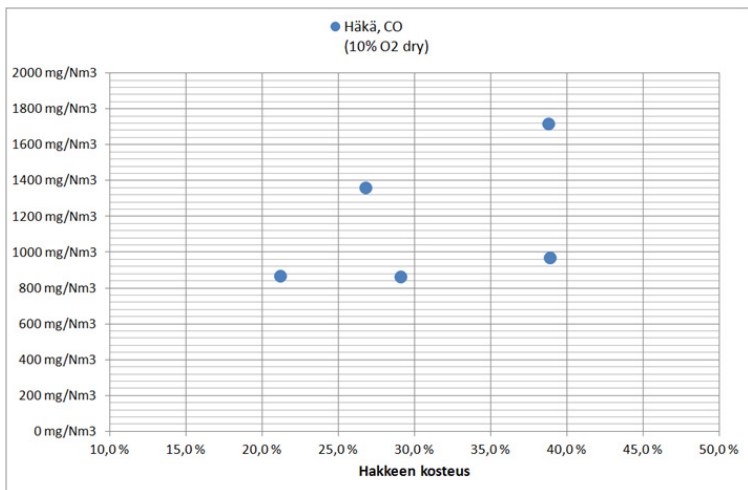
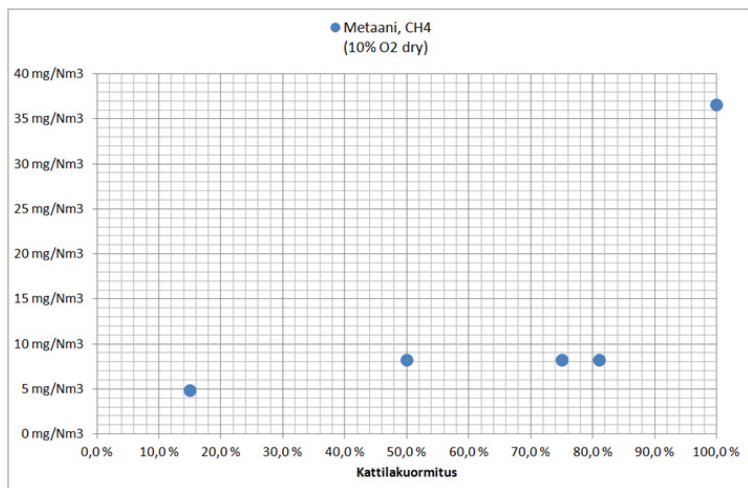


Figure 3.14. Carbon monoxide concentrations in flue gases as a function of wood-chip moisture in units of mg/Nm³ (normalised 10% O₂ concentration in dry flue gases).



Kuva 3.15. Methane concentrations in flue gases as a function of boiler load in units of mg/Nm³ (normalised 10% O₂ concentration in dry flue gases).

3.3.6 Particle emissions of flue gases

Flue gas particle emissions were measured in measurement campaigns conducted 11/2009, 2/2010 and 11/2010, commissioned by the Swedish partners (UmU/ETPC). Table 3.3 shows woodchip type, moisture content and boiler load and Table 3.16 presents the results.

Campaign	Woodchip type	Moisture content	Boiler load
11/2009	Energywood 100%	38.9%	50%
02/2010	Energywood 100%	38.8%	100%
11/2010	Energy wood 50% Forest waste 50%	29.1%	75%

Table 3.3. Woodchip features used in particle emission and ash analyses.

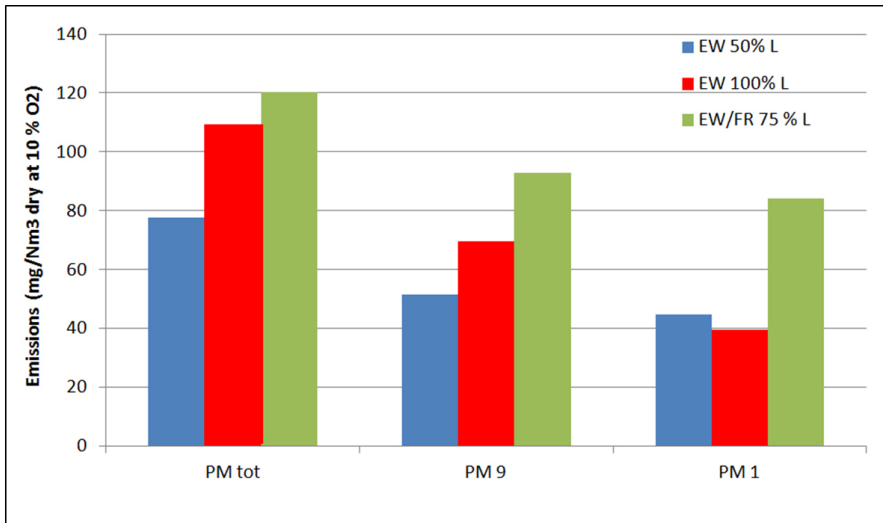


Figure 3.16. Flue gas particle emission normalised to 10% residual oxygen content. Graph: Jonathan Fagerström, Umeå

The term PM_{tot} in Figure 3.16 refers to total particle emission, PM₁ to particles with an effective diameter under 1 micrometre and PM₉ to particles with a diameter under 9 micrometres. The graph indicates that the larger the boiler load, the greater the particle emission. Particle emissions also increase when burning forest waste products. The graph also shows that the majority of particles are exceptionally small belonging to the PM₁ class and their removal from flue gases is difficult. Total particle emission is around 80–120 mg/Nm³.

