LAPPEENRANTA UNIVERSITY OF TECHNOLOGY

Faculty of Technology
Mechanical Wood Processing

VOC EMISSIONS AND CONTROL TECHNIQUES IN SOFTWOOD VENEER DRYERS

Examiners: Professor, D.Sc. (Tech.) & D.Sc. (Agr. & For.) Timo Kärki
R & D Engineer, M.Sc. Pär-Gustaf Relander

Nastola 25.5.2010

Jonathan Sabbah
Kaivauskatu 13
15340 Lahti
Phone: +358 40 7275452

ABSTRACT

Lappeenranta University of Technology
Mechanical Engineering Department
Mechanical Wood Processing Technology

Jonathan Sabbah

VOC emissions and control techniques in softwood veneer dryers

Master’s Thesis

2010

86 pages, 27 figures and 26 tables

Examiners: Professor, D.Sc. (Tech.) & D.Sc. (For. & Agr.) Timo Kärki
M.Sc. Pär-Gustaf Relander (Raute Oyj)

Keywords: veneer, veneer drying, veneer drying emissions, VOC emissions, VOC control techniques

The objective in this Master’s Thesis was to determine VOC emissions from veneer drying in softwood plywood manufacturing. Emissions from plywood industry have become an important factor because of the tightened regulations worldwide. In this Thesis is researched quality and quantity of the VOCs from softwood veneer drying. One of the main objectives was to find out suitable cleaning techniques for softwood VOC emissions.

In introduction part is presented veneer drying machines, wood mechanical and chemical properties. VOC control techniques and specified VOC limits are introduced also in the introduction part. Plywood mills have not had interest to VOC emissions previously nevertheless nowadays plywood mills worldwide must consider reduction of the emissions.

This Thesis includes measuring of emissions from softwood veneer dryer, analyzation of measured test results and reviewing results. Different air conditions inside of the dryer were considered during planning of the measurements. Results of the emissions measurements were compared to the established laws.

Results from this Thesis were softwood veneer dryer emissions in different air conditions. Emission control techniques were also studied for softwood veneer dryer emissions for further specific research.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
Teknillinen tiedekunta
Puunjalostustekniikka

Jonathan Sabbah

VOC päästöt ja päästöjen vähennystavat havuviilukuivaajassa

Diplomityö

2010

86 sivua, 27 kuvaa ja 26 taulukkoa

Tarkastajat: Professori TkT & MMT Timo Kärki
DI Pär-Gustaf Relander (Raute Oyj)

Hakusanat: viilu, viilun kuivaus, viilun kuivauksen päästöt, VOC päästöt, VOC päästöjen vähentäminen

Tämän Diplomityön tarkoituksena oli tutkia VOC päästöjä havuviilukuivaajasta vaneriteollisuudessa. Päästöasiat on tullut tärkeäksi tekijäksi vaneriteollisuudessa maailmanlaajuisesti. Tässä työssä on tutkittu VOC päästöjen määrää ja laatua havuviilun kuivaajasta. Työn yksi päätarkoituksista oli löytää parhaita mahdollisia päästöjen vähentämismenetelmiä.

Teoriaosassa käydään läpi viilun valmistukseen liittyviä laitteita, puun mekaanisia ja kemiallisia ominaisuuksia sekä VOC päästöjen vähentämistä ja VOC päästöjen raja-arvoja. Viilun kuivauksessa syntyneitä VOC päästöihin ei ole aiempina vuosina tarvinnut välittää, mutta yhä useammin vaneritehtaiden on maailmanlaajuisesti täytynyt pohtia päästöjen vähentämistä.

Tämä tutkimus sisälsi päästöjen mittausta havuviilukuivaajasta, mittaustulosten analysointia sekä tulosten tarkastelua. Eri olosuhteet kuivausprosessissa haluttiin ottaa huomioon mittausten yhteydessä. Tässä työssä myös verrattiin päästömittaustuloksia olemassa oleviin säädöksiin.

Testien ja tutkimusten perusteella saatiin selville havuviilukuivaajan päästöt eri olosuhteilla ja löydettiin mahdollisia päästöjenvähennystekniikoita tulevaa tarkastelua varten.

ALKUSANAT

Työ tehtiin Raute Oyj:lle Nastolan toimipisteessä.

Työni tarkastajana ja ohjaajana toimineelle Professori Timo Kärjelle haluan osoittaa kiitokset opastuksesta ja lukuisista hyvistä neuvoista. Raute Oyj:n tuotekehitysinsinööriä Pär-Gustaf Relanderia haluan myös kiittää ohjauksesta. Kiitos kuuluu myös Rauten muulle henkilökunnalle, jotka ovat auttaneet työni valmistumisessa.

Lopuksi haluan kiittää perhettäni antamastanne tuesta ja kannustuksesta opiskeluihini. Suuri kiitos kuuluu myös kaikille ystävilleni lukemattomista hyvistä hetkistä.

Lahdessa 20.5.2010

Jonathan Sabbah

TABLE OF CONTENTS

REFERENCES

1 INTRODUCTION

Environmental factors have become globally important competition value almost all over the world. Environmental awareness has forced the decision makers to determine pollution limits for harmful processes. Lately global warming has increased conversation of industrial emissions. Emission legislation has become more tighter in the past few years globally and the industrialized countries have been forerunners in that process.

Plywood industry has VOC (volatile organic compounds) emissions to the atmosphere from veneer dryers and presses. Previous researches show that the veneer dryers emit the most of the VOC emissions. All the VOCs from the veneer dryers are wood based.

Raute Oyj is the leading supplier of production technology for the plywood industry worldwide. Raute has supplied hundreds of veneer dryers to the customers all over the world. Raute technology has a high reputation in the plywood industry thanks to high invest at in R&D. Raute has an interest in the decrease the emissions from the veneer dryers, which is the subject for this Thesis.

The research problem in this Thesis is to find out the quality and quantity of the emissions from spruce veneer dryers and to find out the possible methods to decrease the emissions to the atmosphere. There are two possible ways to decrease emissions efficiently. One way is production based, where production parameters are adjusted and the other way is to use added emission control systems. The key points of this thesis is to research the emissions from the softwood veneer dryers and to find solutions to decrease those emissions.

1.1. PLYWOOD PRODUCTION

Plywood manufacturing process has many steps and those are shown in Figure 1. Cutting and sorting could also be done before drying. This order is typical when roller jet dryers are used. When screen jet dryers are used, continuous veneer has to be clipped and sorted after drying. The last part of the process is similar in both cases. This thesis focuses on the emissions of veneer drying in roller jet dryers. (Koponen 2002)

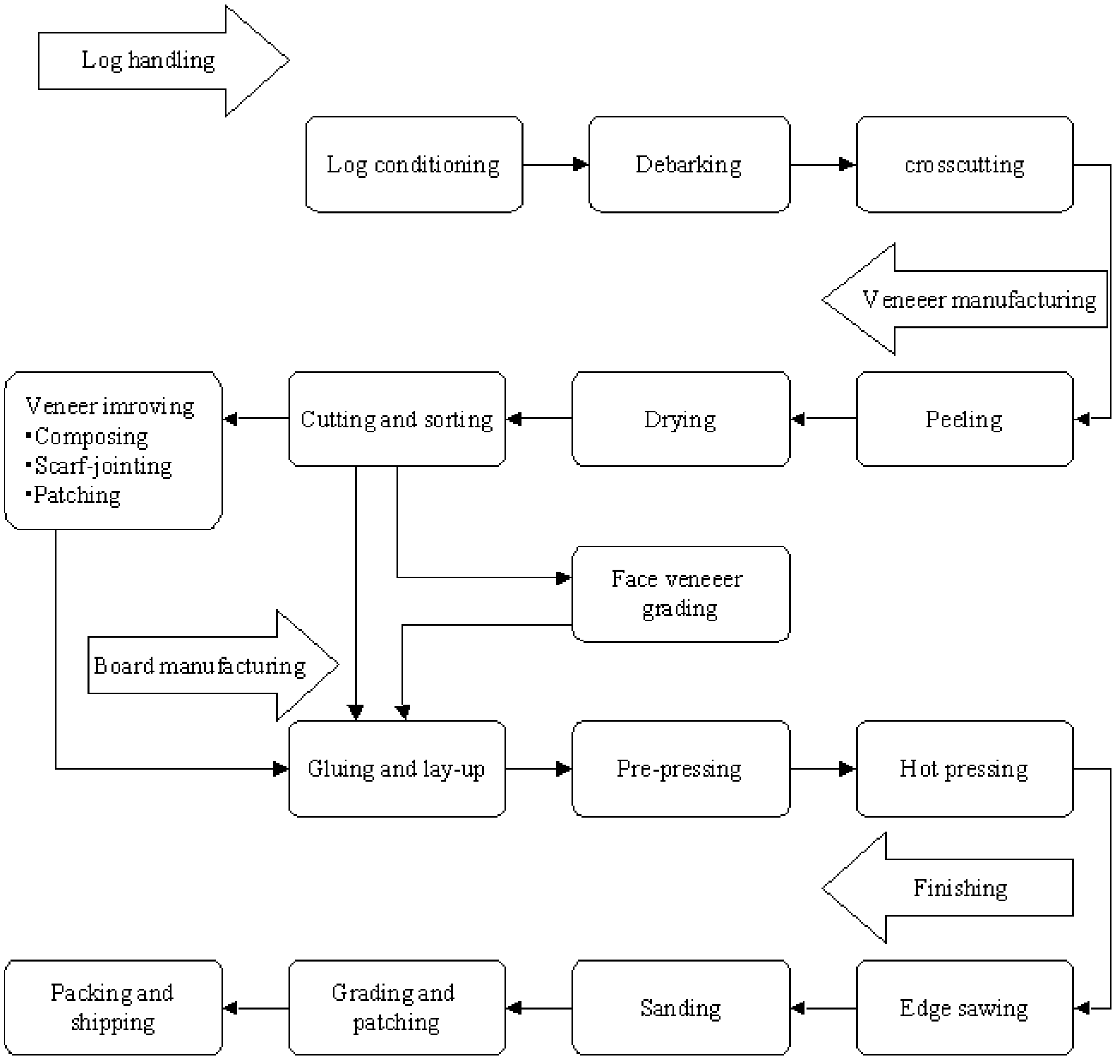

Figure 1. Plywood manufacturing process. (Koponen 2002)

1.2. THE PROPERTIES OF WOOD AND ITS CHEMICAL COMPONENTS

Wood has a heterogeneous structure and many other properties, which affect the drying process. Wood has a cell structure which constituents are cellulose, hemicelluloses, and lignin. Species of the wood are usually divided to softwoods and hardwoods. (Absetz 1999a)

Growing tree increases its diameter by adding new layers of sapwood while the inner parts of wood die. This died inner part is called heartwood and it usually becomes infiltrated with resin, gums and other material. In softwoods (e.g. spruce) water is transported in sapwood and therefore heartwood is drier than sapwood. The moisture content in heartwood is between 30 % and 70 % and the moisture content in sapwood can be as high as 220 %. The moisture content for spruce measured from green veneers is shown in Figure 2. After the drying process the moisture content should be below 7 % for the gluing process. (Simpson 1991, Lehtinen 1997)

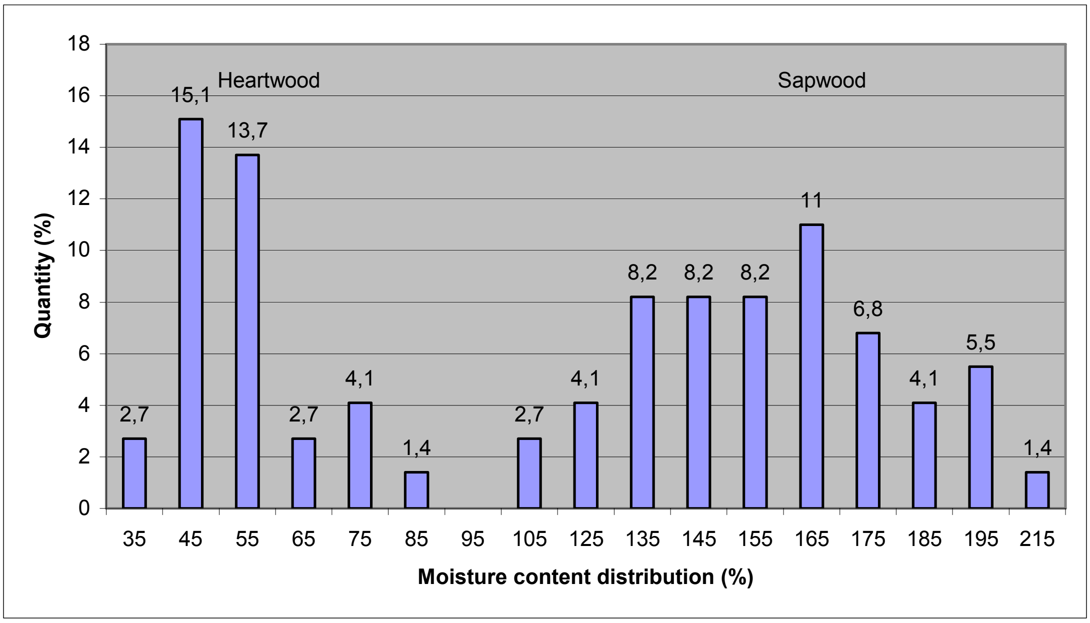

Figure 2. Moisture content distribution for spruce veneer. (Pulkkinen 2000)

The density of wood is dependent on the wood species. The highest wood densities are around 800 kg/m³ and lowest around 350 kg/m³. The dry density of birch is about 550 kg/m³ and 450 kg/m³ for spruce. There can be a huge difference in densities between earlywood and latewood. For spruce the dry density of early wood can be lower than 300 kg/m³ and for latewood it can be even more than 900 kg/m³. (Simpson 1991, Absetz 1999b)

Normally two thirds of wood is composed of polysaccharides. The polysaccharides include cellulose and hemicelluloses. The other substances are lignin and extractives. A general view of the breakdown of chemical wood components is shown in Figure 3. In that scheme wood is divided to low molecular weight and macromolecular substances. Polysaccharides and lignin belong to the macromolecular substances and for example extractives and ash to the low-molecular-weight substances. Extractives have the wide range of constituents. The main sources for the VOC emissions are the extractives. (Fengel 1989, Sjöström 1999)

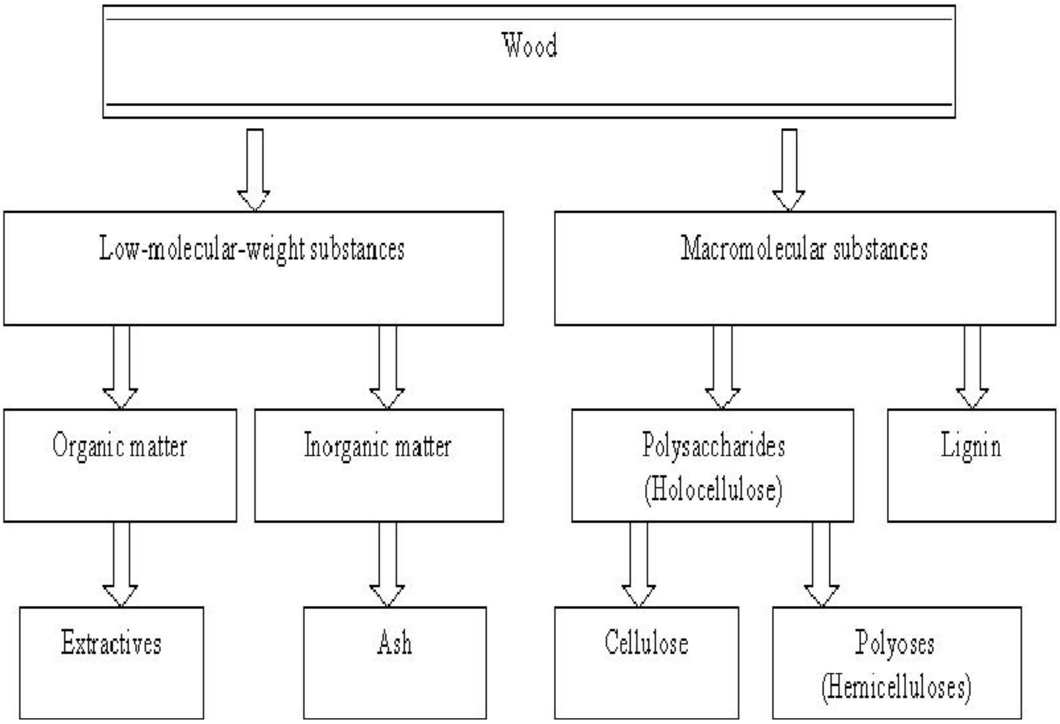

Figure 3. Wood chemical components. (Fengel 1989)

The normal constituents of softwood when dry is shown in Table 1 and in the same table is shown the same data for hardwoods. The main constituents are cellulose, hemicelluloses and lignin.

Table 1. The main constituents of softwood in percent of dry wood weight. (Sjöström 1999)

Constituent	Softwood	Hardwood
Cellulose	37-43	39-45
Calactoglucomannans	15-20	
Glucoronoxylan		15-30
Glucomannan		2-5
Arabinoglucoronoxylan	5-10	
Lignin	25-33	20-25
Extractives	2-5	2-4

1.2.1. POLYSACCHARIDES

Cellulose is the main component of wood. Approximately 50 % of the material in softwoods and hardwoods is cellulose. It is the main structural component of the wood cell walls. It can be characterized as a linear homopolymer of β-D-glucopyranose. (Sjöström 1999)

Hemicelluloses also belong to polysaccharides. They are in close association together with cellulose in cell walls. Hemicelluloses main components are five different sugars, the hexoses glucose, mannose, galactose, the pentoses xylose and arabinose. Some hemicelluloses may additionally contain uronic acids. The molecular chains are much shorter than those in cellulose. Softwoods contain less hemicelluloses than hardwoods and the sugar composition is different. (Fengel 1989)

1.2.2. LIGNIN

Lignin is also a macromolecular wood component as the previously mentioned polysaccharides but its molecular structure is different. Normally there is more lignin in softwoods than in hardwoods. Lignin has also structural differences in softwoods and hardwoods. Depending on the wood species the content of lignin is between 20-33 %. The main physical role of lignin is to reinforce the wood structure. Lignin is located in cell walls and the middle lamella. Lignin encrusts the cell following the formation of cellulose and hemicelluloses. Lignin is an amorphous polymer and it is composed from hydroxylated phenyl-propane units. (Sjöström 1999)

1.2.3. EXTRACTIVES

Wood extractives cover a great number of different compounds, which are extractable from wood. The term extractives is used to subscribe the hydrophobic components in wood that are extractable. The extractives amounts only to a few percent of the material in wood. Inside different parts of the tree and between different wood species the concentration of the extractives vary. The acetone extract and its fractions are shown in Table 2. The wood species of the table are spruce, pine, birch and aspen. The first two species are softwoods and the last two are hardwoods. (Fengel 1989)

Table 2. Percentage of the extracts and those fractions from dry wood. (Fengel 1989)

	Picea abies (Norway spruce) %	Pinus sylvestris (Scots pine) %	Betula verrucosa (Birch) %	Populus tremula (Aspen) %
Acetone extract	2,22	3,1	3,46	4,53
Ethyl ether insolubles	0,95	0,68	1,43	2,01
Ethyl ether solubles	1,24	2,42	2,03	2,3
Petroleum ether insolubles	0,15	0,08	-	0,04
Petroleum ether solubles	1,04	2,29	2,03	2,27
- Free fatty acids	7,52	7,55	-	4,67
- Resin acids	27,37	29,03	0,3	0,75
- Neutral componds	62,13	60,59	99,7	94,58
- Hydrocarbons	1,84	3,21	1,99	5,01
- Waxes	8,41	3,64	9,67	13,53
- Triglycerides	18,67	38,18	39,88	45,68
- Higher alcohols	9,55	6,06	7,68	10,59
- Diglycerides	5,26	1,39	8,48	2,55
- Monoglycerides	5,26	0,79	11,07	5,2
- Oxidized compounds	13,05	1,89	14,46	6,72

Extractives are usually divided into:

- neutrals, consisting of saponified fatty acids and di- and tri-terpenes
- free acids, consisting of fatty and resin acids
- volatiles, consisting of terpene-like materials.