Currently there are no particle emission limits for boilers of this size. This may change in the future. There has been a suggestion at an EU level of applying German norms, which stipulate a particle emission limit of 30 mg/Nm³ by 2015. Particle emissions at Kälviä exceed this limit. A more detailed analysis of particle emissions can be found on the Forest Power website at (see Jonathan Fagerström's presentation in English).

http://www.forestpower.net/sivu.aspx?page_id=921&luokka_id=221&main=2

3.3.7 Ash measurement and analysis

An analysis of ash forming elements in Kälviä's woodchips as well as analysis of ash and sludge samples was conducted at the ETPC unit of Umeå University. Figure 3.17 shows the results through a special "ash triangle". A more detailed explanation of the use of the ash triangle and its formation principles is found on the Forest Power project website at (see Dan Boström's presentation in English). http://www.forestpower.net/sivu.aspx?page_id=921&luokka_id=221&main=2

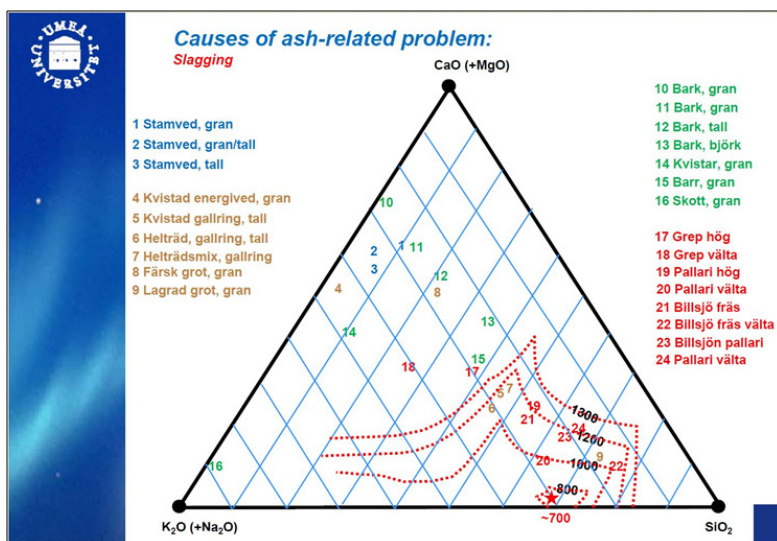


Figure 3.17. Triangle showing the behaviour of melting ash. Graph: Dan Boström, Umeå. The letters A, B and C describe Kälviä's woodchip location in the triangle.

An oval has been added afterwards to Figure 3.17 to describe the area where woodchips to be burned cannot be placed due to the matter formed in its ash. The prevailing conditions within the oval (ash composition and combustion chamber temperature) are such that the ash produced during the burning of woodchips melts either partially or even completely. Melting causes blockages in the grate and contaminates heat exchanger surfaces. A blocked grate prevents the removal of formed ash from the way of a new batch of combustible woodchips and contaminated surfaces lower the thermal capacity transferred from the boiler to the DH-water, raising final temperature of flue gases and thus lowering boiler efficiency.

On the basis of Figure 3.17 woodchips burned at Kälviä (points A, B and C) are located fairly distant from the "problematic" area, so we can conclude that the melting behaviour of ash formed by combusted woodchips to be reasonably good. There should not be a huge danger of a complete melting of the ash, even though partial melting may occur causing a relative fast contamination of the boiler's heat exchanger surfaces. Points 1–24 in the figure represent the UmU/ETPC unit's comparison measurements made with various woodchips as part of other projects.

4. SIMULATION MODEL OF THE KÄLVIÄ WOODCHIP BOILER

4.1 Theoretical initial temperature of flue gases

The theoretical initial temperature of flue gases formed in the combustion chamber during combustion of fuel can be estimated employing an adiabatic combustion temperature. Adiabatic combustion temperature refers to the theoretical maximum temperature of flue gases directly after combustion before any loss occurs. This temperature can be calculated when the fuel energy content, fuel and combustion air mass flow rates, and the quantity and composition of the flue gases formed are known. A higher excess air factor is clearly used with smaller boiler loads (boiler load = fuel efficiency per boiler nominal capacity) than with larger loads. As woodchip moisture increases, combustion air quantity is also often increased. These measures lower the initial temperature of flue gases formed in the combustion chamber, thereby impacting boiler generated thermal capacity and efficiency.

Theoretical initial temperature of flue gases is slightly lower than adiabatic temperature, as now boiler radiation loss into the boiler room and the amount of unburned woodchips must be taken into account. The impact of the combustion excess air factor on theoretical initial temperature of flue gases with woodchip moisture as a parameter has been calculated as an example (Figure 4.1). A woodchip dry matter lower heating value of 18.68 MJ/kg has been applied in the example, woodchip, boiler room and combustion air temperature are 15°C, and relative humidity 60%. The combustible woodchip quantity is a standard 1.0 i-m³/h comprising 2% birch and 98% pine (SRW).

Figure 4.1 shows that when burning these woodchips with an excess air factor of $\lambda = 1$, the theoretical initial temperature of flue gases should be almost 1900°C. In reality, depending on boiler load and woodchip moisture the excess air factor in the woodchip boiler is around $\lambda = 1.3$ –3.5 and woodchip moisture $X = 20$ –40%. The excess air factor of very large boiler loads is typically small, around 1.2–1.8. In these cases, depending on woodchip moisture, theoretical initial temperature of flue gases is 1000–1400°C. With very small boiler loads, for example in the summer, excess air factor, due to modulation system settings, is typically very large, up to 2.5–3.5. Initial flue gas temperature then remains rather low, typically between 600–900°C. Thus the calculated theoretical temperature of flue gases can be used in simulations to describe the initial temperature of formed flue gases before they begin to release heat to the DH-water which cools the boiler walls.

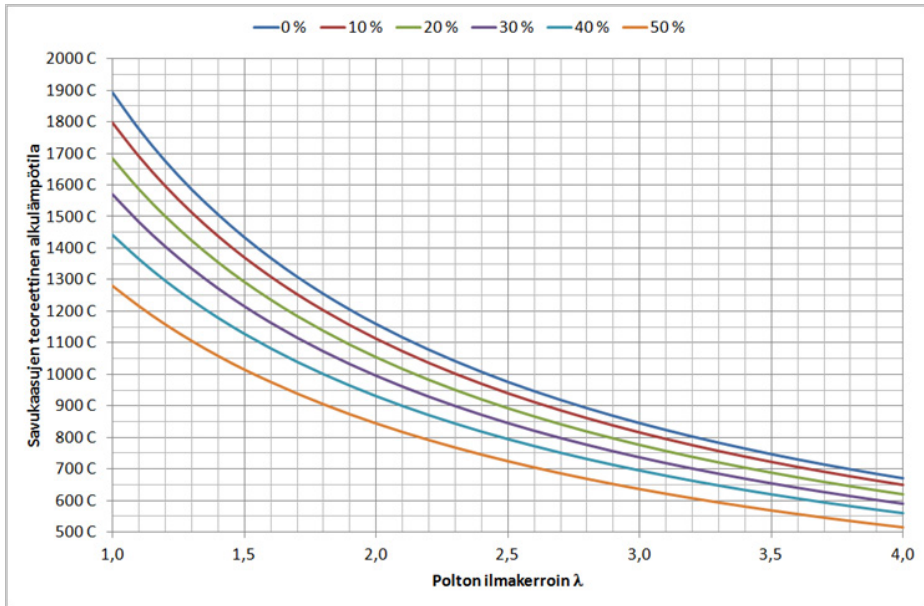


Figure 4.1. Theoretical initial temperature of flue gases as a function of excess air factor and woodchip moisture. The top line depicts moisture 0% and the bottom moisture 50% (lines are drawn in units of 10%).

4.2 Modelling boiler heat exchangers

4.2.1 Conductance and overall heat transfer coefficient

The heat exchange surfaces which transfer thermal energy generated by the boiler to the DH-water comprise the water jacket surrounding the combustion chamber and the convection heat exchanger after the actual combustion chamber. The convection heat exchangers are typically upright and hot flue gases flow alternately up and down in the spaces between them, before exiting into the environment through the chimney with help from a flue gas fan. The flue gases cool as they are emitted and the released thermal energy is transferred to the DH-water flowing in the convection heat exchangers. Estimating overall heat transfer coefficient (U-value) is difficult, but input UA, conductance, can be calculated (A = heat exchange surface area). The manufacturer gives the heat exchange surface area of the Kälviä boiler as 212.7 m².

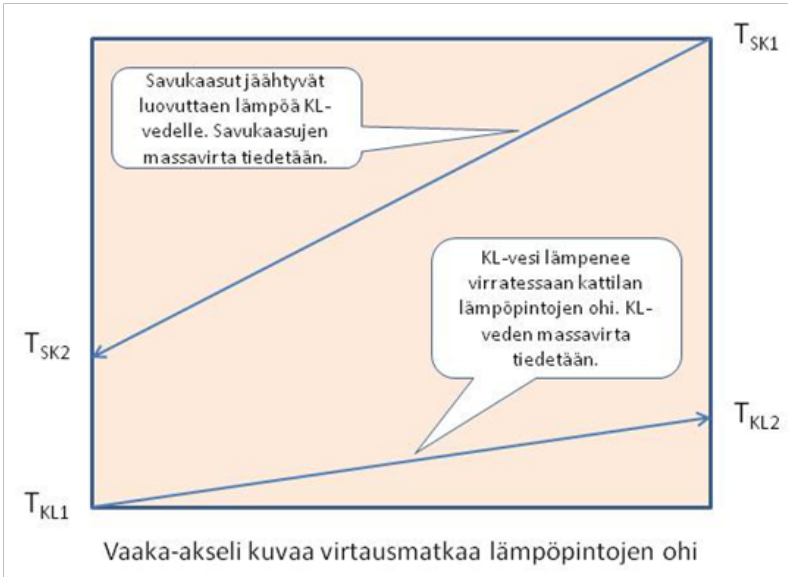


Figure 4.2. Changes in temperature in convection heat exchangers in principle.

Measuring energy capacity released into the DH-water in the boiler (ϕ_{KL}) and simultaneously the outflowing and returning DH-water temperatures (T_{KL1} and T_{KL2}) and also final flue gas temperature exiting the boiler (T_{SK2}), we can calculate the above mentioned input UA. The capacity released into the DH-water can in fact be calculated with the formula $\phi_{KL} = UA\Delta T$, where ΔT is the mean logarithmic temperature difference between hot flue gases and the DH-water to be heated. The initial flue gas temperature released to the heat exchange surfaces T_{SK1} , must also be known in order to use the above mentioned estimation method when measurement possibilities do not exist (see Figure 4.1). Along with efficiency measurements (3/2010 and 5/2011) the above mentioned issues were also measured and these results are presented in Tables 4.1 and 4.2.