The terpene group consists mainly of mono-, sesqui- and diterpenes. Monoterpenes are the most volatile group of wood components. The boiling points for the monoterpenes are 150 °C to 180 °C. Spruces and pines resin consist 25-30 % of monoterpenes. The estimate of the monoterpene content in wood is approximately 0,1 % to 0,15 % for spruce and 0,2 % to 0,6 % for pine. The terpene content for spruce is dominated by three monoterpenes: alfa-pinene, beta-pinene and delta-3-carene and the relation with these terpenes is approximately 3:2:1. The compositions of the monoterpenes in different softwood species are shown in Table 3. (Granström 2005)

Table 3. Composition of the monoterpene fraction from softwoods. (Fengel 1989)

	α-pinene	β-pinene	Δ3-carene	Camphene	Limonene	p-Cymene	Terpinene	Terpinolene	Myrcene	Sabinene	β-Phellandrene
Wood species	%	%	%	%	%	%	%	%	%	%	%
Abies Alba	39	3	4,5	tr.	53,5	-	-	-	tr.	-	tr.
Abies amabilis	15,5	16,5	38	0,5	1	-	-	tr.	1	-	26,5
Abies grandis	13	18,5	0,5	34,5	5	-	-	-	0,5	-	26
Picea abies	58	24	2,1	3	4,5	0,5	-	0,4	-	-	-
Pinus aristata	8,8	11,2	64,1	0,1	7	-	-	3,4	3,6	-	2,3
Pinus balfouriana	81	1,9	tr.	0,9	14,1	0,3	-	1	0,6	-	0,2
Pinus elliottii	62,6	20,6	-	1,4	1,7	-	-	0,4	1,7	-	8,1
Pinus heldreichii	11	0,5	-	0,2	82,8	-	-	-	0,6	-	-
Pinus monophylla											
sapwood	46	2	3	1	7	-	5	4	22	-	8
heartwood	67	2	-	1	3	-	1	1	20	-	3
Pinus occidentalis	63,8	22,2	7,7	0,2	-	-	-	-	1,1	-	-
Pinus ponderosa	10,2	16,5	36,3	1,4	12,1	1	1,4	1,9	-	-	1,4
Pinus strobus	67	18	-	2,9	0,9	-	-	0,5	0,9	-	0,5
Pinus taeda	64	28	-	1,3	1,5	-	-	-	2	-	0,5
Pinus tropicalis	93,2	3,1	-	1,2	0,8	-	-	0,1	0,8	-	0,6
Pseudotsunga menziesii	31	36	10	0,5	5	-	-	5,5	1	9,5	1,5

1.3. VENEER DRYING

1.3.1. HEATING METHODS

There are two common methods to heat veneer. These two methods can be divided to indirect and direct heating. Indirect heating method means that the imported heat is mainly from steam. In the steam heating method the dryer is separated from the boiler. This steam heating method is the oldest and most frequently used in dryers. (EPA 450, 1983; Baldwin 1995)

In direct heating method the heating sources are gas and wood. Dryers that use fossil fuels have slowly vanished because the energy costs have increased rapidly. Wood-waste burners have also become a potential choice for future drying because of the rising energy costs and shortages of gas. (EPA 450, 1983; Baldwin 1995)

1.3.2. AIR FLOW PATTERNS

Dryers can use different ways to circulate hot air over the veneer sheets. The three most common ways to guide the airflow in dryer are:

- longitudinal flow dryer
- cross-circulation dryer
- impingement (jet) dryer (Baldwin 1995).

1.3.3. VENEER DRYERS

Longitudinal flow dryer

In the longitudinal flow dryer method the centrifugal fans located at the end of each zone blow the air. The longitudinal flow dryers have one to three zones and it consists eight to twenty sections. Two-zone longitudinal flow dryer is shown in Figure 4. The air flow in the dryer is parallel to the flow of veneer. (EPA 450, 1983)

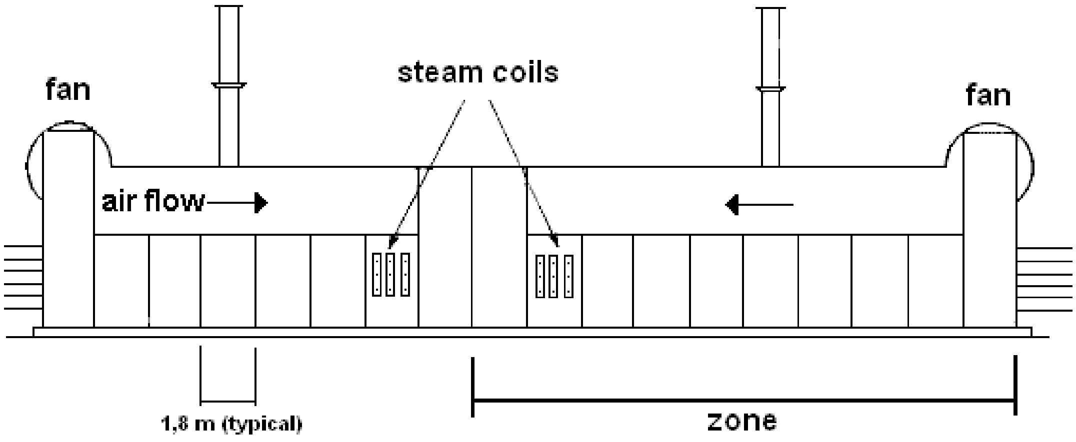

Figure 4. Two-zone longitudinal flow dryer. (EPA 450, 1983)

Cross-circulation dryer

A cross-circulation dryer is normally divided into zones with two sections per each zone. This kind of dryer is usually eight, sixteen or twenty sections long. Axial fans are in the exhaust side of zones and the airflow is across the width of the dryer and the flow of direction changes in each zone. (Baldwin 1995)

Impingement dryer

Impingement dryer is called a jet dryer. This dryer type is the most used and is shown in Figure 5. A jet dryer is similar to a cross-circulation dryer but with some differences. Airflow direction is the same throughout the dryer. In the jet dryer hot air is directed onto the veneer surface through nozzles or tubes. These nozzles direct the air onto the veneer sheets. A section view from dryer is shown in Figure 6. In the jet dryer the air enters through the jet tube and impinge onto the veneer. (Baldwin 1995)

Dampers are placed in each zone to control the moisture content and from each damper the air is directed to the exhaust pipe. While the dampers are closed, the moisture content and pressure inside of the dryer increases. This increases the fugitive emissions from the ends of the dryer. It has been researched that the closed dampers increase efficiency of dryers from 15 to 25 percent. (EPA 450, 1983; Baldwin 1995)

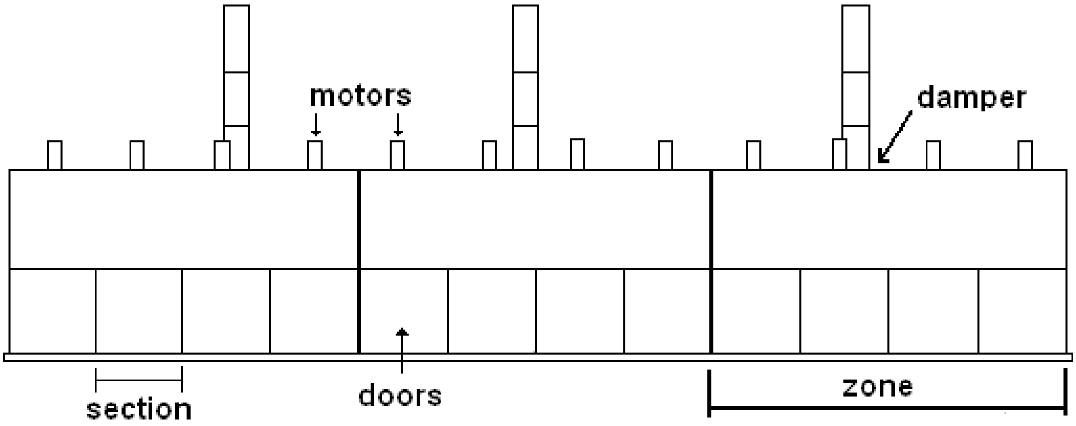

Figure 5. Three zone, twelve section dryer. (EPA 450, 1983)

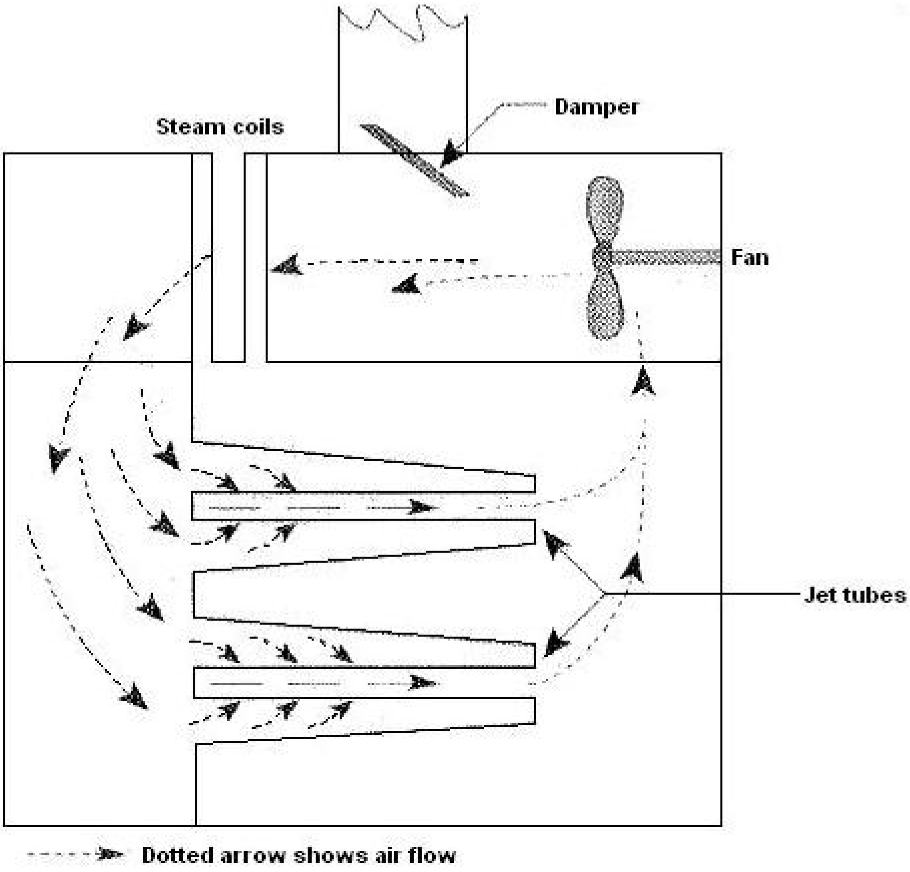

Figure 6. Air circulation in a section of a jet veneer dryer. (Baldwin 1995)

1.4. DRYING INFLUENCES ON WOOD AND THE ENVIRONMENT

The temperatures in veneer drying are high compared to the other wood drying methods. Currently the temperatures are much higher than in the past because of the need for shorter drying times. In some cases the temperatures are even higher than 220 °C. Table 4 shows the averages of temperatures used in veneer drying. The same table also shows the limits of drying times in some factories. (Lehtinen 1997)

Table 4. Veneer drying temperatures and drying times. (Lehtinen 1999)

	Spruce			Birch		
	Average	Min	Max	Average	Min	Max
Drying temperature [°C]	184	170	220	178	170	200
Drying time [min]	-	3	12	-	2,5	5

Traditionally veneer drying is divided into three parts. In a heating zone veneer is warmed up. Veneer moisture content does not change in the warming part of drying. (Pulkkinen 2000)

In the next part the veneer temperature stays constant but the veneer moisture content decreases at constant speed. Free water from wood cells is evaporated in this part. (Pulkkinen 2000)

In the last part of drying the veneer temperature increases fast heading to dryer air temperature. The moisture content decreases but more slowly than during the equilibrium zone. In this final part bound water is evaporated from the wood cells. These three parts can be seen in Figure 7 where drying parameters are shown for red beech. After these three parts there is normally a veneer cooling section. In the cooling section the moisture content and drying tensions differences inside the veneer are decreased. (Lehtinen 1997, Pulkkinen 2000)

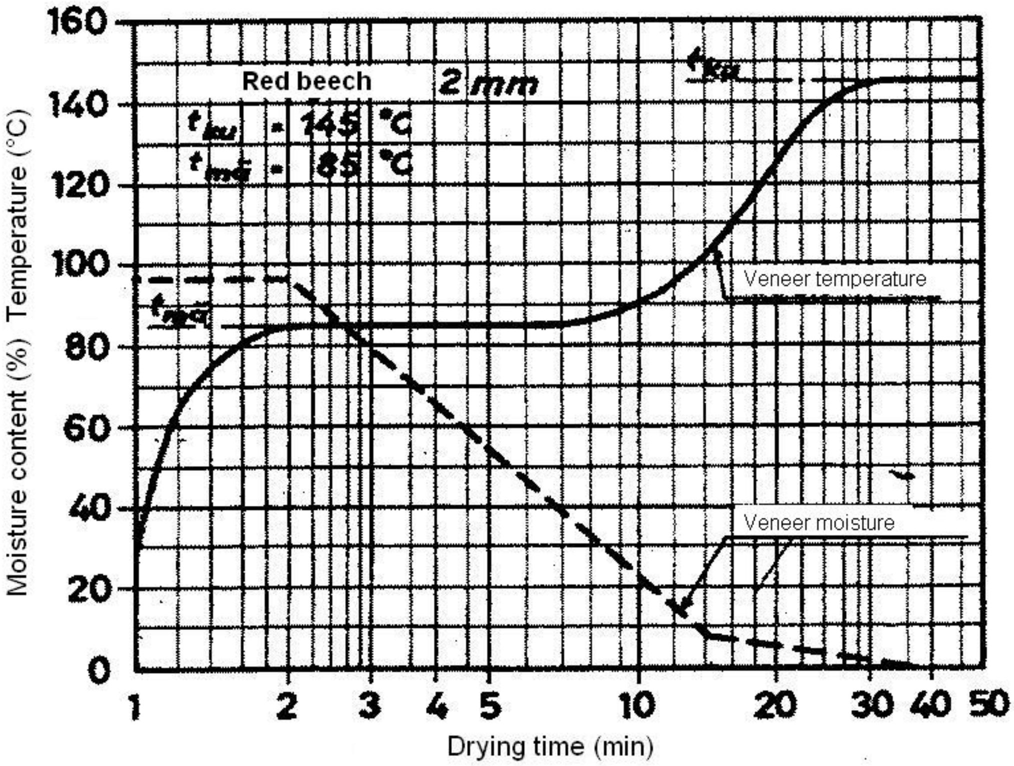

Figure 7. Drying parameters for red beech. (Lehtinen 1997)

In wood thermal treatment studies it has been noticed that between temperatures 170 °C and 220 °C the structure of wood transforms. Some of these transformations are mentioned in following chapters. Similar high temperatures are normally used in veneer drying and therefore you can assume similar affects on veneer. (Lehtinen 1997)

1.4.1. CHANGES IN WOOD DURING DRYING

When wood is heated to over 150 °C, many chemical and physical features of the wood change. As the temperature is lifted up to over 200 °C, the changes are increased. In those temperatures moisture expansion slows, biological living decreases, the color changes, extractives evaporate, wood lightens, equilibrium moisture content lowers and the thermal insulation capacity increases. Those changes are mainly the result of the thermal decomposition of hemicelluloses. Temperature, drying time, wood dimensions and the moisture content of wood and surrounding air influence the decomposition time and intensity. (Viitaniemi 1996)

The following changes occur in wood at different temperatures:

0 - 100 °C	Free and bound water is evaporating.
100 - 150 °C	Wood decomposes slowly, forming first degradation products, water still evaporates and carbohydrate polymer chains start to break.
150 - 200 °C	Wood is still decomposing, carbohydrates starts to decompose, gases start to form.
200 - 290 °C	Wood is decomposing, free acids are formed, carbohydrates are still decomposing, lignin starts to decompose
> 290 °C	Woods decomposing continues, the pyrolysis of the wood begins. (Viitaniemi 1996)

1.4.2. EMISSIONS FROM DRYERS

Most of the drying emissions come from the extractable portions of wood. Organic compounds in veneer dryer emissions comprise terpenes, resin and fatty acids. Type and amount of emissions from dryers is dependent on the dryer type. (A study of organic… 1983)

In gas-fired dryers the atmosphere contains all the products of combustion. Usually unburned methane and other low molecular-weight hydrocarbons are some of the emissions from gas-fired dryers. (A study of organic… 1983)

Wood-fired dryers can emit more organics than gas-fired and steam-heated dryers because it also emits combustion gases. Wood-fired dryers may have less overall organic emissions than steam-heated dryers because of the high temperature of 1100 °C in the combustion unit. (A study of organic… 1983)

One main reason for the emissions is the type of wood dried in the process. For example, on the basis of mass emissions per production unit, drying Spruce veneer may yield over three times the emissions compared to the drying of Birch. The differences in emissions of these wood species are shown in Table 5. (Control techniques… 1983, Nurmi 1997)

The moisture content and pressure inside of the dryer have an influence on the emissions. Therefore damper stack settings also influence the amount of organic material. (Control techniques… 1983)

Particulate matters and VOCs from dryers are dependent on the heating type and wood species. Carbon monoxide (CO) emissions from dryer are only depending on dryer heating type. Wood species have no significant effects on CO emissions. Also sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions depend only on the heating type of the dryer. Wood species are not considered to have significant effect on the NO_x emissions. (Control techniques… 1983)

Table 5. Total volatile organic compounds from a dryer for birch and spruce. (Nurmi 1997)

	Terpenes tot.	Other volatile constituents	TOTAL VOC
	g/veneer-m³	g/veneer-m³	g C/product-m³
Birch			
before scrubber	-	-	59
after scrubber	-	16	22
Spruce			
before scrubber	-	-	150
after scrubber	-	-	130
	g/h	g/h	g C/h
Birch			
before scrubber	-	-	230
after scrubber	-	61	85
Spruce			
before scrubber	-	-	650
before scrubber	260	47	590

1.4.3. ENVIROMENTAL EFFECTS OF VOC EMISSIONS FROM DRYING WOOD

The biggest environmental effect from VOC emissions is the formation of photo-oxidants. Normally the reactions between monoterpenes and ozone (O_3) lower ozone rate. Monoterpenes and ozone reaction with nitrogen oxides (NO_x) and sunlight starts to produce more ozone. Nitrogen oxides and terpene emissions together increase ozone levels considerably. The most favorable condition to form ozone is when the concentration rate of the VOC and the NO_x is between 5:1 and 20:1. (Ailasmaa 1996, Granström 2002)

In the forest sector the nitrogen oxides emissions has a relatively higher share in the formation of ozone than the VOC emissions. The terpene emissions from forest industry are not the most active kind of ozone formers.