	DH cap. (kW)	DH-water mass flow (kg/s)	T_{KL1}	T_{KL2}	T_{SK1}	T_{SK2}	ΔT	Input UA (kW/K)	U-value, W/m ² K (A = 212.7 m ²)
1.	1230	5.78	45	96	1193	126	389	3.155	14.83
2.	1322	6.08	45	97	1193	120	381	3.473	16.33
3.	1269	5.99	46	97	1193	119	378	3.360	15.80
4.	1310	5.92	45	99	1193	122	383	3.418	16.07
ka.	1283	5.94	45.3	97.3	1193	122	383	3.352	15.76

Table 4.1. Mean conductance of boiler heat exchange surfaces, i.e. definition of input UA (A = heat exchange surface area 212.7 m²) for measurement 3/2010.

	DH cap. (kW)	DH-water mass flow (kg/s)	T _{KL1}	T _{KL2}	T _{SK1}	T _{SK2}	ΔT	Input UA (kW/K)	U-value, W/m ² K (A = 212.7 m ²)
1.	258	1.61	46	85	726	83	212	1.218	5.73
2.	276	1.54	46	89	726	87	217	1.270	5.97
3.	262	1.63	46	84	726	88	220	1.191	5.60
4.	245	1.50	46	85	726	83	212	1.157	5.44
5.	232	1.50	49	86	726	88	215	1.080	5.08
ka.	255	1.56	46.6	85.8	726	85.8	215	1.183	5.56

Table 4.2. Mean conductance of boiler heat exchange surfaces, i.e. definition of input UA (A = heat exchange surface area 212.7 m²) for measurement 5/2011.

The bottom row of the tables shows the measurement mean. The calculated mass flow rate of flue gases in measurement 3/2010 was 1.017 kg/s (2867 Nm³/h) and in measurement 5/2011 due to, among other factors boiler load, only 0.358 kg/s (1005 Nm³/h). Total heat transfer factor of the heat exchange surface, the U-value, depends primarily on flue gas conditions, that is flue gas mass flow rate and contamination of the surfaces. The boiler's heat exchange surfaces were cleaned just prior to both measurements, so the results can be considered clean surface values. The following expression for flue gas heat transfer factor is derived from the laws of thermodynamics:

$$\frac{1}{h_{fg}} = \frac{1}{U} - \left(\frac{s}{\lambda} \right)_{steel} - \frac{1}{h_{water}} - \left(\frac{s}{\lambda} \right)_{slag} \quad (22)$$

where s = layer thickness and λ = thermal conductivity.

Let $(s/\lambda)_{steel} = 0.0025/25 = 0.0001 \text{ m}^2\text{K/W}$ (constant) and $1/h_{water} = 1/1500 = 0.00067 \text{ m}^2\text{K/W}$ (assume to be constant) and contaminant layer resistance to be zero, so using formula (22) the value derived for flue gas heat transfer factor is $h_{fg} = 15.95 \text{ W/m}^2\text{K}$. This value strongly depends on flue gas mass flow rate. Let's assume that dependency is expressed $h_{fg} = 15.95 \cdot (m_{fg}/1.017)^N$, for which the two conducted measurements give a value of N = 1.03 for exponent N. Dependency therefore is almost linear. Now we know how flue gas heat transfer factor depends on flue gas mass flow rate.

4.2.2 Taking into account surface contamination

Surfaces on the flue gas side become contaminated over time due to impurities in the flue gases that gradually accumulate on the heat exchange surfaces thereby increasing flue gas side heat exchange resistance. The contaminant level's impact on the overall heat transfer coefficient U can be taken into account with

formula (22), where contaminant level resistance is marked with the term (s/λ) slag. Assume heat conduction of the contaminat level is 0.25 W/mK and maximum thickness before cleaning is 5 mm , deriving a maximum heat exchange resistance of $0.005/0.25 = 0.02 \text{ m}^2\text{K/W}$ for the contaminant layer. The boiler is always cleaned after this, so it is assumed the contaminant layer is completely removed. The total heat transfer factor can be expressed as:

$$\frac{1}{U} = \frac{1}{h_{fg}} + \left(\frac{s}{\lambda}\right)_{steel} + \frac{1}{h_{water}} + 0,02A \quad (23)$$

where contaminant degree A can in the simulation be used to take into account the contaminant layer's impact (for clean surfaces $A = 0$ for and completely contaminated surfaces $A = 1$).

Boiler heat exchangers are finally modelled assuming countercurrent heat transfer coupling, even though in reality it is not. The error is however negligible.

4.3 Unburned gases and carbonised residue quantities

In real combustion unburned gases, such as carbon monoxide and methane, always form in the flue gases. It is not possible to calculate their formation using flue gas analysis, so their presence is determined using measurements. Additionally, for whatever reason, unburned residue, carbonised residue, is present in the boiler ash bin and its quantity can also be estimated using measurements. Generally speaking, the smaller the combustion excess air factor, the more unburned gases and carbonised residue are formed, and vice versa. Let's assume that only combustion excess air factor is significant and that the dependency of formed quantities on the air-fuel ratio is linear.

Figures 4.3, 4.4 and 4.5 present results from all measurements for carbon monoxide and methane content in the flue gases and carbonised residue. Apart from the latter, the dependencies do not converge with linear dependency, but these are the results we will use. The correlations required in the calculations are shown in the graphs. Carbon monoxide and methane are volatile gases and their presence in flue gases always means partial burning and thus boiler heat losses. Similarly, carbonised residue in the ash sludge also means heat loss. The loss can be calculated as the concentrations and thermal values of the components are known (carbon monoxide: 10.1 MJ/kg , methane 51.4 MJ/kg and carbonised residue 32.8 MJ/kg).