Terpenes are also emitted from forests. Finnish meteorological institute has researched that forestlands in southern Finland annually produce 1070 kg/km² VOCs. (Ailasmaa 1996, Kellomäki 2001)

Blue haze from stack gas emissions has been a concern in many places. For example in the plywood mill in the Willamette Valley in Oregon emissions consisted of two types of hydrocarbons. There were hydrocarbons that condensed quickly in cool air and there were also hydrocarbons that remain volatile. (Rogers 1978)

The gaseous less volatile emissions as resin and fatty acids, di- and triterpenes that cool in the surrounding air and condense to form small droplets. These droplets are also known as sub-micron aerosols. These sub-micron aerosols are known to cause the blue haze. Those sub-micron aerosols have no known harmful effects. Dryer exhaust gas can also be so dry that water vapor does not condense and therefore aerosols are visible as the blue haze. (Baldwin 1995, Granström 2002)

Plants are very sensitive to ozone and peroxoacetyl nitrates. Lower atmosphere ozone affect plant cells and decelerate photosynthesis. Ozone decreases the production of carbohydrates and slows down the growth of plants. Emissions also affect the plants resistance against illnesses and destructive insects. The sensitivity to ozone depends on many reasons such as wind speed, temperature, moisture content of air, light and plant itself. Ethene and formaldehyde are the components of volatile organic compounds that have a direct effect on the plants. Ethene can make plants grow old faster and formaldehyde affects for example the photosynthesis and cell respiration. Formaldehyde is also known to have an affect on needle loss. (Ailasmaa 1996)

There are also some health risks for humans with ozone. High ozone levels can lead to short-term changes in lungs and respiratory organ symptoms. There is a substantial amount of ignorance about how volatile organic compounds affect human health. Many compounds are harmful for health in high volumes. Organic compounds may also affect the central nervous system. The volumes of VOC are usually quite low in nature but exposure times are long. (Ailasmaa 1996)

1.5. VOC CONTROL TECHNIQUES

According to Mroueh (1992), reducing VOC-emissions can be divided to three different methods:

1. Substitute products and raw materials that contain volatile organic compounds.
2. Utilize process changes that prevent the volatilizing of compounds
3. Cleaning techniques for exhaust gases

Solutions that aim to prevent the formation of emissions are better for environment than cleaning techniques. These solutions are often cheaper and have better applicability. These were the main reasons why manufacturers usually start from the limitation of emissions. In many cases it is not possible or it is not enough to use the limitation of emissions. Decreasing the techniques might also be needed to control the emissions to the levels that are required. (Mroueh 1990b, Mroueh 1992)

It is difficult to find proper cleaning techniques for all processes. There are some difficulties to process industrial exhaust gases when:

- the organic compounds are mixed with high quantity of air
- multiple different pollutants appear at the same exhaust gas.

Because all the processes are more or less unique, the best solution for VOC control is to solve the problems individually for each process. (Mroueh 1990b)

There are numerous different methods in industrial use that are used to decrease VOC. These methods are (Jussila 1995):

1. Thermal oxidization (recuperative and regenerative)
2. Catalytic oxidization (recuperative and regenerative)
3. Bio filtration and bio scrubber
4. Different absorption methods
5. Different adsorption methods (activated carbon, zeolite and polymer)
6. Condensation
7. Membrane separation technique

Methods 1-3 are called disposal or conversion processes. Methods 5-7 are recovery processes. Absorption methods belong to both of those groups. Some of absorption methods are clear recovery or disposal processes. Between these basic cleaning techniques there are many different combinations of cleaning techniques that can also be used to prevent emissions. (Jussila 1995)

1.5.1. OXIDIZATION PROCESSES

Recuperative thermal oxidization

Thermal recuperative oxidization is a very effective method to destroy VOCs from exhaust gases. The thermal recuperative oxidation is called the three Ts combustion: time, temperature and turbulence. Thermal oxidization means that volatile organic compounds are burned in temperatures between 650-985 °C depending on the composition of the VOCs. In the thermal oxidization residence time is usually between 0,3-1,5 s and this recuperative method needs a turbulent flow. Sometimes extra oxygen must be added to the process stream. A sketch of the thermal oxidization system is shown In Figure 8. (Jussila 1995, Rafson 1998)

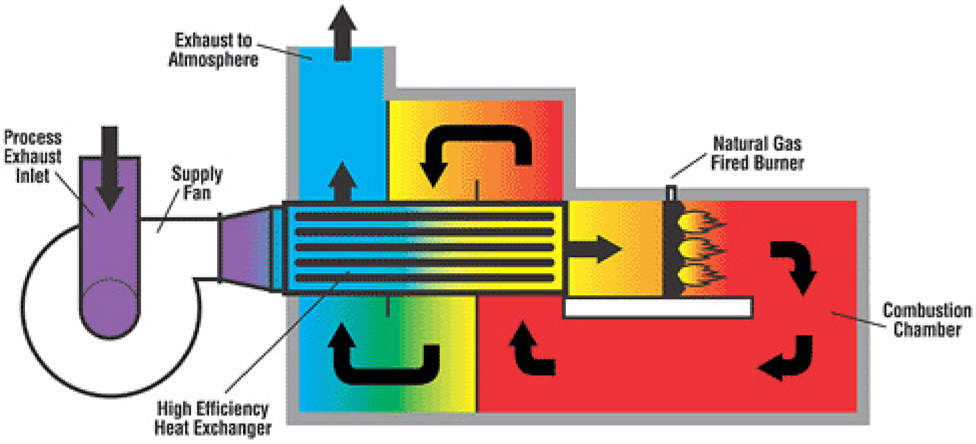

Figure 8. Recuperative thermal oxidizer. (The CMN Group, LLC 2009)

Poisonous organics can also be burned in this process and that is a benefit to recuperative thermal oxidizing. Recuperative thermal oxidizer can be considered if the organic concentration is high. The concentration of the organic compounds should be between 5-10 g/m³. For autothermal reaction the organic concentration should be between 8-15 g/m³. (Mroueh 1990b, Rafson 1998)

Thermal recuperative oxidization is an expensive process because of the cost of the additional energy that is used in the process. Operating costs increases a lot if the organic concentration of the exhaust is too low. The problem is the metallic heat exchanger that only recovers a maximum of 70 % of the generated heat. With this kind of process it is possible to burn up to 99 % of the organic compounds from the exhaust gases. (Mroueh 1990b, Rafson 1998)

Regenerative thermal oxidization

The regenerative thermal oxidizer consists two or more ceramic heat-transfer beds. Sand is one of the materials that is used in the regenerative thermal method as a heat-transfer bed. In this method the exhaust gases are oxidized and converted to CO_2 and H_2O. The operation of a twin bed regenerative thermal oxidizer is shown in Figure 9. (Rafson 1998)

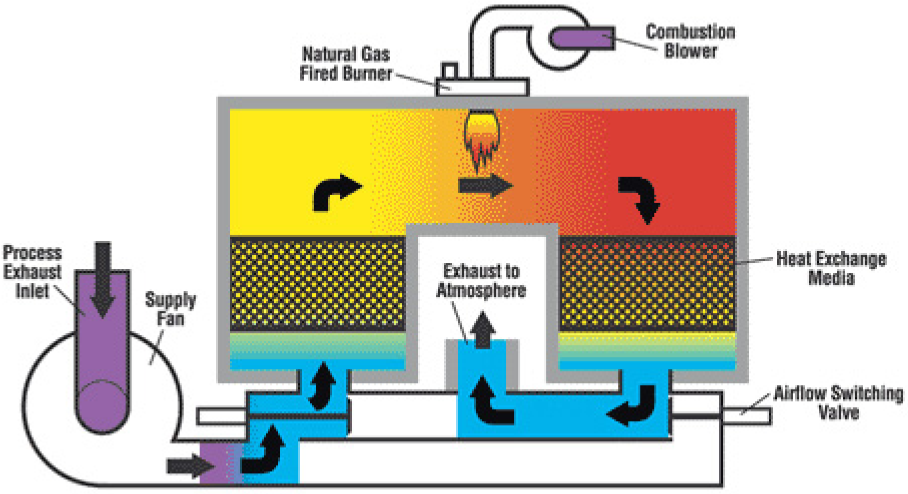

Figure 9. Twin-bed regenerative thermal oxidizer. (The CMN Group, LLC 2009b)

Main difference between recuperative and regenerative thermal oxidizing is that in the regenerative thermal oxidizing method the heat exchangers recover 85-98 % of the heat. The exchanged heat is used to warm exhaust gases. The heat in this method is inside the ceramic or sand beds from 815 °C to 1000 °C. 90-95 % of the volatile organic compounds can be burned in this method. Regenerative thermal oxidizing needs the organic concentration level to be constant between 0,5-4,5 g/m³ and the flow to be more than 10 000 m³/h. For an autothermal reaction the organic concentration should be more than 0,7 g/m³. (Karlsson 1990, Mroueh 1990b)

Catalytic oxidization

Catalytic oxidation is a process where preheated exhaust gas is in contact with a porous catalytic active material. This oxidization method is a fast and flameless combustion. Operating temperature is considerably low only 200-500 °C because of the catalyst. The organic compounds in the exhaust gas define the operating temperature of this method. In this method the exhaust gases are oxidized and converted to CO_2 and H_2O. The conventional process of recuperative catalytic oxidization is shown in Figure 10. (Jussila 1995, Ehovoc Oy 2009)

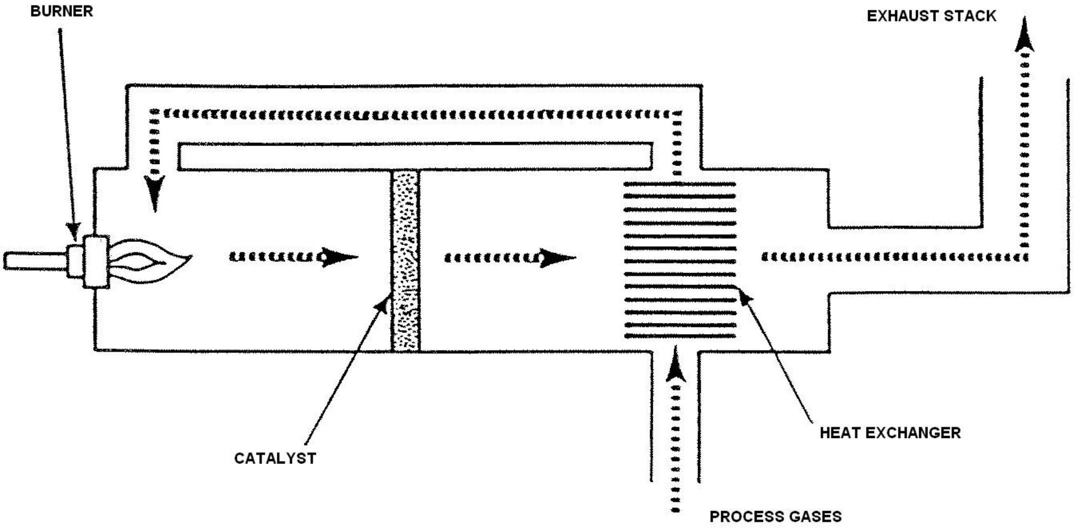

Figure 10. The conventional process of recuperative catalytic oxidization. (Jussila 1995)

Catalytic oxidization can destroy more than 98 % of the volatile organic compounds. This method uses 20 % to 40 % of energy compared to recuperative thermal oxidization. The conventional recuperative catalytic oxidization needs only 2 g/m³ for an autothermal reaction. This method is however quite sensitive to dust and other compounds that can harm the catalysts. Therefore the particulates in the stream need to be less than 0,12 g/m³. The catalysts life expectancy is from one to five years and is dependent on the conditions during oxidization. Catalytic oxidization needs very stabile conditions. (Jussila 1995, Ehovoc Oy 2009)

1.5.2. BIOLOGICAL CLEANING METHODS

Biological gas cleaning methods can be applied in every case where emissions are biodegradable. In the bio-cleaning process microorganisms metabolize volatile organic and inorganic contaminants. The biofiltration processes are suitable for a high flow volumes of diluted gas. The best range of organic compounds concentration is between 100-1000 mg C/ m^3. Biological cleaning methods have lower costs compared to oxidizing methods. (Mroueh 1990b, Jussila 1995)

Biofiltration is the simplest and the cheapest biological process to clean volatile organic compounds. In this method the filtration takes place in an open or closed filter bed. Depending on the volatiles the cleaning effectiveness is between 10-95 %. If the volatiles are at the aromatic type, the cleaning effectiveness is poor. (Mroueh 1990b)

In a biofiltration process an exhaust gas pretreatment is needed so that the microorganisms have an optimal environment to operate. Microorganisms need the exhaust gas to be at 98-100 % moisture and the operating temperature in the filter bed needs to be between 14 °C and 50 °C. When the gas flow is 20 000 m^3/h, the space needed for the filter is approximately 170-250 m^3. The costs in this method can rise extensively if the waste material from filter increases. High volume of exhaust gas pretreatment also increases the costs. (Karlsson 1990, Mroueh 1990b)

A bioscrubber is almost the same process as a biofiltration. The main difference in the process is that the bioscrubber has a free liquid phase. Bioscrubbers are used instead of biofiltration in VOC control if the breakdown products harm microorganisms in biofiltration. The bioscrubber does not use as much space as the biofiltration process. (Jussila 1995)

1.5.3. ABSORPTION METHODS

Absorption is a physical or chemical process in which atoms, molecules, or ions enter some bulk phase – liquid in this case. Absorption methods can be divided to physical and chemical absorption. The physical absorption has two main methods: absorption to water and absorption to an organic phase. The chemical absorption is also divided to two groups: absorption to watery solution and absorption in a bioscrubber. (Karlsson 1990)

Absorption methods need a very constant environment and therefore the exhaust gases are normally pretreated. The absorption process needs the organic concentration level to be between 1-50 g/m³. The gas flow is typically 1 500- 170 000 m³n/h. One problem in absorption is that it can be very expensive to clean the water if the concentration of volatile organic compounds in exhaust gases is too low. This method is also complicated because the problem from gases is transferred to the liquid. Running costs increases when the cleaning effectiveness is raised to a higher level. Normally more than 95 % effectiveness is wanted which means an increased costs of absorbent medium. (Karlsson 1990, Mroueh 1990b)

1.5.4. ADSORPTION METHODS

Molecules from exhaust gases are adsorbed to the surface of a solid material. This adsorption usually involves multiple beds because at least one bed remains on-line while the others are being regenerated. (Jussila 1995)

Adsorption can be divided into physical and chemical. Chemisorption has a disadvantage comparing to physisorption because in chemisorption only one component can be stripped from the gas flow. (Jussila 1995)

The most common adsorption material is activated carbon. With carbon activated adsorption the effectiveness of cleaning the gases is even better than 95 %. This method operates in quite low temperatures. The optimal temperature for carbon adsorption cleaning is less than 35 °C. The problem with active carbon adsorption is that there are many compounds that do not adsorb properly. Active carbon adsorption needs the organic concentration level to be between 2-20 m^3/h. Gas flow needs to be between 2000 m^3 and 200 000 m^3/h for economical reasons. Relative humidity needs to be less than 50 % in active carbon adsorption. A secondary problem with this method is the wastewater that comes from steam desorption. (Karlsson 1990, Mroueh 1990b)

There are also other adsorption materials similar to active carbon like polymers and zeolite. Adsorption with zeolite material gives other solutions than with active carbon or polymers. The zeolite adsorption works best when the organic concentration level is less than 0,5 g/m^3. The gas flow needs to be less than 100 000 m^3/h. Adsorption with polymers is suitable for constant high concentrations. Concentration should be between 0,1-10 g/m^3 and volume flow 100-100 000 m^3/h. (Karlsson 1990, Mroueh 1990b, Ailasmaa 1996)

1.5.5. CONDENSATION

In condensation organic compounds are recovered from liquid after the exhaust gases are condensed. Condensation needs either lower temperature or higher vapor pressure until the saturation point of the compounds in the condensation has been reached. Condensation can be done using a direct or indirect heat exchanging. In direct heat exchanging the cooling liquid is mixed to the exhaust gas. In indirect heat exchanging the cooling occurs in a gas heat exchanger. In Figure 11 is shown direct cryogenic condensation. (Jussila 1995)

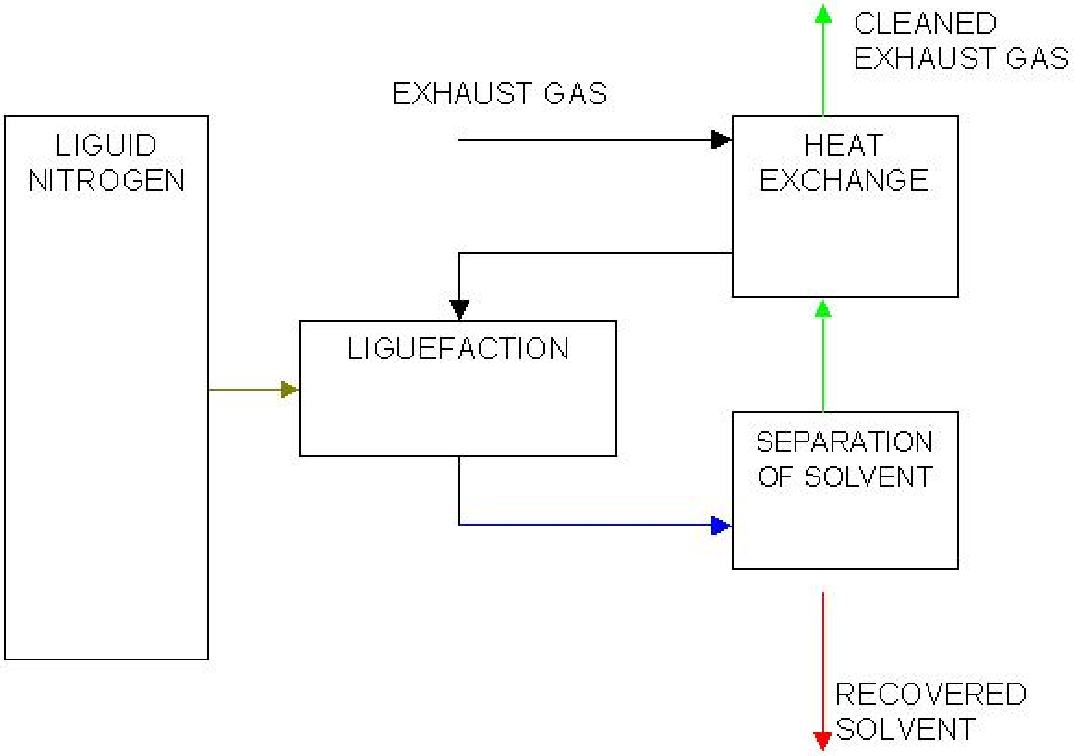

Figure 11. Direct cryogenic condensation. (Air Liquide 2008)