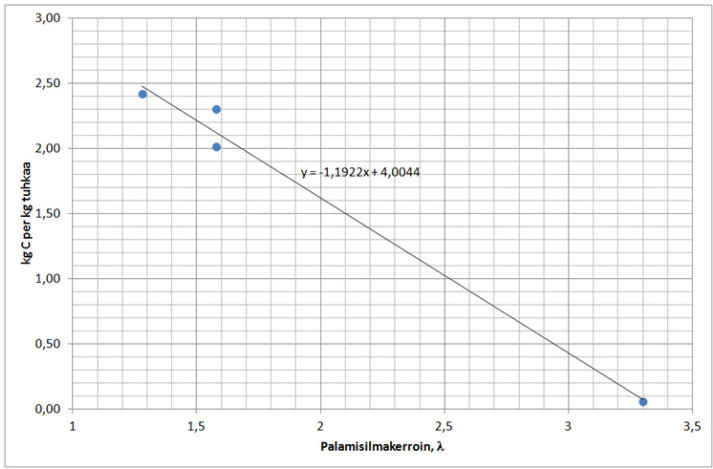


Figure 4.3. Dependency of carbonised residue quantities on excess air factor.

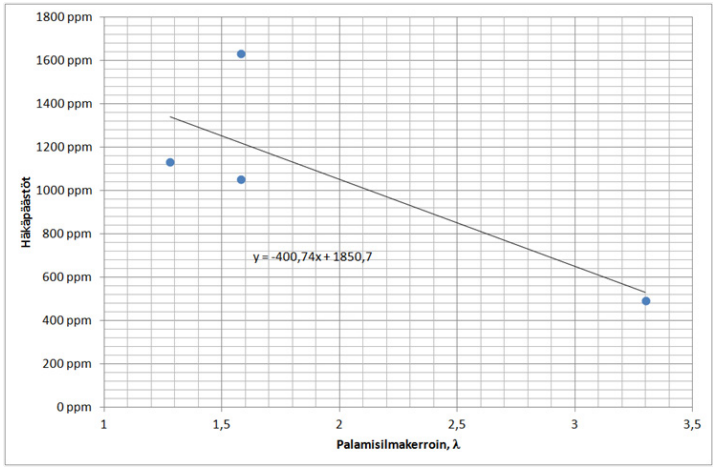


Figure 4.4. Dependency of carbon monoxide (CO) on excess air factor.

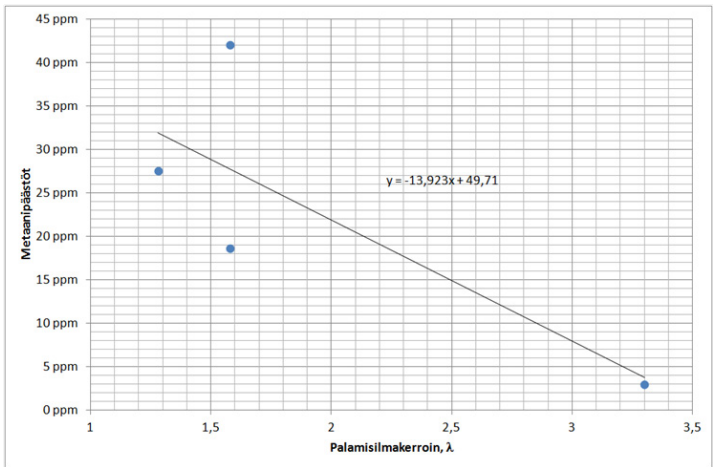


Figure 4.5. Dependency of methane (CH₄) on on excess air factor.

4.4 Simulation calculations

4.4.1 Impact of boiler load on efficiency

Efficiency calculations are conducted with pine woodchips with a moisture content of $X = 40\%$, assuming boiler heat exchange surfaces to be either completely clean (contamination degree $A = 0\%$) or completely contaminated ($A = 100\%$). Initial temperature of woodchips and combustion air are $+10^\circ\text{C}$ and relative humidity of combustion air is 60% . A constant value of $\lambda = 1.74$ has been used for combustion air coefficient (equates to 9% residual oxygen content in dry flue gases). Figure 4.6 also shows boiler efficiency in conditions where the combustion air coefficient becomes linear between $1.3 < \lambda < 3.3$ so that the smallest value corresponds to boiler load $K = 100\%$ and the greatest to $K = 10\%$, better describing reality.

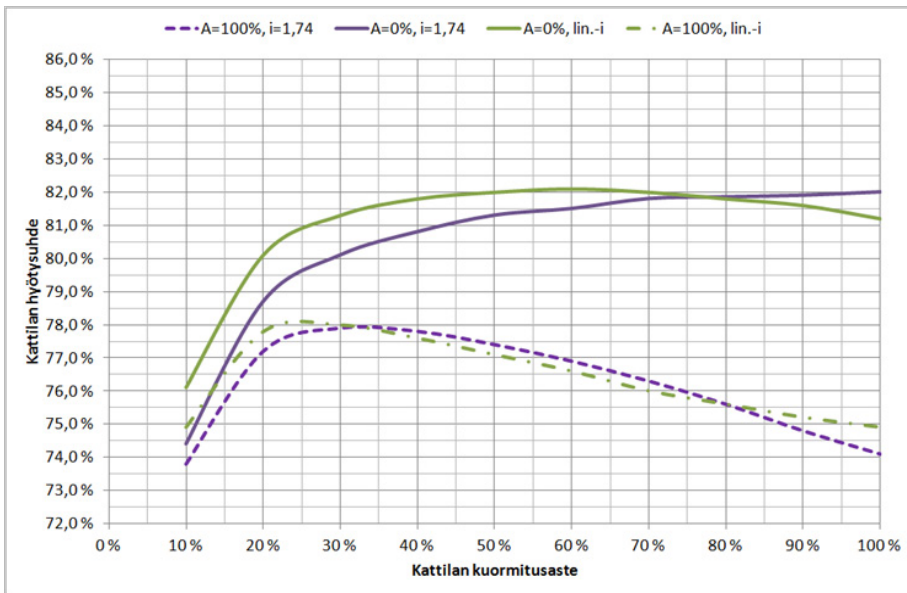


Figure 4.6. Boiler efficiency as a function of boiler load.