1.5.6. FREQUENTLY USED CLEANING EQUIPMENT IN WOOD INDUSTRY

An ionizing wet scrubber (IWS) combines electrostatic forces with packed bed scrubbing techniques to reduce emissions. An electrified filter bed (EFB) uses electrostatic forces to attract pollutants to an electrically charged gravel bed. Wet electrostatic precipitator (WESP) technique is explained in chapter 6.7.3. Because these applications are quite new, there is only limited data on their performance for veneer dryer emission control. (Emission factor… 1997)

The recuperative thermal oxidization (RTO) can achieve a high efficiency in VOC destruction. There have also been industrial experiments with biofiltration emission control in U.S oriented strandboard mill. The test results have been encouraging for reducing emissions with a biofiltration system. In the following chapters are introduced a few frequently used methods to reduce VOCs in veneer dryers. (Emission factor… 1997)

Scrubbers

Scrubbers have become the most used method to decrease the emissions from the dryer. There are several sizes and shapes of scrubbers and the technique has frequently been used from 1970s. Usually each process has its own scrubber. Some units uses scrubbers for primary cleaning and after the scrubber the emerging gases are directed to sand beds for final filtering. (Baldwin 1995)

In Finland these wet scrubbers are installed primarily for heat exchange. The warmed water is usually directed to the soaking tank. The operating method of the wet scrubber is shown in Figure 12. (Baldwin 1995)

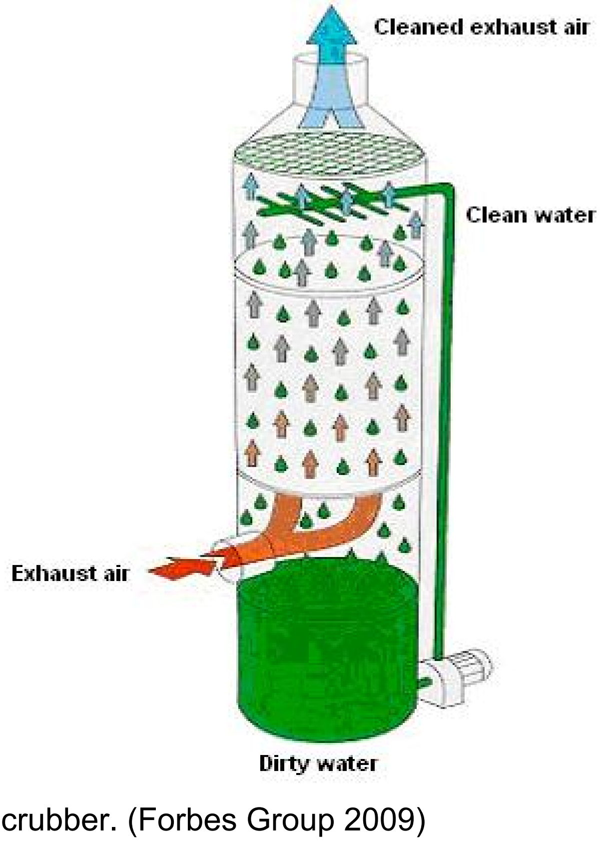

Figure 12. Wet scrubber. (Forbes Group 2009)

The incinerator

Incineration means that the dryer gases are transmitted directly to the powerhouse. First time this technique was successfully used in the mid 1970s in Albany, Oregon. In Albany the exhaust gases were collected and conveyed 350 feet through 28-inch diameter pipe. The pipes must be well insulated because the gases must reach the boiler before they condense. This method requires a large furnace therefore this system is limited to locations that operate a suitably sized boiler on site. This system can be very energy efficient because it can recycle hot dryer gases into usable heat at the furnace. This method achieved low emissions from the dryers as well as at the boiler stacks. This method has low capital costs, low operating costs and high-energy efficiency. (Baldwin 1995)

Wet electrostatic precipitators (WESP)

Figure 13 shows the WESP technique. In wet electrostatic precipitators gases are pushed through the box with the assistance of a fan. The airflow is directed into lanes formed by the collection plates or tubes. Discharge electrodes are centered between each collection plate or tube to provide a negative charge to the surrounding dust particles. The collection plates or tubes are positively charged and act as a magnet for the negatively charged particles. The collected dust is transported down the collection plates and electrode with the assistance of continuously downward moving film of water. The WESP has high initial capital costs but the ongoing maintenance is low and it operates well with all kinds of processes. (Baldwin 1995)

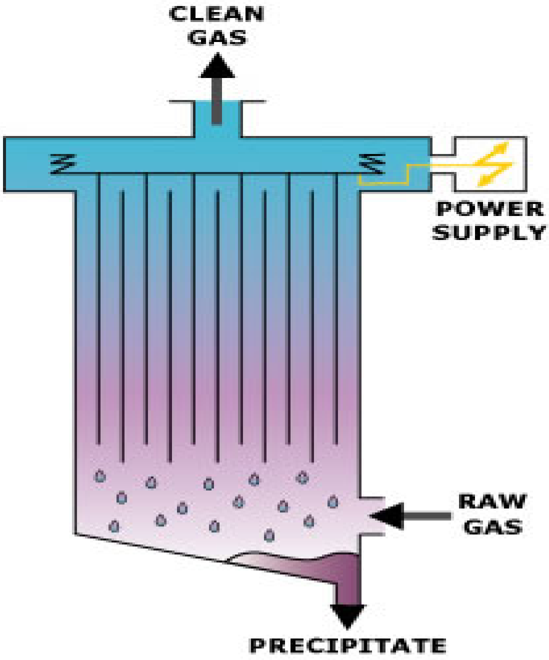

Figure 13. Wet electrostatic precipitator. (AirScience Inc. 2008)

1.6. CURRENT ENVIRONMENTAL LEGISTLATION FOR DRYER EMISSIONS

1.6.1. REGULATIONS IN FINLAND AND EUROPEAN UNION

In the European Union the emission limits for the plywood industry are inadequately defined. The integrated pollution prevention control (IPPC) directive has collected VOC limits for some industrial branches. IPPC directive appendix 1 recites all industrial branches that belong to that directive. Plywood industry does not belong to that group. The authorities use “best practice” method to evaluate the emission limits for various industries. (Integrated pollution… 1996)

Finnish environmental protection law requires the plywood industry to have an environmental license. The environmental license application for plywood industry is dealt with at regional environmental agencies. There are not any exact limits for VOC emissions in Finnish environmental law for plywood industry. This environmental license commits plywood factories to investigate the emissions from exhaust stacks. Environmental authorities compare VOC emissions from plywood factory with other plywood factories and set the emission limits if needed. (Ympäristönsuojeluasetus 18.2.2000/169, 2000)

Legislation in Central Europe is quite similar as in Finland. There are no legislation for pollution measurements in plywood industry and there are no need to clean the exhaust air from the veneer dryers. (Kaislaoja 2009)

Turpentine is composed from terpenes and Ministry of social affairs and health in Finland has set limits for turpentine content. The limits are for industrial health legislation and concern indoor emissions. The turpentine limits for eight-hour or fifteen minute averages are:

- HTP_{8h} = 140 mg/m^3
- HTP_{15min} = 280 mg/m^3. (HTP-arvot… 2007)

Ethanol is the main constituent in veneer dryer emissions when birch veneers are dried. The same authority as before has also set the limits for ethanol. Limits for ethanol are:

- HTP_{8h} = 1900 mg/m^3
- HTP_{15min} = 2500 mg/m^3. (HTP-arvot… 2007)

1.6.2. U.S. FEDERAL REGULATIONS

Regulations for emissions in plywood and wood product industry in U.S. have become stricter in the last years. U.S federal regulations traditionally have not been rigorous because some states in U.S have stricter limits for emissions. There has been many regulations that regulate emissions from facilities. The statutes that regulate emissions are:

- Clean Air Act (CAA)
- Resource Conservation and Recovery Act (RCRA)
- Toxic Substances Control Act (TSCA)
- Comprehensive Environmental Response, Compensation and Liability act of 1980 (CERLA)
- Occupational Safety and Health Act (OSHA) (Rafson 1998)

Regulations for emissions from plywood industry have been specified in one category. Code for Federal Regulations (CFR) title 40 part 63: National Emission Standards for Hazardous Air Pollutants: Plywood and Composite Wood Products have set limits for different processes in plywood manufacturing. The regulations affect the current and new plywood processes. Emission limits and control techniques for dryers and presses are listed in that regulation. (National emission… 2004)

EPA defines limitation for VOCs in certain areas. Those areas are defined by the exceeding of the ozone limits. The strictest limits are 10 t/a in Los Angeles. The other limits are 50 t/a or 100 t/a for less sensitive areas. (Mroueh 1992)

1.6.3. CFR COMPLIANCE OPTIONS AND OPERATING REQUIREMENTS FOR NEW VENEER DRYERS

This regulation applies to the manufacturing of plywood and composition wood products (PCWP) and if the manufacturing emit any single hazardous air pollutants (HAP) 10 tons or more per year or any combination of HAP 25 tons or more per year. Total HAP includes acetaldehyde, acrolein, formaldehyde, methanol, phenol, and propionaldehyde. This subpart applies to each new, reconstructed, or existing affected source at a PCWP manufacturing. The affected source is the collection of dryers, refiners, blenders, formers, presses, board coolers and other process in PCWP manufacturing. (National emission… 2004)

There are two compliance options for new emission sources. The first compliance option is production-based and second is for add-on control systems. In the production based compliance option its needed to meet the total HAP compliance options in Table 6. For the production-based compliance option no emission control techniques are to be used. (National emission… 2004)

Table 6. Emission limits for product-based compliance option. (National emission… 2004)

For the following process units	**You must meet the following production-based compliance option (total HAP basis)**	
(1) Fiberboard mat dryer heated zones (at new affected sources only)	0.022 lb/MSF 1/2&inch;	8,46 g/m³ veneer
(2) Green rotary dryers	0.058 lb/ODT.	0,03 g/kg oven dried veneer
(3) Hardboard ovens	0.022 lb/MSF 1/8&inch;	33,80 g/m³ veneer
(4) Press predryers (at new affected sources only)	0.037 lb/MSF 1/2&inch;.	14,22 g/m³ veneer
(5) Pressurized refiners	0.039 lb/ODT.	0,02 g/kg oven dried
(6) Primary tube dryers	0.26 lb/ODT.	0,13g/kg oven dried
(7) Reconstituted wood product board coolers (at new affected sources only)	0.014 lb/MSF 3/4&inch;.	3,59 g/m³ veneer
(8) Reconstituted wood product presses	0.30 lb/MSF 3/4&inch;.	76,88 g/m³ veneer
(9) Softwood veneer dryer heated zones	0.022 lb/MSF 3/8&inch;.	11,27 g/m³ veneer
(10) Rotary strand dryers	0.18 lb/ODT.	0,09 g/kg oven dried veneer
(11) Secondary tube dryers	0.010 lb/ODT.	0,005 g/kg oven dried veneer

In the add-on control system compliance option the use of emission control techniques is required. The resulting emissions must meet the compliances from both Table 7 and Table 8.

Table 7. Add-on control systems compliance options. (National emission… 2004)

For each of the following process units	You must comply with one of the following six compliance options by using an emissions control system
Fiberboard mat dryer heated zones (at new affected sources only); green rotary dryers; hardboard ovens; press predryers (at new affected sources only); pressurized refiners; primary tube dryers; secondary tube dryers; reconstituted wood product board coolers (at new affected sources only); reconstituted wood product presses; softwood veneer dryer heated zones; rotary strand dryers; conveyor strand dryer zone one (at existing affected sources); and conveyor strand dryer zones one and two (at new affected sources)	(1) Reduce emissions of total HAP, measured as THC (as carbon or methane), by 90 percent; or
	(2) Limit emissions of total HAP, measured as THC (as carbon or methane), to 20 ppmvd; or
	(3) Reduce methanol emissions by 90 percent; or
	(4) Limit methanol emissions to less than or equal to 1 ppmvd if uncontrolled methanol emissions entering the control device are greater than or equal to 10 ppmvd; or
	(5) Reduce formaldehyde emissions by 90 percent; or
	(6) Limit formaldehyde emissions to less than or equal to 1 ppmvd if uncontrolled formaldehyde emissions entering the control device are greater than or equal to 10 ppmvd.

Table 8. Work practice requirements. (National emission… 2004)

If you operate a(n)	You must	Or you must
(1) Thermal oxidizer	Maintain the 3-hour block average firebox temperature above the minimum temperature established during the performance test	Maintain the 3-hour block average THC concentration[a]in the thermal oxidizer exhaust below the maximum concentration established during the performance test.
(2) Catalytic oxidizer	Maintain the 3-hour block average catalytic oxidizer temperature above the minimum temperature established during the performance test; AND check the activity level of a representative sample of the catalyst at least every 12 months	Maintain the 3-hour block average THC concentration[a]in the catalytic oxidizer exhaust below the maximum concentration established during the performance test.
(3) Biofilter	Maintain the 24-hour block biofilter bed temperature within the range established according to §63.2262(m)	Maintain the 24-hour block average THC concentration[a]in the biofilter exhaust below the maximum concentration established during the performance test.
(4) Control device other than a thermal oxidizer, catalytic oxidizer, or biofilter	Petition the EPA Administrator for site-specific operating parameter(s) to be established during the performance test and maintain the average operating parameter(s) within the range(s) established during the performance test	Maintain the 3-hour block average THC concentration[a]in the control device exhaust below the maximum concentration established during the performance test.
(5) Process unit that meets a compliance option in Table 1A of this subpart, or a process unit that generates debits in an emissions average without the use of a control device	Maintain on a daily basis the process unit controlling operating parameter(s) within the ranges established during the performance test according to §63.2262(n)	Maintain the 3-hour block average THC concentration[a]in the process unit exhaust below the maximum concentration established during the performance test.

a: You may choose to subtract methane from THC measurements.

In U.S. different States can have their own regulations. For example California have had the strictest regulations concerning emissions. Most of the states emission laws are developed from the Clean Air Act. In San Francisco the highest price for the paid VOC ton in emission trading cost 75 000 U.S dollars. (National emission… 2004, Ehovoc Oy 2009)

1.6.4. LEGISLATION FROM OTHER REGIONS

In Latin America the emission legislation is similar than in Europe. There are no legislation for pollution measurements in plywood industry and there are no need to clean the exhaust air from the veneer dryers. (Kaislaoja 2009)

Countries in Oceania has strict legislation as in North America. There are regulations for pollution measurements and there must be cleaning devices after veneer dryers. The regulations varies a lot within the countries. (Kaislaoja 2009)

1.7. PLANNED RESEARCH

Targets to this survey were to:

- measure VOC emissions from the Dryer 2 longer than it is normally needed to the environmental license.
- measure VOC emissions from the Dryer 1 to see the difference between Dryers 1 & 2.
- measure VOC emissions from all (three) exhaust stacks separately.
- find out the cleaning affect of the scrubber in the Dryer 2.
- research the affect of lower moisture content and temperature on VOCs in Dryer 2.
- research the contents of VOCs in every cases.

The VOC emissions are usually measured from one spot where all the exhaust stacks are connected to one pipe. For the environmental license in Finland the emissions are usually measured after scrubbers. Full-scale emission measurements from the dryers are rarely done. The measuring places for the dryer VOC emission measurements are sketched in Figure 14.

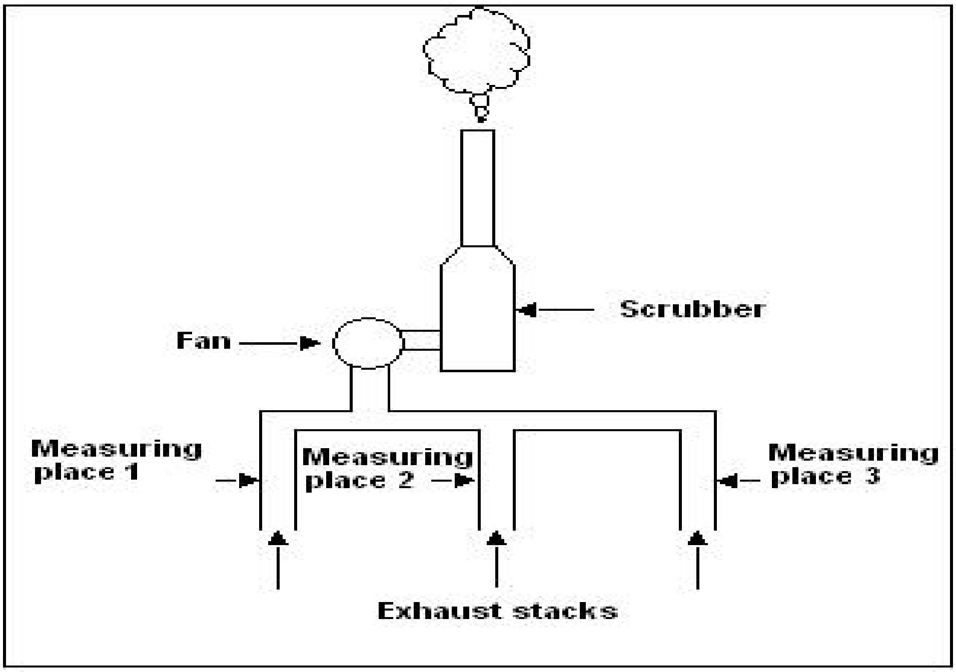

Figure 14. VOC measuring places from the exhaust stacks.

The measurements are to be done while the dryers are running normally. These measurements need to be done for a longer time to find out the real emission qualities and quantities during drying. Usually the environmental license needs the measurement of the VOCs. The measuring time for the environmental license is two hours, which is a quite short-duration. In this case the measuring time should be twice as long that what needed for the license.

The affect of lower moisture content and lower temperature is also measured in this survey. The reason for the measuring of these changes is to find out the possibility to reduce emissions by changing production parameters. Production based emission reducing is usually correct and recommended way to achieve the emission limits. It is also possible that the only reasonable way to control emissions is to add an emission control system.

The exhaust gases are directed to the scrubbers. The main function of the scrubber is heat recovery. The recovered heat is primarily used for the log soaking tanks. These wet scrubbers have also a secondary function to clean the exhaust gases. The separation capability of the scrubber is also measured to find out the possibility to use the scrubbers primarily as cleaning devices. This means that the measuring places should be before and after scrubber as it is shown in Figure 15.

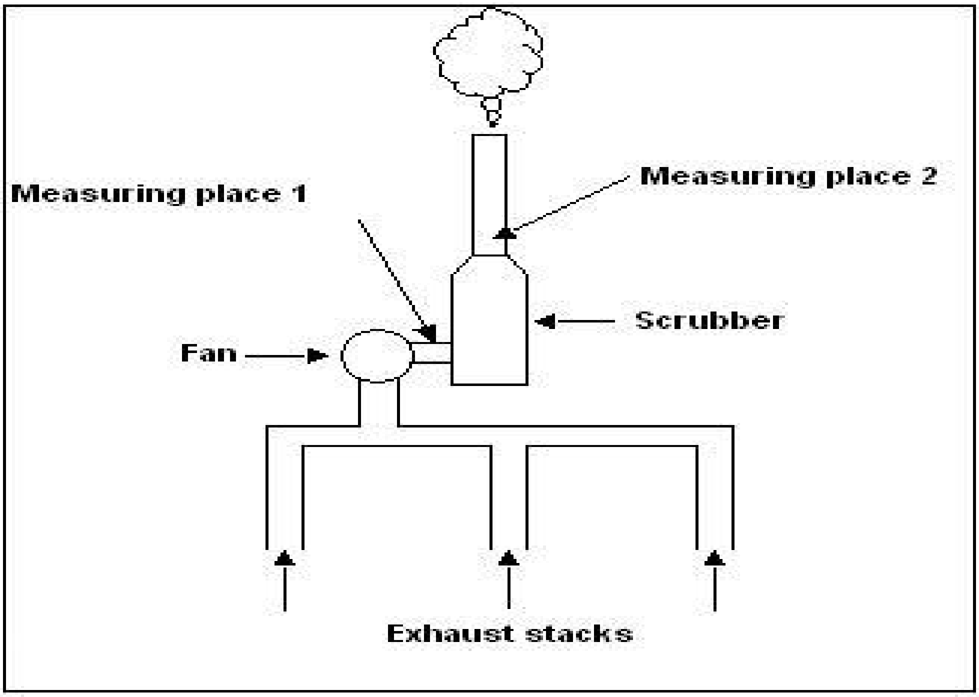

Figure 15. Voc and particle measuring places in the scrubber.

Timetable

The survey was scheduled for week 36/2008. In weekly schedule must be noticed that the dryers might have stoppages during the week. The timetable for the measurements is shown in Table 9.

Table 9. Timetable for the survey in target mill.

	Morning	Afternoon	Evening
Monday 1.9.	Arriving to the mill Installation of measuring devices	Scrubber •3 pcs particle measurements per measuring point •TOC (continuous) •VOC-absorption sample •Moisture content, air flow and temperature	
Tuesday 2.9.	Dryer exhaust stacks (3 pcs.) Process: heartwood, normal production Duration: 4h •TOC (continuous) •VOC-absorption sample •Moisture content, air flow and temperature	Dryer exhaust stacks (3 pcs.) Process: heartwood, dry dryer Duration: 4h •TOC (continuous) •VOC-absorption sample •Moisture content, air flow and temperature	Dryer exhaust stacks (3 pcs.) Process: sapwood, normal production Duration: 4h •TOC (continuous) •VOC-absorption sample •Moisture content, air flow and temperature
Wednesday 3.9	Dryer exhaust stacks (3 pcs.) Process: sapwood, normal production Duration: 4h •TOC (continuous) •VOC-absorption sample •Moisture content, air flow and temperature		Dryer exhaust stacks (3 pcs.) Process: heartwood, normal production Duration: 4h •TOC (continuous) •VOC-absorption sample •Moisture content, air flow and temperature
Thursday 4.9	Dryer exhaust stacks (3 pcs.) Process: heartwood, normal production Duration: 4h •TOC (continuous) •VOC-absorption sample •Moisture content, air flow and temperature	Dryer exhaust stacks (3 pcs.) Process: heartwood, colder dryer Duration: 4h •TOC (continuous) •VOC-absorption sample •Moisture content, air flow and temperature	Packaging of measuring devices Heading back to home

The measurements should followed the timetable to ensure that the measurements were done as planned. Production was the same than in normal usage except the production changes, which were contained also to the survey. The measuring equipments also needed some maintenance which was done before or after the measuring periods.

The information from the production was collected during the emission measuring. To compare the different measuring periods there was also information collected from veneer before and after the drying. Also the drying conditions were collected for further study. The data collected from the veneers and the dryers are shown in Table 10.

Table 10. Data that was collected during VOC measurements.

Data from dryer	Data from veneer
moisture content(s)	moisture before drying
temperature(s)	moisture after drying
damper stack settings	
dryer speed	
capacity	

Measuring devices

Flow meter

S-pitot tube method was used with DPM micro-nanometer to measure flow in exhaust stacks. The head of the S-pitot tube is shown in Figure 16. The pitot pipe was put inside of the exhaust stack and the result was read from the DPM micro-nanometer. The Pitot tube was faced into the gas stream flow and the pressure difference between the two ports equated to the velocity and pressure. The airflow was measured from several places through the cross section of the pipe because the flow was not constant.

Figure 16. S-pitot tube.

Toc measuring

The total volatile organic compounds were measured using flame ionization detectors (FID). This method was suitable for determination of the VOCs measured as total gaseous nonmethane organics and reported as propane equivalent. The FID measurements were continuous.

A gas sample was extracted from the source through a heated sample line. The sample was introduced into the flame and ionization process was started. A high polarizing voltage was applied between two electrodes which produces an electrostatic field. Negative ions migrate to the collector electrode and positive ions migrate to the high voltage electrode. The generated ionization current between the two electrodes was analyzed to find out the total hydrocarbons. Principle of the FID technique is shown in Figure 17.

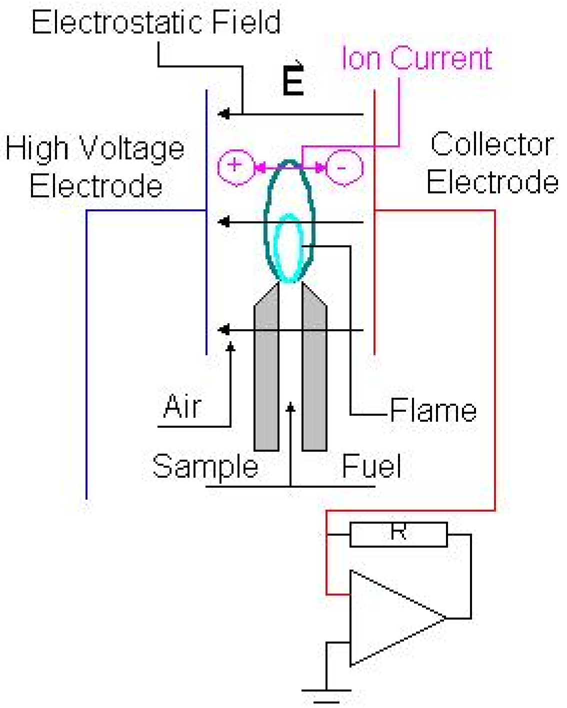

Figure 17. Principle of the FID (JUM 2009)

During this measurements for the Thesis three different FIDs were used. Two of the devices were Thermo Environmental Instrument's (T.E.I.) Model 51 and one was a J.U.M. Engineering HFID Model 3-200. T.E.I. and J.U.M FID devices are shown in Figure 18.

Figure 18. On the left is shown the T.E.I. FID and on the right is shown the J.U.M FID.

The FIDs were calibrated with 50 ppm propane gas before and after the measurements. The results were stored to a Yokogawa DR 130 hybrid plotter at 60 seconds intervals. The Yokogawa data logger is shown in Figure 19.

Figure 19. Yokogawa DR 130 data logger.

Problems were expected with the FID because of the high moisture contents inside the dryer exhaust stacks. The flame inside of the FID doesn't burn in high moisture contents. For this problem the solution was to condensate the water out from the air flow before the FIDs.

Thermometry

Temperature was continuously followed with a Ni-Cr-Ni thermocouple, which was installed to the same place with the TOC measuring. The thermocouple contains two dissimilar metals, which are joined from one end. Warming or cooling the thermocouple produces voltage, which correlates to different temperatures. The temperatures were recorded to the same Yokogawa DR 130 hybrid plotter together with the TOC results.

Moisture meter

Moisture content measurements from the exhaust stacks were based on the standard SFS 3869 "Air quality. Determination of gaseous emissions." The moisture content measurements were done using condensation.

Some air from the exhaust stacks was suctioned and the air was then condensed to two a bottles. In the first bottle most of the moisture was condensed to a water in phase and in the second bottle the rest of the moisture was condensed to a silicate. The amount of the dry air was measured after the condensation and the condensed water was weighed. The moisture measuring devices is shown in Figure 20. On the left side of the figure are the condensate bottles and on the right side of the figure is the suction machine, which measures the amount of dry air.

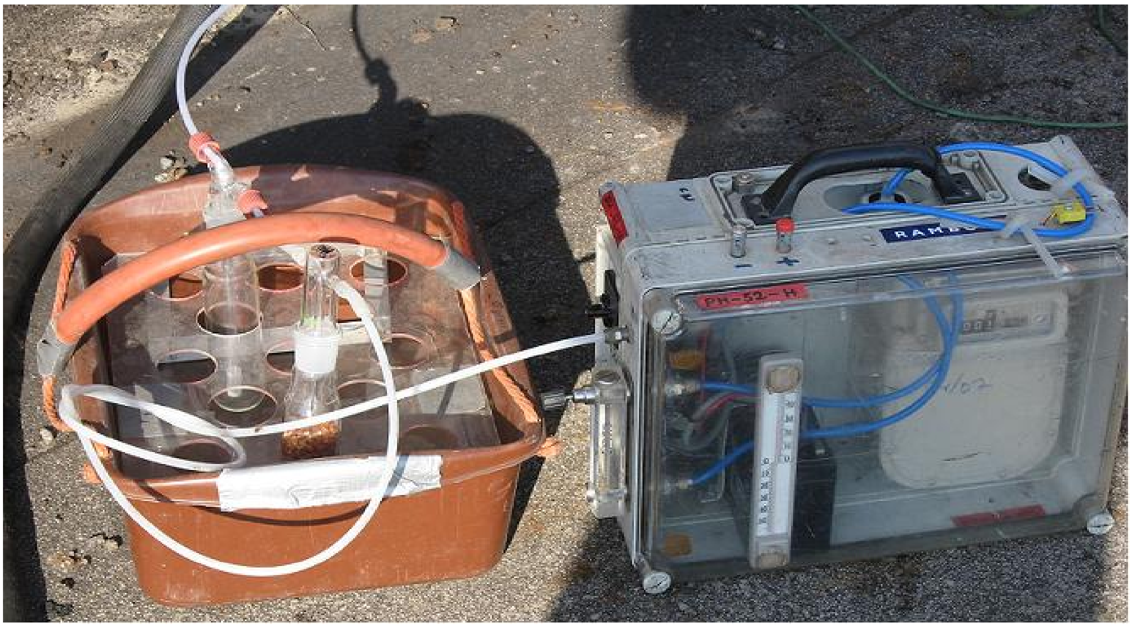

Figure 20. Moisture content measuring device.

Measurement of particles

Particle measurements were only done before and after the scrubber. The measurements were done applying the SFS 3386 “Air quality. Stationary source emissions. Determination of particulate emissions, manual method.” The measurements of particles were made isokinetically, which means that the gas entered the sampler at the same speed as it was in the exhaust stacks. In sampling a in-stack method was used with quartz filters. In-stack filtration means that the filtration in the duct is placed immediately downstream of the sampling nozzle.

Measurements were done using two devices at the same time. The devices were Emas sampling devices and these are shown in Figure 21. VTT Technical Research Centre of Finland built one device and the other one is built by Ramboll Analytics Finland.

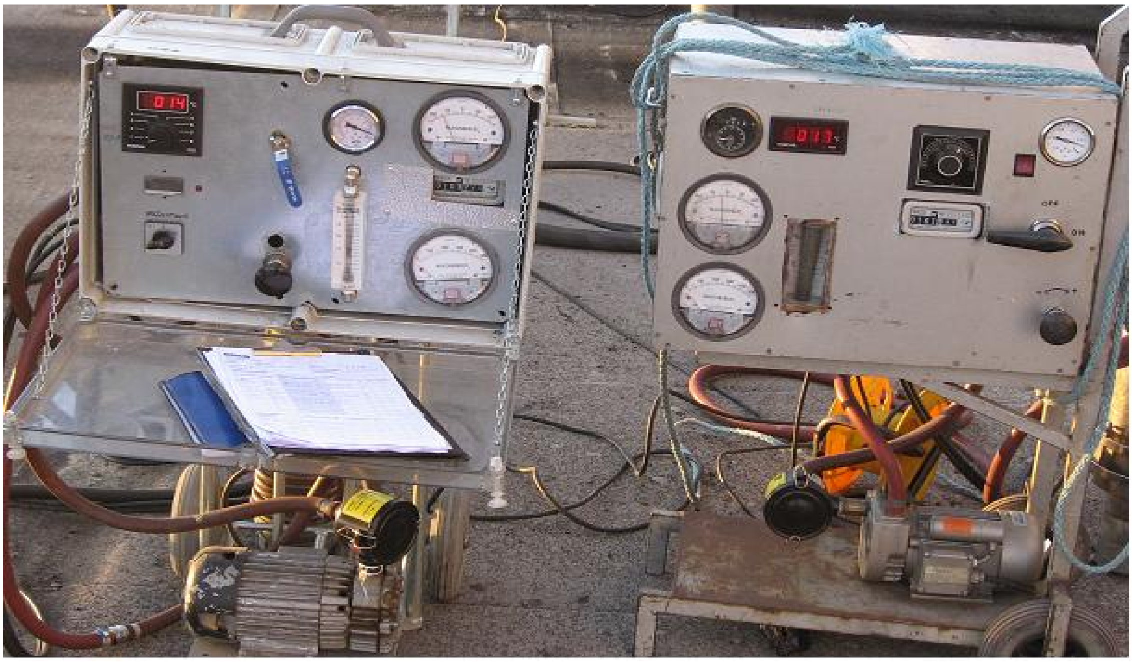

Figure 21. Emas- particles sampling devices.

2 MATERIAL AND METHODS

2.1. CASE PLYWOOD MILL

2.1.1. DRYERS

Two different softwood dryers were chosen to this study. The reason for this decision was that it was needed to compare emissions from softwood dryers. Raute Oyj has manufactured both of those (Dryer 1 and Dryer 2) dryers.

Dryers 1 and 2 have the same kind of structure. Dryer 1 is a little bit longer than dryer 2. Both of the dryers feed veneers with an automatic feeder. There are operators that help the feeder to get only one veneer at a time. After the feeders there are smoke extraction cells, which suck smoke if the dryers have over-pressure inside. Without those cells the operators might breath smoke.

Next part of the dryers are the hot zones, which heat and dry the veneers to the wanted moisture contents. After these hot zones there are also smoke extraction cells. These cells are very important for the air quality inside of the mill.

After the hot zones and smoke extraction cells come the cooling sections. These cooling sections main purpose is to lower the veneer temperatures slowly to the outside air temperature. After the cooling section comes a crossing station, which feeds the veneers from the four drying decks to one conveyor.

The plywood mill has a full drying and grading line, which means that after the crossing station there are veneer moisture and veneer defects analyzers. Those analyzers together decide the quality of the dried veneers. Veneers are stacked after analyzers to five different stacks. These two drying and grading lines are shown in Figure 22.

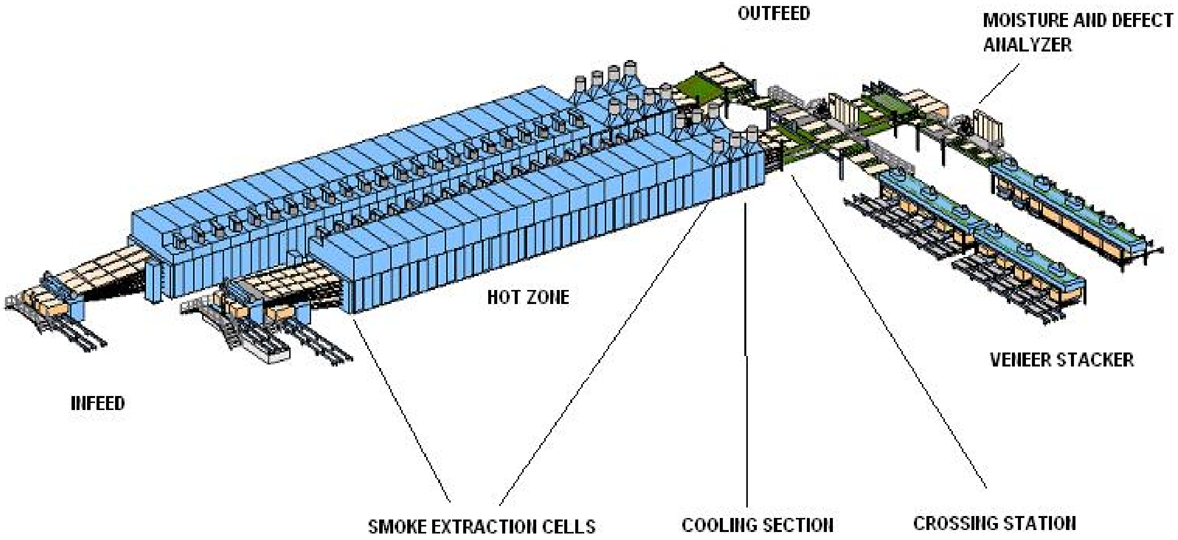

Figure 22. Veneer dryers in plywood mill.

The veneer that were dried in this survey were 8 feet long and 4 feet wide. Thickness of those veneers was approximately 3,15 mm. The veneers were filled in to the dryer three pieces next to each other to four decks.

Peeled veneer is divided to three groups by moisture content. Group 1 includes the driest veneers from heartwood. Group 2 is for the middle moisture veneers and group 3 is for the wettest veneer from sapwood. The average moisture contents of those groups are shown in Table 11.

Table 11. Average moisture contents of the groups that are fed to the dryers.

	GROUP 1	GROUP 2	GROUP 3
Average veneer moisture (%)	32,7	50,3	130,3

Every dryer has a wet scrubber for heat recovery. The scrubbers provides all the heat that is needed in the soaking tanks.

2.1.2. PREVIOUS VOC MEASUREMENTS

In Finland every plywood plant must have an environmental license. The environmental license contains the requirements to measure VOC emissions from the veneer dryers. The measurements take two hours for each dryer. The dryers should be in normal usage and the production should also be normal during the veneer drying.

Dryers almost always contain wet scrubbers in Finland. The measurements are usually done after the scrubber, which means that some of the VOCs are condensed to the water in the scrubber.

The VOCs have been measured from dryers for the environmental licenses. The duration of those measurements are usually two hours. Those measurements are to short in duration to find out the real emissions from the dryers. During the measurements normal production can mean that the dryer is empty from veneers and the dryer might be stopped.