Figure 4.6 shows that the efficiency line begins to fall with contaminated heat exchange surfaces ($A = 100\%$) and increasing boiler load. This is due to increased flue gas mass flow resulting from greater boiler load. Diminished heat exchange due to contamination is emphasised with large mass flow values. With clean surfaces ($A = 0\%$) efficiency does not fall even with large boiler loads. Applying a combustion air coefficient that changes linearly in accordance with boiler load, a more constant efficiency is achieved for clean surfaces. Also, efficiency is better with small boiler loads. The significance of excess air factor control decreases with contaminated surfaces.

4.4.2 Impact of woodchip moisture

Figure 4.7 shows the impact of woodchip moisture on efficiency. Other variables are boiler load K and heat exchange surface contamination degree A . Combustion excess air factor is constant 1.74 (equivalent to 9% residual oxygen content in flue gases). The graph clearly demonstrates that as woodchip moisture content increases, efficiency decreases. As moisture content increases from 20% to 50%, efficiency falls by around 2% units. Surface contamination becomes more important especially with large boiler loads ($K = 80\%$), when efficiency with clean surfaces is up to 6–7% units higher than with contaminated surfaces. The difference with smaller loads is only around 1% units.

4.4.3 Impact of surface contamination

Figure 4.8 shows the impact of boiler heat exchange surface contamination on exiting flue gases temperature (woodchip moisture content 40%). Flue gas temperature rises as contamination increases with larger boiler loads.

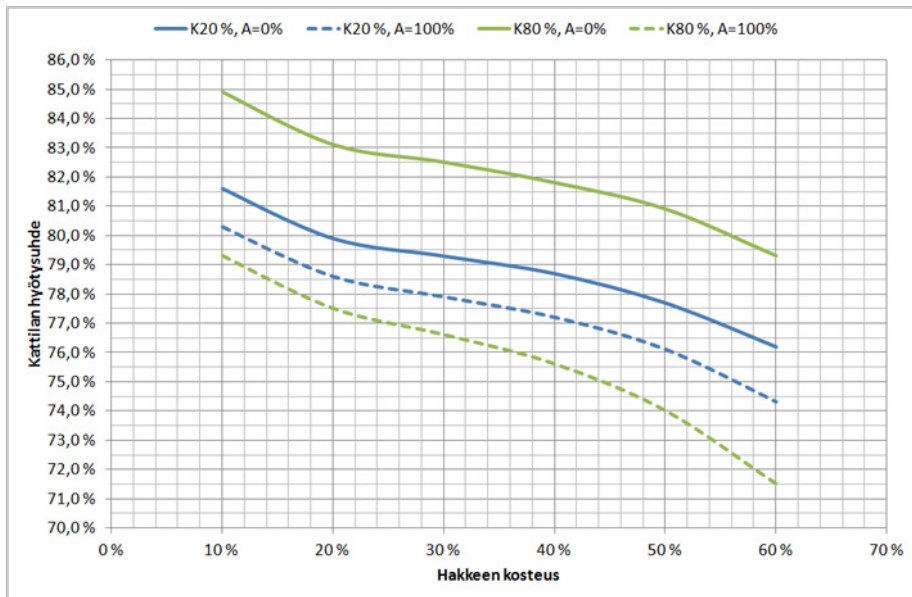


Figure 4.7. Boiler efficiency as a function of woodchip moisture content.

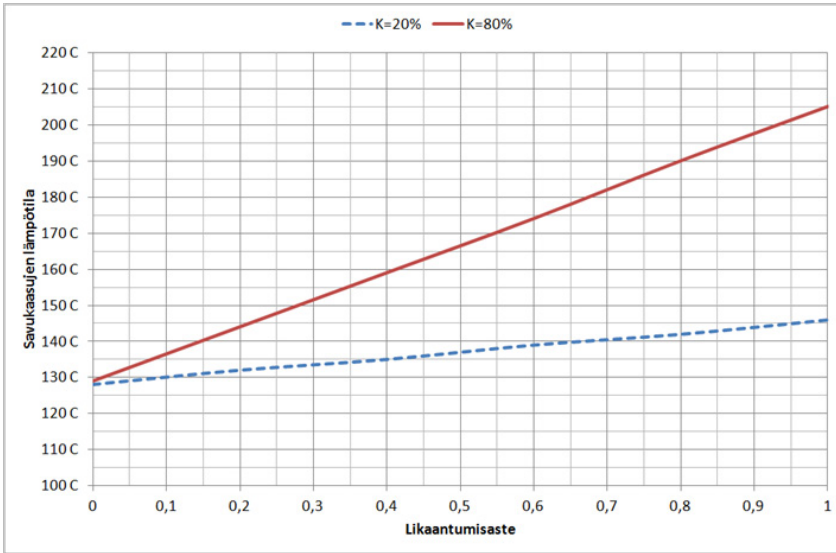


Figure 4.8. Impact of boiler heat delivery surface contamination on flue gas exit temperature.