3 RESULTS

3.1. DRYER 1

The total organic compounds from the dryer 1 were measured twice. Quantities and qualities of the measured TOCs at day 2 are shown in Table 12. Quality 3 in Table 12 means that the veneer in this dryer was mainly sapwood at an average moisture content of 130 %.

Table 12. TOCs measured from Dryer 1 2.9.2008.

Time	18:00-22:00						
Veneer	Quality 3						
Place	Front		Mid		End		Total
		±		±		±	
Temperature °C	157	1	161	1	148	1	
Moisture %	45,3	4,7	36,8	3,9	14,3	2,6	
TOC concentration mg/m^3 C n*	473	49	415	43	166	17	351
TOC emission g/h C	625	81	4228	530	335	44	5188
VOC-main components							
Alfa-pinene	65 %		68 %		72 %		
Delta-3-carene	14 %		13 %		8 %		
Beta-pinene	20 %		12 %		11 %		

n = gas in NTP 0 °C, 101,3 kPa

Tolerances in the measured moisture content and temperature comes from the measuring equipments inaccuracy. Tolerances in the measured TOC emissions comes from the measuring equipments inaccuracy and from the unfavorable measuring place for the air flow measurement.

In this measurement the highest TOC concentration in air comes from the front exhaust stack. It is almost the same concentration as in the mid exhaust stack and those concentrations are three times higher than in the end exhaust stack. The total TOC emissions from the mid exhaust stack covers 81 % of all emissions in this measurement.

The results of the second measurement are shown in Table 13. The survey of VOC main components could not be defined from the mid exhaust stack because there was not enough hydrocarbons in the Tenax tube.

Table 13. TOCs measured from Dryer 1 3.9.2008.

Time	8:10-12:15						
Veneer	Quality 3						
Place	Front		Mid		End		Total
		±		±		±	
Temperature °C	165	1	165	1	168	1	
Moisture %	56,9	5,8	34,5	3,8	38,3	4,0	
TOC concentration mg/m^3 C n*	415	42	173	18	319	33	302
TOC emission g/h C	1997	528	364	46	514	71	2875
VOC-main components							
Alfa-pinene	68 %		-		72 %		
Delta-3-carene	3 %		-		2 %		
Beta-pinene	28 %		-		23 %		

n = gas in NTP 0 °C, 101,3 kPa

Table 12 and Table 13 show that the main constituents of TOCs are alfa-pinene, delta-3-carene and beta-pinene. Almost 97 % of all VOCs are of those three main constituents. The average VOC concentration from every stack is calculated from both measurements. The alfa-pinene average concentration is 69 % of all TOCs. The average concentration of the beta-pinene is 19 % and the third main component delta-3-carene has an 8 % average concentration.

To calculate the total emissions for one year production in Dryer 1 its assumed that the dryer operates for approximately 11 months each year, 7 days per week and 24 hours per day. With the maintenance breaks operating time is approximately 8 000 hours every year. The total emissions is calculated in Table 14. The emissions in those calculations are averages from the two measurements that were done for Dryer 1.

Table 14. Total emissions from Dryer 1.

Place	Front	Mid	End	Total
Avg. TOC concentration mg/m^3 C n*	444	294	242,5	326,5
Avg. TOC emission g/h C	1311	2296	424,5	4031,5
TOC emissions tons/year*	10,49	18,37	3,40	32,25
Avg. dried veneer m^3/h				11,61
Avg. TOCs/ dried veneer g/m^3 C	112,92	197,76	36,56	347,24

n = gas in NTP 0 °C, 101,3 kPa
year = dryer operates approximately 8 000 h/year

The total TOC emissions before the scrubber from Dryer 1 are approximately 32 tons carbon per year. The highest volume 57 % of the Dryer 1 TOCs come from the Mid exhaust stack but the highest TOC concentration in air is from the Front exhaust stack at 444 mg/m^3 carbon. The lowest emission concentration and volume comes from the end exhaust stack. The average concentration in the end exhaust stack is 243 mg/m^3 carbon and volume is 11 % of the Dryer 1 TOCs. The average quantity of TOCs for sapwood is 327 mg/m^3 carbon in air.

Some authorities need the emissions to be announced as grams per dried veneer cubic meter. The emissions compared to the dried veneer is shown in Table 14. In these measurements the average TOCs per dried sapwood cubic meter is 347 g/m^3 carbon. The dried veneer is calculated as a one hour average and compared to the emissions. Production data was collected from the mill information systems.

3.2. DRYER 2

Most of the measurements for this survey were done to Dryer 2. This chapter concentrates only on the normal production of Dryer 2. In the Dryer 2 the dried veneer is either quality 1 or quality 2. This means that the dried veneer is mainly from heartwood. The average moisture contents of the veneer in quality 1 is 30 %. The moisture content of quality 2 is circa 50 %. Those qualities can be changed in the dryer while it is operating. Usually the quality is changed after the certain quality of stacks have run out.

In this survey the Dryer 2 emission were measured three times. The result of the first measurement is shown in Table 15. The dried veneer was quality 1 in this measurement.

Table 15. TOCs measured from Dryer 2 2.9.2008.

Time	9:00-13:00						
Veneer	Quality 1						
Place	Front		Mid		End		Total
		±		±		±	
Temperature °C	146	1	170	1	176	1	
Moisture %	32,3	3,4	29,4	3,1	34,7	3,9	
TOC concentration mg/m^3 C n*	902	93	786	81	2667	276	1452
TOC emission g/h C	524	132	1097	143	5506	694	7127
VOC-main components							
Alfa-pinene	61 %		70 %		63 %		
Delta-3-carene	31 %		16 %		8 %		
Beta-pinene	5 %		8 %		20 %		

n = gas in NTP 0 °C, 101,3 kPa

In this measurement the highest TOC concentration in air comes from the end stack. The concentration is almost three times higher than in the other exhaust stacks. The total TOC emissions from end exhaust stack is 77 % of all emissions in this measurement. The main three VOC components are alfa-pinene, delta-3-carene and beta-pinene. In this measurement the main three VOC components cover 94 % of all VOCs.

The second measurement was done to veneer quality 1. The result of the second measurement is shown in Table 16. From the Mid exhaust stack the survey of VOC main components could not be defined because there were not enough hydrocarbons in the Tenax tube.

Table 16. TOCs measured from Dryer 2 3.9.2008.

Time	14:30-18:30						
Veneer	Quality 1						
Place	Front		Mid		End		Total
		±		±		±	
Temperature °C	142	1	171	1	176	1	
Moisture %	33,4	3,7	51,3	5,3	40,6	4,3	
TOC concentration mg/m^3 C n*	927	95	1287	133	1470	152	1228
TOC emission g/h C	520	140	1310	175	2855	361	4685
VOC-main components							
Alfa-pinene	54 %		-		68 %		
Delta-3-carene	40 %		-		17 %		
Beta-pinene	4 %		-		9 %		

n = gas in NTP 0 °C, 101,3 kPa

The highest emission concentration comes from the end exhaust stack. The highest TOC emissions also come from the end exhaust stack. The total TOC emissions from the end exhaust stack is 61 % of all emissions in this measurement. The main VOC components are alfa-pinene, delta-3-carene and beta-pinene. In this measurement these three main components cover 96 % of all the VOCs.

The third measurement from normal production was made in two parts because the quality of dried veneer changed during the measurement. The End exhaust stack was not measured because the veneer quality was changed suddenly. The results of third measurements are shown in Table 17. The VOC main components could not be measured from all the exhaust stacks because there were not enough hydrocarbons to get a defined result.

Table 17. TOCs measured from Dryer 2 3.9.2008.

Time	8:00-10:00						
Veneer	Quality 2						
Place	Front		Mid		End		Total
		±		±		±	
Temperature °C	146	1	178	1			
Moisture %	36,6	4,0	37,2	4,1			
TOC concentration mg/m^3 C n*	535	55	473	49			506
TOC emission g/h C	330	71	955	120			1285
VOC-main components							
Alfa-pinene	71 %		83 %		-		
Delta-3-carene	12 %		1 %		-		
Beta-pinene	15 %		15 %		-		
Time	10:00-12:00						
Veneer	Quality 1						
		±		±		±	
Temperature °C	143	1	165	1	178	1	
Moisture %	36,8	3,8	42,4	4,4	37,2	4,1	
TOC concentration mg/m^3 C n*	1159	120	1754	181	1283	133	1399
TOC emission g/h C	714	154	2068	550	2605	329	5387

n = gas in NTP 0 °C, 101,3 kPa

The highest emission concentration comes from the mid exhaust and is 50 % higher than from the other stacks. The largest amount of TOCs come from the end stack and the amount covers almost 50 % of all TOC emissions in this measurement. The first part of this measurement, where the emissions from the end exhaust stack were not measured, is not calculated to the summary of the Dryer 2 emissions.

The previous tables show that the main constituent of the TOCs are alfa-pinene, delta-3-carene and beta-pinene. Almost 96 % of the VOCs are of those three main constituents. The average VOC concentration from every stack is calculated from each measurements. Alfa-pinene average concentration is 67 % of all TOCs. The average concentration of the second main component delta-3-carene is 18 % and the third main component beta-pinene has 11 % average concentration.

To calculate the total emissions for one year production for Dryer 2 it is assumed that the dryer operates 11 months a year. The Dryer 2 is operating 7 days per week and 24 hours per day. With the maintenance breaks the operating time is approximately 8 000 hours every year. The total emissions are calculated in Table 18. The emissions in this calculations are averages from the three measurements which were done for Dryer 2. Only the second part of the third measurement was calculated to this Dryer 2 summary because of the incompleteness of the first part.

Table 18. Total emissions from Dryer 2.

Place	Front	Mid	End	Total
Avg. TOC concentration mg/m^3 C n*	996	1276	1807	1360
Avg. TOC emission g/h C	586	1492	3655	5733
TOC emissions tons/year*	4,7	11,9	29,2	45,9
Avg. dried veneer (m^3/h)				14,6
Avg. TOCs/ Dried veneer (gC/m^3)	40	102	250	393

n = gas in NTP 0 °C, 101,3 kPa
year = dryer operates approximately 8 000 h/year

The total TOC emissions before the scrubber from the Dryer 2 are approximately 46 tons carbon per year. The main volume 64 % of the Dryer 1 TOCs come from the end exhaust stack and the highest TOC concentration in air is from the same exhaust stack at 1 807 mg/m^3 carbon. Lowest emission concentrations and volumes come from the front exhaust stack. The average concentration in the front exhaust stack is 996 mg/m^3 carbon and the total volume in the front is 10 % of the Dryer 1 organic compounds. The average quantity of the TOCs for heartwood is 1 360 mg/m^3 carbon in air.

The emissions compared to the amount of dried veneer is also shown in previous table. In these measurements the average TOCs per dried heartwood cubic meter is 393 g/m^3 carbon. The dried veneer is calculated as one hour average and compared to the emissions. Production data was collected from the mill information systems.

3.3. CHANGED CONDITIONS

Changed conditions inside of the veneer dryer were researched on Dryer 2. the changed parameters were lower moisture content and lower drying temperature. The results from the changed conditions are presented in the following chapters. The other drying parameters were changed in these measurements so that the veneer is dried to an acceptable production moisture content.

3.3.1. LOWER MOISTURE CONTENT

In this measurement the moisture content was kept as low as possible. There was risk of fire if the moisture content was dropped too low. The moisture content was kept down with the damper stacks. The damper stacks were open enough to keep wanted moisture content inside the dryer.

The emissions using lower moisture content in Dryer 2 was measured once. The moisture content was kept near 350 gw/kgda during this measurement. In normal production the moisture content is near 600 gw/kgda. The quantities and qualities of the measured TOCs at the lower moisture content are shown in Table 19.

Table 19. TOCs measured from Dryer 2 2.9.2008.

Time	13:17-17:17						
Veneer	Quality 2						
Place	Front		Mid		End		Total
		±		±		±	
Temperature °C	159	1	174	1	183	1	
Moisture %	26,3	3,4	28,6	3,1	25,3	3,0	
TOC concentration mg/m^3 C n*	677	70	674	70	1072	111	807
TOC emission g/h C	417	105	1948	244	3756	473	6121
VOC-main components							
Alfa-pinene	54 %		89 %		64 %		
Delta-3-carene	37 %		5 %		20 %		
Beta-pinene	5 %		5 %		8 %		

n = gas in NTP 0 °C, 101,3 kPa

During this measurement the highest TOC concentration was measured from the end exhaust stack. The highest concentration was 1072 mg/m^3 carbon and the total TOC concentration was 807 mg/m^3 carbon. Total TOC emissions were 6121 g/h carbon. Emissions from the End exhaust stack were 3 756 g/h, which is 61 % of all the TOCs. The three main VOC components were alfa-pinene, delta-3-carene and beta pinene. In this measurement these three main components cover 96 % of all VOCs.

The total TOC emissions before the scrubber from Dryer 2 are approximately 49 tons carbon per year with these production parameters. The dryer runs 8 000 hours per year. In these measurements the average TOCs per dried veneer cubic meter is 513 g/m^3 carbon when 44,75 m^3 veneer were dried during this survey. The dried veneer is calculated as one-hour average and compared to the emissions. Production data was collected from the mill information systems.

3.3.2. LOWER TEMPERATURE

In this VOC emission measurement the temperature in the Dryer 2 was dropped approximately 20 degrees Celsius to 170 degrees Celsius. In normal production the temperatures are 190 degrees Celsius. The dryer was operating four hours with this lower temperature. The resin needs to be boiled out of the veneer and that was the reason why the temperature was not dropped even more.

The emissions from this survey are shown in Table 20. The emissions with these production parameters were measured once during day 4. The veneer quality changed during the measurement from quality 1 to quality 2. The results are summarized and the average results are shown in Table 20. The average was calculated with the times that the each quality was dried. In this measurement the quality 1 ran 135 minutes and quality 2 ran 105 minutes.

Table 20. TOCs measured from Dryer 2 4.9.2008.

Time	12:10-16:10						
Veneer	Quality 1 (135 min) & 2 (105 min)						
Place	Front		Mid		End		Total
		±		±		±	
Temperature °C	144	1	157	1	162	1	
Moisture %	33	3,6	36,6	4,0	38,7	4,2	
TOC concentration mg/m^3 C n*	610	63	514	53	937	97	687
TOC emission g/h C	578	90	912	116	1736	222	3225
VOC-main components							
Alfa-pinene	77 %		87 %		79 %		
Delta-3-carene	6 %		8 %		7 %		
Beta-pinene	14 %		3 %		13 %		

n = gas in NTP 0 °C, 101,3 kPa

The highest TOC concentration was 937 mg/m^3 carbon from the End exhaust stack and the total TOC concentration was 687 mg/m^3 carbon. Total TOC emissions were 6 121 g/h carbon. Emissions from the End exhaust stack were 3 225 g/h, which is 54 % of all TOCs. The three main VOC components were alfa-pinene, delta-3-carene and beta pinene. In this measurement these three main components cover 98 % of all VOCs.

The total TOC emissions before the scrubber from the Dryer 2 are approximately 26 tons carbon per year with these production parameters. The dryer runs 8 000 hours per year. In these measurements the average TOCs per dried veneer cubic meter is 225 g/m^3 carbon because 57,22 m^3 veneer were dried during this survey. The dried veneer is calculated as one-hour average and compared to the emissions. Production data was collected from the mill information systems.

3.4. SCRUBBER

The scrubbers in mills are mainly heat recovery devices. The exhaust gases from the dryers go through the scrubber. In this survey the emissions were measured before and after the scrubber. This measurement gives information about the separating capability of the scrubber for the TOCs and particles. The emissions before and after the scrubber were measured from the Dryer 2.

The measurement of particulate emissions were done to find out the separation capability of the scrubber. Particles were measured before and after the scrubber and the results are shown in Table 21. The air volume flow measurements were not done before the scrubber and therefore the used air flow is the same than after the scrubber.

Table 21. Particles measured from the scrubber in Dryer 2 1.9.2008.i

Time	18:25-18:50				19:00-19:24				19:32-19:56			
Test	1				2				3			
Place	Before		After		Before		After		Before		After	
		±		±		±		±		±		±
Temp. °C	165	1	62	1	165	1	68	1	166	1	66	1
Moisture %	35,5	3,6	19,3	2	35,5	3,6	18,9	2	35,5	3,6	18,7	2
Particulate concentration mg/m^{3}n*	292	60	277	56	318	65	333	68	454	93	436	89
Particulate emission kg/h	1,8	1,2	1,7	0,5	1,9	1,3	2,1	0,6	2,8	1,8	2,7	0,8

n = gas in NTP 0 °C, 101,3 kPa

The average particulate concentration before the scrubber is 355 mg/m^3 and after the scrubber the average is 349 mg/m^3. The total particulate emissions after the scrubber are calculated using the average running time of Dryer 2. The Dryer 2 operates approximately 8 000 h each year. The total particulate emissions after the scrubber are 17 tons particles a year.

The other study made in this survey measures the separation capability of the TOCs in the scrubber. The scrubber can absorb water soluble VOCs to the water. Also some VOCs condensate to the colder surfaces and water in the scrubber. The results of the TOC measurements before and after scrubber are shown in Table 22.

Table 22. TOCs measured from the scrubber in Dryer 2 1.9.2008.

Time	14:00-16:05				16:10-18:05			
Quality	1				2			
Place	Before		After		Before		After	
		±		±		±		±
Temperature °C	159	1	63	1	167	1	68	1
Moisture %	35,5	3,6	19,3	2	35,5	3,6	18,7	2
TOC concentration mg/m^3 C n*	1960	203	1080	110	1034	107	555	58
TOC emission g/h C	11900	2800	6720	900	6280	1500	3450	440
VOC-main components								
Alfa-pinene	82 %		70 %					
Delta-3-carene	6 %		11 %					
Beta-pinene	12 %		16 %					

n = gas in NTP 0 °C, 101,3 kPa

The average TOC concentration was 1 516 mg/m^3 carbon before the scrubber and 828 mg/m^3 carbon after the scrubber. The total TOC emissions before the scrubber was 9 207 g/h carbon. After the scrubber the total TOC emissions were 5 153 g/h carbon. Those TOC emission mean that the emissions in one year are approximately 74 tons carbon before scrubber and 41 tons carbon after scrubber.

The separation capability of the scrubber drying quality 1 veneer was 44 % of the TOCs and drying the quality 2 veneer the separation capability was 45 % of the TOCs. After the scrubber the average TOC concentration was reduced 44 % from the TOCs measured before the scrubber.

The VOC main components before the scrubber are alfa-pinene, delta-3-carene and beta-pinene. Those three main VOC components consists 99 % of all VOCs. The alfa-pinene concentration of the VOCs reduces after the scrubber from 82 % to 70 % while delta-3-carenes and beta-pinenes concentrations increases some percentages.

The Formaldehyde concentration before the scrubber is 24,2 mg/m^3 air. With average air flow 1,7 m^3/s before scrubber the emissions are 148,1 g/h. The average formaldehyde emission in one year is 1,18 tons. These formaldehyde emissions are important in the U.S regulations for new veneer dryers.