4.4.4 Condensation of water vapour in the flue gases

Figure 4.9 shows the added efficiency available from the flue gases if these are cooled with a separate heat exchanger before being led up the chimney. As flue gas temperature falls, added efficiency is released, but heat is also generated through condensation of water vapour in the flue gases. The water vapour begins to condense into liquid as soon as flue gas temperature falls below the water vapour condensation point. Condensation point temperature depends on flue gas pressure and water vapour concentration (calculations assume flue gas pressure at 101.3 kPa).

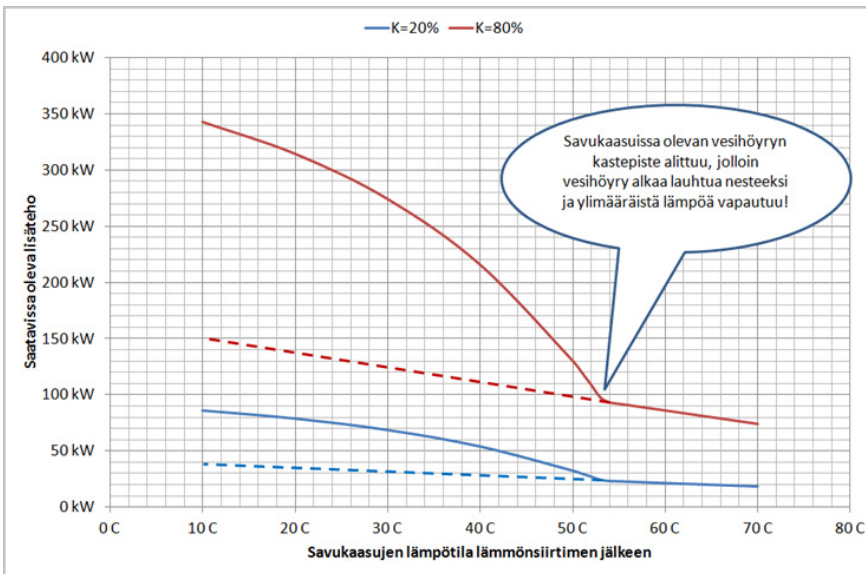


Figure 4.9. Additional efficiency available through condensation of water vapour in flue gases. Broken lines show conditions where condensation does not occur at all.

The example in Figure 4.9 shows burning of pine chips with a moisture content of 40% and boiler load at either 20% or 80%. Combustion air factor is a constant $\lambda = 1.74$ (equivalent to 9% residual oxygen content in flue gases). Using these values, flue gas temperature immediately after exiting the boiler is around 130–132°C and water vapour condensation point temperature is around 52°C. Figure 4.9 clearly indicates that as soon as flue gas temperature falls under the condensation point, there is a huge quantity of excess additional efficiency available, this quantity increasing as the potential temperature to which flue gases can be cooled decreases. The broken line represents no condensation of water vapour. How can this excess thermal energy be utilised? The DH-water returning from consumers is typically around 45–50°C, and would not cool flue gases much under 70°C. The released efficiency would only preheat DH-water by a few degrees. Another possibility of utilising flue gas condensation is preheating the combustion air. Especially in winter, combustion air temperature is very low, so at least in principle cooling flue gases well below condensation point temperature and concurrently using the released heat to preheat cold combustion air by several tens of degrees is possible.

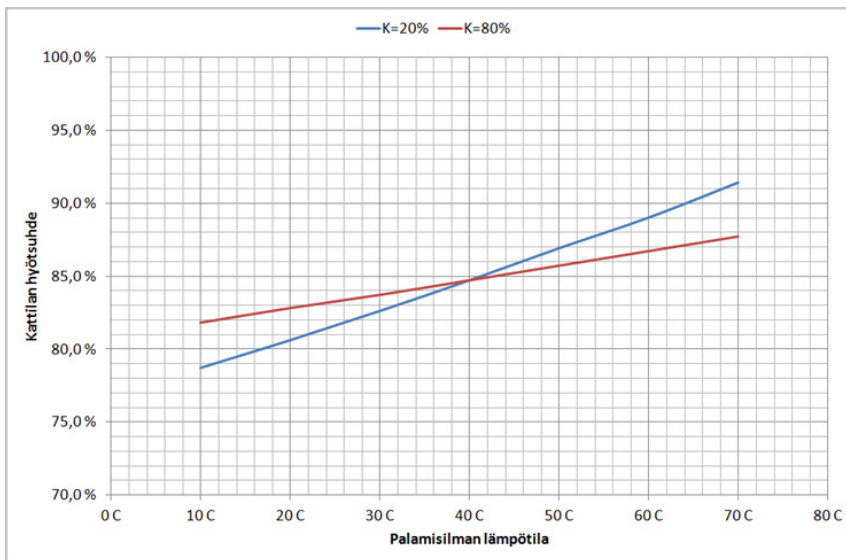


Figure 4.10. Significance of the temperature of combustion air on boiler efficiency.

The calculations assume a basic value for combustion air temperature of 10°C and relative humidity 60%, so absolute moisture content is 0.00454 kg water/kg dry air. Further heating of air does not decrease the water present in it, it only causes a rise in temperature. Therefore no more water than what would come anyway returns to the boiler with the heated combustion air. Figure 4.10 shows the impact of initial combustion air temperature on boiler efficiency when boiler load is either 20% or 80%. The graph indicates that raising combustion air temperature from 10°C -> 50°C, improves efficiency up to 4–8 % percentage units depending on boiler load. The impact is greater with smaller boiler loads and after a certain temperature efficiency is even greater with smaller loads.

4.4.5 Mixing pellets with woodchips

Mixing dry wood pellets with wet woodchips lowers average moisture content of the fuel and raises combustion temperature thereby raising initial temperature of the formed flue gases. Furthermore energy content of the fuel mixture calculated per loose cubic metre rises. Using only pine chips ($X = 40\%$) energy content is 767 kWh/l-m^3 . If 5 vol-% pellets are added, energy content is 883 kWh/l-m^3 and if 10 vol-% pellets are added, energy content is as much as 998 kWh/l-m^3 .