4 DISCUSSION

4.1. ANALYZING RESULTS

The annual TOC emissions from the Dryer 1 and 2 together are 78 tons a year. In this case each dryer has a scrubber to recover the heat from the exhaust air. The measurements shows that the separating capability at the scrubber is 44 % of the TOCs. Dryer 1 emits 32 tons carbon each year and after the scrubber the annual TOC emissions to air are approximately 18 tons carbon. The TOC emissions from the Dryer 2 are 46 tons carbon each year. After the scrubber the annual TOC emissions are 26 tons carbon. The scrubber absorbs some of the VOCs from the exhaust air and some of the VOCs condensate to the exhaust stacks and the surfaces of the scrubber. The least volatile compounds and the most water soluble VOCs are most likely to absorb or condensate to the water or the surfaces in the scrubber. In Figure 23 are shown the annual TOC emissions from the softwood veneer dryers.

Figure 23. The annual TOC emissions before the scrubbers from softwood veneer dryers.

The scrubbers have no found effects on particulate emissions from softwood dryers exhaust air. The particles from the Dryer 1 are 17 tons a year. There were three different measurements and in every case the amount of particles did not change. The total particle emissions from all three dryers are calculated from an average of Dryer 1 particle emissions. Two times 17 tons of particles means 34 tons of annual particle emissions from both of the softwood dryers.

The highest VOC concentrations in air from the Dryer 1 comes from the front exhaust stack. In the Dryer 2 the highest VOC concentrations are from the end exhaust stack. The total emissions from the dryer exhaust stacks depends on the air flow. The damper stacks are adjusted in some positions that the moisture content inside of the dryer is optimal. In this Dryer 1 case the mid exhaust stack is typically fully opened because the moisture in this section needs to be removed out of the dryer. Because of the air flow the TOCs from the Mid exhaust stack are 57 % of the total air flow. In the Dryer 2 the damper stacks are more open in the end section of the dryer for both qualities 1 and 2. The total TOCs from the End exhaust stack from Dryer 2 is 64 %.

Emission measurements and data collection were done at the same time. The emissions were compared to the data from production. The main reason for the comparison was to find any connection between production parameters and emission concentrations. The analysis was made using the Pearson method. The production parameters compared to emissions were moisture content, temperature and the speed of the dryer. The results of the analysis shows that the moisture content might have some affect on the TOCs. Moisture content correlates also to the drying temperature inside of the dryer. This method did not find any correlations between the temperature and TOCs from the dryer. The emission concentrations change significantly during drying and it is difficult to compare the results. The main reason of concentration changes is that the dried wood is not homogenous. The wood grown in one area might have much higher concentration of extracts than same wood specie in other area. Still some of the production parameters must have some effects because for example the temperature during drying affects the boiling of resin and the rate of decomposition. Also dried veneer quantity must have affect on TOCs. Clean and empty dryer will not emit any emissions to air. More veneer dried in the dryer emits more TOCs to the air because the resin from the wood boils out. Also the temperature affects to the TOCs because higher temperature combusts wood faster.

The VOC emissions were measured from two different softwood dryers. The results of VOCs were only terpenes because the Tenax-tube does not adsorb water soluble components. The main water soluble components from softwood are ethanol and methane. Formaldehyde is also a component, that does not adsorb in to the Tenax-tube.

4.1.1. COMPARISON TO PREVIOUS MEASUREMENTS

In the Raute information system the emissions data for softwood is calculated from previous measurements which were done for softwood dryers. The emission volumes are separated for sapwood and heartwood. The Raute data shows that the TOC emissions from sapwood is 381 g/m³. The same results for heartwood is 336 g/m³. The results from Raute data collection are contrary to this survey. In this survey the emissions from the heartwood dryer were higher than in the sapwood dryer. In this survey the emissions from sapwood dryer were 347 g/m³. The emissions from heartwood were 393 g/m³. Comparison between the previous results shows that the emissions from softwood are somewhere between 340 - 400 g/m³. The heartwood is saturated with resin and other materials, which keeps the TOC emissions higher than in sapwood.

The previous results from measurements show that the emissions from veneer dryers vary. Year 2000 Raute made an emission survey to one plywood mill. For example the TOC concentration in exhaust air from a softwood veneer dryer was 428 mg/m³. The TOC emissions in one hour were 4,2 kg/h which means 33,6 tons carbon annually from that dryer. TOCs compared to dried veneer was 381 g/m³ for sapwood and 336 g/m³ for heartwood. The cleaning effect of the scrubber was 33 %. The measuring time in this survey was only one hour. The VOCs were measured with activated carbon sorbent tubes. The results from those measurements were that the main components from softwood drying are alfa-pinene (56 %), beta-pinene (19 %), limonene (6 %), delta-3-carene (3 %) and other organic compounds (15 %).

The main problem with activated carbon sorbent tubes is the moisture in exhaust air. This tubes do may not adsorb all the constituents because the tubes might be filled with water. The Tenax-tube used in this measurement was not able to adsorb some organic compounds as methane, ethanol and formaldehyde. The Tenax-tubes and activated carbon sorbent tubes are not suitable to measure the VOC components because those do not give the right fractions of components. The VOC compounds measurements in this thesis were almost only different terpenes. The compounds were alfa-pinene, beta-pinene, delta-3-carene, limonene and toluene.

During 2001 the emissions were also measured the emissions from softwood veneer dryer in a plywood mill. The TOC emission concentration in exhaust air from this softwood veneer dryer was 238 mg/m³ after the scrubber. The TOC emissions in one hour were 2,83 kg/h which means 22,6 tons carbon annual from the dryer after the scrubber. The total emissions in the case was an average 21 tons from one dryer after the scrubber. In this survey the ethanol and methanol emissions were also measured from the exhaust stacks. The measured ethanol emissions were 780 g/h, which is 292 g/h as carbon. Methanol emissions were 960 g/h, which is 499 g/h as carbon. The fraction of methanol and ethanol emissions from TOCs was 28 %.

Different emission surveys publish the results in many ways. The best way to compare different results is to choose the caused emissions per dried veneer. In

Figure **24** are shown the emissions from two different case.

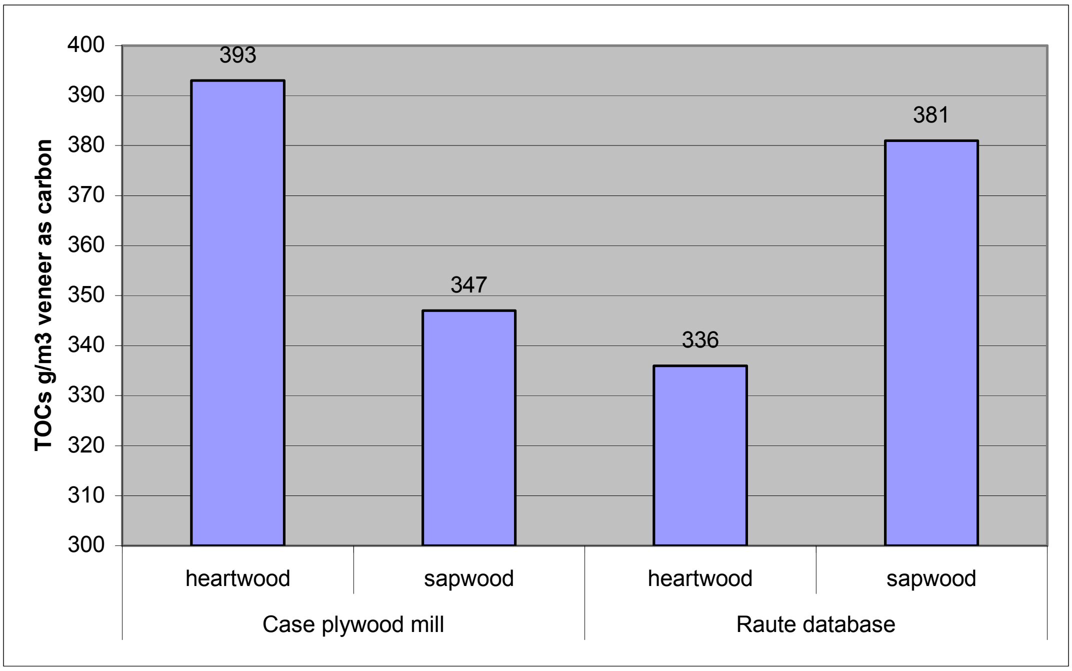

Figure 24. The emissions from different measurements for softwood veneer.

4.1.2. EFFECT OF CHANGED PARAMETERS IN VENEER DRYING

The changed production parameters have at least some affects on emissions in veneer drying. Survey was made changing different parameters separately. The parameters changed during this survey were moisture content and temperature. The measuring time for each changed parameter was four hours. The changed production parameters were used at Dryer 2. The parameters were changed as much as possible to ensure normal production. The limiting factors were the risk of fire and the risk of poor quality of the veneer.

A lower moisture content was used in this survey because of the hypothesis that Raute dryers emit less emissions than competitors dryers. The other hypothesis was that Raute dryers keep more moisture inside of the dryer than competitors. In this survey the Dryer 2 was set to have a moisture content of less than 400 grams water in kilogram dry air. In normal production the moisture content is approximately 600 to 700 grams water in kilogram dry air. This means that the moisture content was dropped more than 31 % for this test. The emission concentration in exhaust air from the drier dryer was 807 mg/m³. The TOC emissions from this dryer was 6 121 g/h as carbon. In this measurement the average TOCs per dried veneer cubic meter was 513 g/m³ as carbon during the drying of 44,75 m³ veneer. The comparison is done with the emissions from the same dryer in normal production with normal production parameters. The emissions in the Dryer 2 normal production was 393 g/m³ as carbon per dried veneer cubic meter. The emissions at lower moisture content drying was 23 % higher than in normal production. That difference between lower moisture content drying and normal production are quite high but however still inside the margin of error.

A lower temperature in veneer drying was used in this survey because there was an assumption that the temperature inside of the dryer affects the emissions. In this survey the Dryer 2 was set to have temperature lower than 170 °C. In the normal production the temperature is set to be 185 to 195 °C. This means that the temperature was set to be 10 % lower than in normal production. The temperature could not be lower because all the resin needs to be taken out from the veneer. The emission concentration from the colder dryer was 687 mg/m³ as carbon. The TOC emissions from that dryer were 3 225 g/h as carbon. In this measurement the average TOCs per dried veneer cubic meter was 225 g/m³ as carbon during the drying of 57,22 m³ veneer. The comparison is done with the emissions from the same dryer in normal production with normal production parameters. The emissions in normal production compared to the dried veneer cubic meter in the Dryer 2 was 393 g/m³ as carbon. The emissions at lower temperature drying was 43 % lower than in normal production. That difference between lower temperature drying and normal production are significant but can still be inside the margin of error. The reason for lower emissions with lower temperatures can be the consequence that the part of the VOCs condensates to the surfaces of the dryer also. One reason for the lower emissions in lower temperature is that the decomposition of the wood is slower. At the low temperatures the resin may not boil out of the veneer, which is not acceptable in plywood making. The TOC emissions from changed production is compared in Figure 25 to the normal production in Dryer 2.

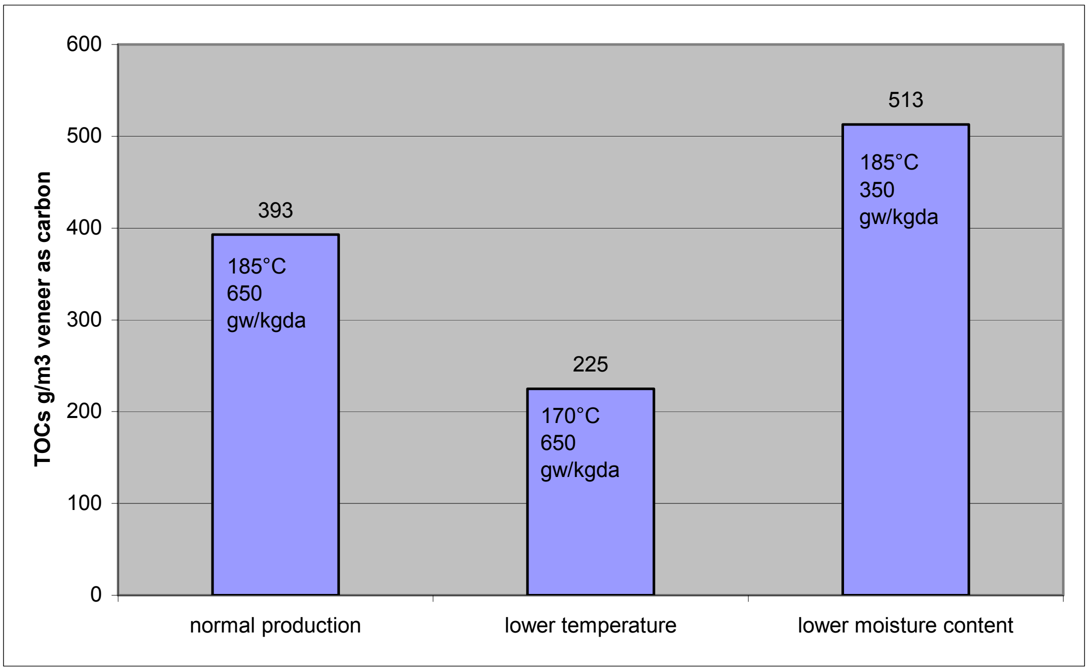

Figure 25. TOC emissions from changed production in Dryer 2.

4.2. IMPACT OF REGULATIONS

The regulations in Finland are guided by European Union legislation. European Union regulations do not have specific regulations for plywood manufacturing. The European Union has set maximum limits for certain pollutants, which cannot be exceeded as of 2010. This European Union regulation affects the Finnish legislation now and in future. The Finnish environmental laws concerning the emissions are to be updated in the near future. The Finnish national laws need to achieve the decreasing targets that European Union has set.

The current Finnish environmental law demands plywood mills to have an environmental license. In the environmental license application Finnish plywood factories announce their emissions to air and the environmental administration decides the emission limits if needed. Their decision is based on the best available techniques at the current moment. The best available techniques are searched from other mills in Finland. The environmental license determines the emission limits to each mill considering its area. Mills next to settlements have more strict limits than mills in sparsely populated areas. There are some best available technique reference documents (BREF) for other branches to reduce VOCs but not for mechanical wood industry. Finnish administrators could find out the emission control techniques used for example in U.S to determine the emission limits in Finland.

The environmental licenses in Finland will become more stricter, when the first air pollution control devices are installed in a plywood mill. There have been some experiments to try to convey the exhaust gases straight to boiler. That experiment did however not work because of the long distance between the dryers and boiler.

The U.S VOC emission limits for plywood industry are only for hazardous air pollutants. From those pollutants methane and formaldehyde have been found in the exhaust air. The limit for those HAPs are 11,27 g/m³ veneer as carbon. The average emissions from this case were 370 g/m³ veneer as carbon between sapwood and heartwood before the scrubber. From previous measurements 15 % of all TOCs are other organic compounds like methane, ethane and formaldehyde. 15 % of 370 g/m³ veneer as carbon is 55,5 g/m³ as carbon. From other measurement we can assume that the methanol and formaldehyde are no more than two thirds of that 55,5 g/m³ as carbon. Two thirds of 55,5 g/m³ is 37 g/m³ veneer as carbon. The total HAPs in this case were approximately 37 grams per veneer cubic meter. It means that in this case the add on control system is needed to reduce the HAP emissions. In this case the U.S regulations regulates that add on control system is needed.

There are six different compliance options and one of the compliance options must be complied with. Three of the compliance options were to reduce either HAP, formaldehyde or methane emissions by 90 %. The three other compliances were to limit the HAP emissions to 20 ppmvd or limit the methane emissions to 1 ppmvd or limit the formaldehyde emissions to 1 ppmvd. In Figure 26 is shown the HAP emissions in this plywood mill and the U.S regulations.

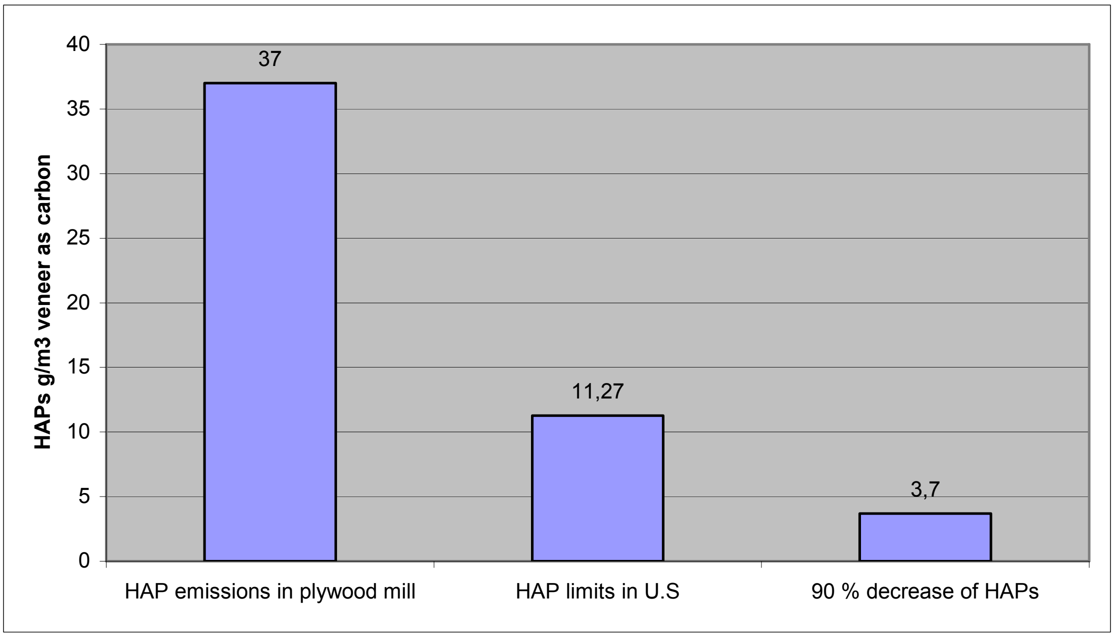

Figure 26. U.S.A regulations for HAPs.

4.3. SUITABLE CLEANING METHODS FOR VENEER DRYER

To find the appropriate cleaning methods for the veneer drying emissions is not simple. The different variables in this case are: process conditions, cleaning effectiveness and costs. The exhaust air might be very wet and the VOC emissions condensate easily to surfaces. The changes of the process conditions and VOC emission concentrations set challenges to the cleaning. The air flow from the Dryer 1 and the Dryer 2 is 1-4 m³/s dry air which is 3 600-14 400 m³/h dry air. The VOC concentrations varies between 300-1 500 mg/m³ as carbon in dry air. The moisture content that comes out from the dryers varies between 30-50 %.

There are several methods to clean the exhaust air from veneer dryers. The condensation is not the solution in this case because the TOC concentrations are considerably low to achieve efficient and economical cleaning. The biological cleaning methods are not either optimal to clean the VOCs because the air flow and the concentration of organics is not constant. In veneer drying most of the emissions are not water soluble components that are not suitable for biological cleaning methods. The best temperature in exhaust air for the biological cleaning methods are less than 40 degrees Celsius. The temperatures in exhaust air are much higher and therefore the cooling of the exhaust air would not be an efficient solution.