Figure 4.11 shows boiler efficiency as a function of boiler load when pellets with a moisture content of 10% have been added to pine chips. Woodchip moisture content is 40%. Calculations assume boiler heat exchange surfaces to be completely clean. The graph demonstrates that boiler efficiency improves with the addition of pellets. Initially efficiency rises an average 1% unit up to a pellet amount of 5 vol-%. If only pellets are burned, calculated efficiency would only be 6% units greater than with only wet woodchips.

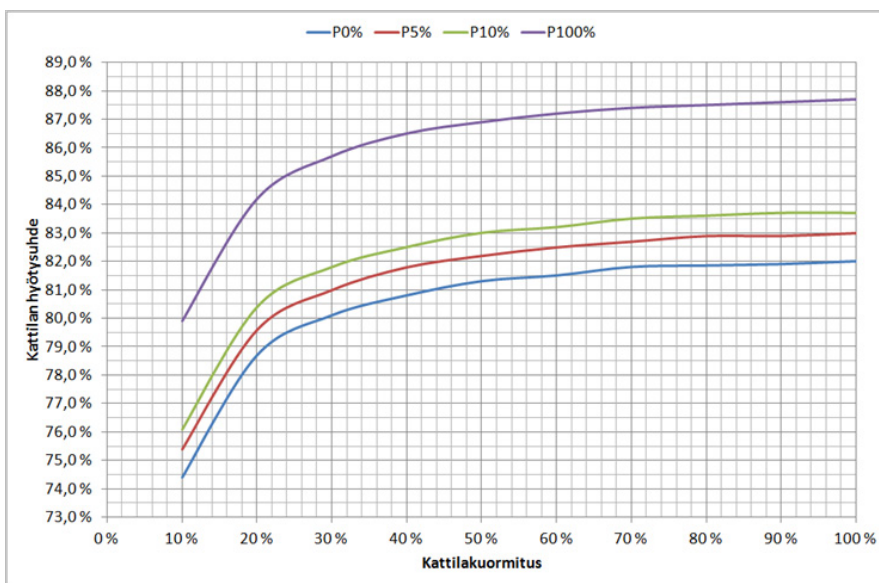


Figure 4.11. Impact of pellet addition on efficiency. Bottom line shows woodchip only ($X = 40\%$). Contamination degree is $A = 0 \%$.

5. CONCLUSION

This woodchip heating booklet is the final report for CENTRIA's areas of responsibility in the broad joint Nordic countries' Forest Power project. CENTRIA's part in the project was the investigation of small-scale woodchip heating plants owned by energy cooperatives in the Central Ostrobothnia region: survey energy cooperatives and heating plants, conduct measurements to clarify efficiency, gaseous and solid emissions of one or several woodchip heating plants, and produce material for users of wood energy and those interested in this energy form in the region. The research was conducted during 2009–2011 in collaboration with for example the Central Ostrobothnia Association of Forest Owners and Umeå University's ETPC unit.

Seven energy cooperatives and one woodchip cooperative operate in the Central Ostrobothnia region. These groups are responsible for six small-scale woodchip heating plants with nominal capacity of 120–2000 kW. Each heating plant was visited, cooperative managers and heating plant supervisors were interviewed, and as a summary of each site a datacard was drawn up. In total, the heating plants currently use 27000 l-m³ woodchips annually, generating around 17000 MWh/a of district heating energy for their customers.

The older heating plant under the responsibility of the Kälviä energy cooperative was selected for more detailed study due to its greater degree of use. This plant was commissioned in 2003 and has a nominal capacity of 2 MW. A total of five field measurement campaigns were conducted at the heating plant during the project, and on three occasions our Swedish partners from Umeå University were also present. Efficiency was determined with direct measurements but also using indirect methods based on heat loss and flue gas analysis. Boiler efficiency varied very little during the measurement campaigns, this being 82–84%. Moisture content of the burned chips varied between 21–39% and boiler load between 15–100%. The woodchips used in the measurements were good quality mainly pine energy trees, though in one measurement case poorer quality woodchips made from thinning wastes was burned as a trial. Gaseous emissions of flue gases (normed to 10% residual oxygen content in dry flue gases) were reasonably low: carbon monoxide emissions were between 1000–2000 ppm, methane emissions between 5–100 ppm and nitrogen oxide emissions around 50–70 ppm. Sulphur oxide concentrations in the flue gases were only negligible. Flue gas particle concentrations were around 80–120 mg/Nm³. On the basis of ash analyses conducted at Umeå University the energy trees burned at the heating plant is a very suitable fuel for small-scale woodchip heating plants due to the low melting tendency of ash. No actual emission limits exist for heating plants of this size. According to the measurements, at least the Kälviä heating plant emissions are generally speaking small. There may perhaps be problems in the future concerning particle emissions if the strict limits planned at an EU level are adopted.

Based on the data accumulated during the measurements, a static Excel simulation model was drawn up for the Kälviä woodchip heating plant. The

model's viability was ensured by direct efficiency measurements and simultaneous flue gas measurements. The model was used to simulate boiler operations with various initial values and fuel mixtures without conducting actual measurements. The results are reasonable, but have not been confirmed with measurements.

One final project on the feasibility of electricity production in connection with woodchip heating plants was also completed as part of this venture. The final project compiled various electricity production methods, from which example calculations for ORC, Stirling, and hot air turbine processes were drawn up.

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