Absorption is not a possible choice because the VOCs from the softwood veneer dryers are mostly not water soluble. Absorption is recommended for reasonably high concentrations while air flow and TOC concentration is constant. In this case the air flow and concentration varies substantially, which makes absorption a poor method to remove emissions from veneer dryers. Raute has sold wet scrubbers to some plywood producers mainly for the heat recovery but their cleaning effect is considerably low to achieve strict U.S.A rules. The cleaning effect might be better with the wet scrubbers if they were in fact designed for the cleaning of the exhaust air rather than for heat exchange.

Previous research has shown that the different adsorption methods to clean the VOCs are more expensive compared to other cleaning methods such as RTO. High moisture content might be harmful to some adsorption systems. The adsorption could still be a possible cleaning method in veneer drying in future because the process is suitable for this kind of exhaust air. Adsorption can remove over 90 % of all organic compounds from the exhaust air.

Recuperative and regenerative catalytic oxidizers are possible ways to clean the VOCs from softwood veneer dryers. The main problem with the catalytic oxidizers is the unstable VOC concentrations. The dryer might stand without any veneer load and sometimes the dried wood has so much extracts that the catalyst might be damaged. The RCO manufacturer EHOVOC remarks that their product can operate with changing VOC concentrations. EHOVOC promises that the exhaust gases are optimal for their control technique. The main concern is the high concentration of terpenes because those might form polymers. Polymers harm the catalyst and heat exchanger to work properly if they sticks to the catalyst surfaces. EHOVOC promises 98 % conversion for the VOCs in their machine. Regenerative catalytic oxidizer has high investment costs and it is not usually used in small and medium-sized businesses. Nowadays the small and medium-sized companies has invested to regenerative catalytic cleaning system because of the tightened regulations. Small concentrations of VOCs are advantage for this technique.

A recuperative thermal oxidizer is an efficient way to destroy the VOCs from the exhaust air. This kind of oxidizer can remove more than 99 % of the VOCs. This recuperative thermal oxidizer is the cheapest device from the suitable cleaning methods but the operating costs are very high because recuperative thermal oxidizer has an autothermal point between 8-15 g/m³ VOCs in exhaust air. The VOCs from the softwood dryer were only 2 g/m³ VOCs in exhaust air, which means that there is high demand of additional fuel. The usage of additional fuel increases operating costs considerably. The usage of recuperative thermal oxidizer with veneer dryers come an issue if all the excess heat energy is used in some process in the plywood mill. In recuperative thermal oxidizer the heat exchanger is however poor because it can recover only 30-60 % of the generated heat.

Regenerative thermal oxidizer is also an efficient way to destroy the VOCs from exhaust air. This kind of oxidizer can destroy more than 90 % of the VOCs. This regenerative thermal oxidizer is the optimal way to destroy the VOCs because it needs only 0,7 g/m³ for autothermal oxidizing. The main reason for this kind of add on control system is its efficiency to recover the generated heat. In regenerative thermal oxidizer the heat recovery to the exhaust air pre heating can be even 98 %. This system can manage with changing air flow and VOC concentrations. In veneer drying process it is very important that there are no need for additional fuel. This system achieve high cleaning effect with reasonable low operating costs.

The exhaust air can also be conveyed to the boiler in power plant. The VOCs burn in boiler and the cleaning effect is 100 %. There are few limiting factors for this VOC control system. This method requires large a furnace on site and the dryers should be close to the furnace. The pipes must be well insulated or heated because the gases must reach the boiler before they condense. This method achieves low emissions from the dryers as well as at the boiler stacks. This method has low capital costs and low operating costs. This should be the primary method for a VOC control system in softwood veneer drying.

In Table 23 are shown some details from the different control techniques. The VOC reduction percentages, recommend VOC concentrations and autothermal points are shown. In the same table noted the suitability of these control techniques for softwood veneer drying.

Table 23. VOC control techniques and potential usages.

VOC control technique	VOC reduction %	Recommend VOC concentration g/m^3	Autothermal burning g/m^3	Potential control technique?
Condensation	99	10+		no
Biological methods	75-95	0-1		no
Absorption	85-95	1+		no
Adsorption (different methods)	90	0-20		no/yes
Recuperative catalytic oxidizer	98	1-8	2	yes
Regenerative catalytic oxidizer	98+	1-8	2	yes
Recuperative thermal oxidizer	99	5-15	8	yes
Regenerative thermal oxidizer	90+	0-5	0,8	yes
Incinerator	99+	0+		yes

4.4. EMISSION SURVEY FOR VENEER DRYERS IN FUTURE

The legislation in Finland and in Europe is insufficient compared to the regulations in U.S.A. In Finland the environmental license puts plywood mills under obligation to measure and announce the emissions to air. The environmental authorities sets limitations using best known practices. The authorities have not set any rules for the measurements done for veneer dryers. The main problem with the measurements is that the wood is not homogenous material and the emission measurement needs longer measuring time than one hour. The Finnish environmental license authorities should give enough information how to measure those emissions. Nowadays the results in environmental licenses are not comparable because of the different ways of measurements used in gathering the information.

The other problems in veneer drying processes are the exhaust gas from smoke sections and cooling section. In this case the exhaust gases from the smoke sections and cooling section was very thick smoke. There is a need for further development to measure the smoke and cooling sections in drying.

The results from changed conditions were done only once for this survey and the results were interesting. The lower TOC emissions with lower temperature was expected and the hypotheses for the lower moisture content was accurate. The result for the lower moisture content was that the emissions were reduced 31 %. If the hypothesis is correct that Raute dryers keeps higher moisture content inside of the dryers than competitors, it can be said that Raute dryer emits less VOCs than competitors. The need for the further development is that the lower moisture content should be measured at least a few more times. The lower temperatures should be considered in veneer drying if the veneer quality does not decrease, because in this measurements the emissions were 43 % lower than in normal production. However if the temperatures are decreased the production in veneer dryers comes slower. Veneer dryers are usually the bottleneck in a plywood process, means that the lower temperature will not be considered as a possible option for pollution control in plywood mills.

5 CONCLUSIONS

Tightened regulations in environmental affairs have put the plywood industry in new circumstances. Production plants need more often to know the emissions of their processes at some level.

Plywood production has two sources that form VOC emissions. In veneer drying the VOC emissions come from the wood. High temperatures and resin in wood cause the VOC emissions from the dryer. Boiled resin and wood combustion affects the emissions from the veneer dryer. The other emission source from the plywood processes is pressing. The glues used in pressing cause the VOC emissions. In this survey the main focus is in the VOC emissions from spruce veneer dryers.

Wood is a heterogeneous material, which means that the structure and components changes between different wood species and even inside of one small piece of wood. Wood has a cell structure which constituents are cellulose, hemicelluloses, lignin and extracts. The constituents vary a lot between hardwoods and softwoods. The extracts in wood are one of the main sources of VOCs. Extracts are divided to neutrals, free acids and volatiles. The volatiles consists mainly of terpenes and the terpenes are usually less than a percent of wood depending on the wood species. Softwood has more terpenes than hardwood, which causes most of the VOCs. The terpene group consists mainly of mono-, sesqui- and diterpenes. Other main VOCs from wood drying are ethanol, methanol and formaldehyde. The VOC emissions from hardwoods are mainly ethanol and methanol, which are water soluble. Softwood emissions consist mainly of terpenes, ethanol and methanol. Terpenes are not water soluble components.

The drying temperature is considerably high in veneer drying. The temperatures used in drying are usually between 150 and 250 degrees Celsius. When wood is heated to over 150 °C, many chemical and physical features of the wood change. As the temperature is lifted up to over 200 °C, the changes are increased. In those high temperatures wood starts to decompose and transform. Carbohydrates start to decompose and gases start to form in those temperatures.

The emissions from the dryers depend on the dryer type. Gas fired dryer emissions contain some unburned methane and wood fired dryers may have less overall organic emissions than steam-heated dryers because of the high temperature at 1100 °C in the combustion unit. The main reason for the emissions from the dryers is the type of wood dried in the process. For example, spruce veneer drying may yield over three times the emissions compared to the drying of birch.

A major environmental effect from the VOC emissions is the formation of photo-oxidants. Nitrogen oxides and terpene emissions together increase ozone levels considerably. High ozone levels are a health risk for human. Plants are also very sensitive to ozone. The emissions from the plywood industry as the terpenes are not the most active kind of ozone formers. It must be remembered that the forests also produces VOCs.

There are three different methods to reduce VOCs. The best methods are process or product changes to prevent VOCs. Sometimes the only way to prevent VOCs efficiently is to use some cleaning technique. Different types of oxidation, adsorption, absorption, condensation and biological cleaning are the most common cleaning methods. Each of those cleaning methods are suitable for some kind of exhaust gases. In this Thesis the best cleaning methods are evaluated and chosen for the emissions from a softwood veneer dryers.

The European Union has set regulations for some industrial branches but the plywood industry is outside of that legislation. The European Union recommend that the authorities should use “best practice” method to evaluate the emission limits for various factories. Finnish environmental protection law requires plywood mill to have an environmental license. There are not any exact limits for VOC emissions in law for plywood industry. The ministry of social affairs and health has set the indoor limits for some compounds. Turpentine, ethanol, methanol and formaldehyde has limits for indoor air quality. The USA has very strict emission regulations for forest industries. The regulations in the USA regulates the VOC limits for veneer dryers and it is 11,27 gC/m^3 veneer. If the emissions are higher than 11,27 gC/m^3, the emissions should be 90 % less than normal emission amounts. Some states might have stricter total emission limits for VOCs.

Softwood veneer dryer emissions were measured from two different dryers. One dryer measured dries mainly sapwood and the other dryer measured heartwood. Each dryer has three measuring spots. From each spot the TOCs, moisture, temperature, air flow and VOC component fractions were measured. Those measurements were done while the dryers were operating normally with normal production. The production parameters were also changed in the heartwood dryer to research pollution levels in a drier and also a colder dryer. The separation capability of the water scrubbers were also measured from the heartwood dryer.

The emissions from the heartwood dryer before any cleaning equipment in normal production is 1360 mgC/Nm^3 and total annual emissions from the same dryer is 46 tC/a. The emissions compared to the dried veneer volume are 393 gC/m^3. The emission from the sapwood dryer before any cleaning equipments in normal production is 327 mgC/Nm^3 and total annual emissions from the same dryer is 32 tC/a. The emissions compared to the dried veneer volume are 347 gC/m^3. The emissions were also measured in changed conditions. The emissions in lower temperature drying were 225 gC/m^3 veneer. The emissions in lower moisture content drying were 513 gC/m^3 veneer.

There are many cleaning methods for different kind of process emissions. The plywood emissions are unstable, dilute and the amount of air is quite high. The emissions from the softwood dryers are very difficult to process because the volatile compounds condense easily to colder surfaces. If the emission limits tighten in Europe, the emission must however be cleaned somehow. The scrubber is not enough to clean the softwood dryer emissions because all the emissions are not water soluble. In this Thesis different methods were considered and three methods are suitable for this process. The best and the cheapest method is so called incineration where the emissions are conveyed to the boiler. Incinerating is suitable method if the boiler is not far away from the emission sources. The other possible cleaning methods are regenerative thermal oxidizer (RTO) and regenerative catalytic oxidizer (RCO). The RTO is used cleaning method in Northern America for the wood based emissions. The RCO is quite new method in process gas cleaning and it has become competitive method because the autothermal point is lower than in the RTO. The problem in the RCO was high price and inefficient heat recovery but new solutions have made it more competitive. RTO and RCO has the same conversion efficiency more than 99 %. The main difference in the usage is the operating temperature. The RCO operates approximately in 350 degrees Celsius and the RTO needs more than 800 degrees Celsius to operate. The RCO uses chemical oxidation and the RTO uses thermal oxidation.

REFERENCES

BOOKS

A study of organic compound emissions from veneer dryers and means for their control. Technical bulletin 405. National council of the paper industry for air and stream improvement (NCASI). 1983. New York. 144 p.

Absetz, I. 1999. Moisture transportation and sorption in wood and plywood - Theoretical and experimental analysis originating from wood cellular structure. Doctoral dissertion. Helsinki University of Technology Laboratory of Structural Engineering and Building Physics Publications. Espoo. 90 p. ISBN: 951-22-4642-2.

Ailasmaa, V. 1996. Haihtuvat orgaaniset yhdisteet (VOC) massa- ja paperiteollisuudessa. Metsäteollisuus ry. Helsinki. 45 p.

Baldwin, R. 1995. Plywood and veneer-based products : manufacturing practices. Miller Freeman. San Francisco. 388 p. ISBN: 0-87930-371-9.

Control techniques for organic emissions from plywood veneer dryers. Office of air quality planning and standards. EPA-450/3-83-012. United States Environmental Protection Agency (EPA). 1983. Research triangle park. North Carolina. 113 p.

Ehovoc Oy. 2009. Product description. Oulu.

Emission Factor Documentation for AP-42 Section 10.5. Plywood Manufacturing. Final report. EPA Contract 68-D2-0159. United States Environmental Protection Agency (EPA). 1997. 62 p.

Fengel, D. et al. 1989. Wood - chemistry, ultrastructure, reactions. Walter De Gruyter Inc. Berlin. 613 p. ISBN: 0899255930.

Granström, K. 2002. Emissions of volatile organic compounds during drying of wood. Karlstad University. 51 p. ISBN: 91-89422-77-5.

Granström, K. 2005. Emissions of volatile organic compounds from wood. Karlstad University. 126 p. ISBN: 91-85335-46-0.

Jussila, J. 1995. Prosessissa syntyneiden VOC-päästöjen vähentämisen teknis-taloudellinen tarkastelu. Master's thesis. Department of chemical technology. Helsinki University of Technology. Espoo. 122 p.

Karlsson, L. Reningsteknik för industriella utsläpp av flyktiga organiska ämnen. Naturvårdverkets rapport 3734. Naturvårdverket. Solna. 38 p. ISBN: 91-620-3734-X.

Kellomäki, S. 2001. Density of foliage mass and area in the boreal forest cover in Finland, with applications to the estimation of monoterpene and isoprene emissions. University of Joensuu. 13 p.

Koponen, H. 2002. Puulevytuotanto. Opetushallitus. Helsinki. 199 p. ISBN: 952-13-1450-8.

Lehtinen, M. 1997. et al. Kuivauslämpötilan vaikutus viilun ominaisuuksiin. Helsinki University of Technology. Espoo. 50 p. ISBN: 951-22-3597-8.

Mroueh, U-M. 1990. Hiilivetypäästöjen rajoittamisen tekniset ja taloudelliset edellytykset. VTT. Espoo. 108 p. ISBN: 951-38-3810-2.

Mroueh, U-M. 1990b. Liuotteita käyttävän teollisuuden päästöjen rajoitusmahdollisuudet, VTT tiedotteita 1146, VTT, 142 s. ISBN 951-38-3756-4.

Mroueh, U-M. 1992. Haihtuvien orgaanisten yhdisteiden (VOC) vähentämisstrategia. Ympäristöministeriön ympäristönsuojeluosaston muistio 6/1992. Finland's environmental administration. Helsinki. 215 p. ISBN: 951-47-4781-X.

Nurmi, J. et al. 1997. Sahojen ja vaneritehtaiden kuivaamojen ympäristövaikutukset - päästömittaukset. Tutkimusselostus N:O KET2582/87. VTT. Espoo. 7p.

Pulkkinen, P. et al. 2000. Veneer drying - Effects of wood raw material and drying process on product properties. Helsinki University of Technology, Department of Forest Products Technology, Laboratory of Wood Technology. Otamedia Oy. Espoo. 60 p.

Rafson, H. 1998. Odor and VOC control handbook. MCGraw-Hill. New York. 800 p. ISBN: 0-07-052523-4.

Raute. 2009. Raute data collection.

Sjöström, E. et al. 1999. Analytical methods in wood chemistry, pulping, and papermaking. Springer. Berlin. 316 p. ISBN: 3-540-63102-X.

Viitaniemi, P. et al. 1996. Puun modifiointi lämpökäsittelyllä. VTT. Espoo. 57 p. ISBN: 951-38-4523-0.

ELECTRIC REFERENCES

Air Liquide. Direct cryogenic condensation. 2008. From: http://www.airliquide.com/en/chemicals/equipment-4/cryogenic-condensation-of-vocs-4.html

AirScience Inc. Wet electrostatic precipitator. 2008. From: http://wetelectrostaticprecipitator.com/index.htm

Forbes Group. Wet scrubber. 2009. From: http://www.forbesgroup.co.uk/product.php/78/33//c720a4c3a9de5e8043c3d814ad3b869c

Forest products laboratory. Madison. 41 p. From: http://www.fpl.fs.fed.us/documnts/usda/ah188/chapter01.pdf

HTP-arvot: Haitallisiksi tunnetut pitoisuudet. Kemian Työsuojeluneuvottelukunta. 2007. 67 p. From: http://www.ketsu.net/htp/HTP2007.pdf

Integrated pollution prevention and control. Council Directive 96/61/EC. EUR-Lex. 1996. From: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31996L0061:EN:HTML

J.U.M. Engineering Ges.m.b.H. Flame ionization detector. 2009. From: http://www.jum.com/

National emission standards for hazardous air Pollutants: plywood and composite wood products. Code for Federal Regulations (CFR). Title 40 part 63 subpart DDDD. National archives and records administration. 2004. From: http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr;sid=225a505a023e16cfa04bd649ad6e6a4e;rgn=div6;view=text;node=40%3A12.0.1.1.1.11;idno=40;cc=ecfr

Rogers, I. 1978. Environmental effects of terpenoid chemicals: a review. Journal of the American Oil Chemists' Society. Vol. 55, n. 2 p. 113-118. Springer. Berlin. ISSN 1558-9331. From: http://www.springerlink.com/content/047x600831528272/fulltext.pdf

Simpson, W. 1991. Dry kiln operators manual. Agricultural hadbook AH-188. Chapter 1: Properties of wood related to drying. Department of agriculture.

The CMN Group, LLC. Recuperative thermal oxidizer. 2009. From: http://www.thecmmgroup.com/img/14.jpg

The CMN Group, LLC. Regenerative thermal oxidizer. 2009b. From: http://www.thecmmgroup.com/img/10.jpg

Ympäristölupapäätös YS 574. Uudenmaan ympäristökeskus. Finland's environmental administration. Helsinki. 2003. 8 p. From: http://www.ymparisto.fi/download.asp?contentid=17564&lan=FI

Ympäristölupapäätös KSU-2004-Y-370/111. Keski-Suomen ympäristökeskus. Finland's environmental administration. Jyväskylä. 2006. 42 p. From: http://www.ymparisto.fi/download.asp?contentid=48932&lan=FI

Ympäristönsuojeluasetus 18.2.2000/169. Finlex. 2000. From: http://www.finlex.fi/fi/laki/ajantasa/2000/20000169

INTERVIEWS

Kaislaoja, Jarkko. Technology manager. Raute Oyj. 20.3.2009