

# CHAPTER 6

## Gaseous Emissions from the Combustion of Biomass Pellets

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### Abstract

Biomass is a sustainable energy source with significant potentials for replacing fossil fuels and electricity for heating purposes. Present residential wood combustion can, however, be a significant source of ambient urban air pollutants such as volatile organic compounds, polycyclic aromatic hydrocarbons and particulate matter. Ambient exposure to these pollutants in general has been associated with different health effects such as cardiopulmonary disease/mortality and cancer risks [1–3]. Wood pellets are generally a clean, dry and easily fed fuel to be used in special boilers, burners and stoves on the residential market. Compared with other modern technologies, the majority of the wood-fired appliances currently used suffer from poorly optimized conditions, resulting in considerable emissions of products from incomplete combustion. New and upgraded biomass fuels provide possibilities of more controlled and optimized combustion with less emission of PIC [4]. For future health impact assessments, regulatory standards and evaluations concerning present and future residential biomass combustion, as well as a solid qualitative and quantitative knowledge of the emissions from different sources, are of vital importance. In consequence, there is still a strong need for detailed characterization and quantification of the emissions from residential biomass appliances when using different fuels and combustion techniques [5].

*Keywords: Pellets, biomass, emissions, pollutants, combustion.*

### 1 Introduction

The environmental impacts of air pollution from most biomass combustion appliances today are far from negligible. However, they show significant advantages in comparison to those that use fossil fuels [6].



Table 1: Average energy consumption at procurement of different fuels [8].

	Energy consumption at procurement	
	MJ/tonne	% of energy content
Native wood pellets	627	3.6
Imported wood pellets	787	4.5
Natural gas	2,840	5.8
Oil	4,617	11.4
Coal	1,764	6.7

Biomass is a renewable fuel considered to be CO<sub>2</sub>-neutral with respect to the greenhouse gas balance. However, this is only true if we are able to achieve very low levels of emissions from incomplete combustion [7], and if we do not consider the energy consumption from fossil fuels in biomass treatment and logistic processes such as harvesting, transportation or compaction (Table 1).

To evaluate the real environmental impacts of biomass combustion, a life cycle assessment (LCA) should be carried out. This type of evaluation includes the various stages of the life cycle of the biomass, from procurement of the fuel, transportation, storage and conversion to the discharge and handling of ashes [9]. The construction, operation, maintenance and decommissioning of the energy converting technology should also be included in the assessment according to the LCA method. The exchanges to the surrounding environment in terms of emissions to air, soil and water are then inventoried for each stage in the life cycle. These exchanges are added up to indicate environmental impacts such as global warming, acidification and ozone depletion in the environmental impact assessment. Therefore, it is not fully correct to define biomass fuels as CO<sub>2</sub>-neutral when considering the complete life cycle [10].

Emission reduction measures are known and available for all harmful emission components, and whether the emission reduction measures are implemented or not merely depends on emission limits and cost-effectiveness. Technology to reduce emissions and improve combustion efficiency is being developed continuously. Wood burning appliances have gradually been improved because of the permanent R&D activities that have been developed during the last years and that has led to an advanced understanding of the combustion process as well as of emission formation mechanisms. Better knowledge about the basic mechanisms governing the process also has led to a more focused further development of primary measures for emission reduction.

## 2 Gaseous Emission Components from Biomass Combustion

Gaseous emissions from biomass combustion applications can be divided into two major groups: emissions from complete combustion and emissions from incomplete combustion.



Table 2: Average proximate analysis of wood pellets and combustion products [11].

Matter	Share	Combustion product
H <sub>2</sub> – Hydrogen	5.8	H <sub>2</sub> O – Water vapour in flue gas
C – Carbon	46.5	CO <sub>2</sub> – Carbon dioxide/carbonic acid gas
O <sub>2</sub> – Oxygen	39.5	O <sub>2</sub> – As surplus oxygen
A – Ash	0.9	Ash – Partly as dust in the flue gas
S – Sulphur	0.05	SO <sub>2</sub> – Sulphur dioxide
N <sub>2</sub> – Nitrogen	0.28	N <sub>2</sub> – Nitrogen in the flue gas
H <sub>2</sub> O – Water	7.0	H <sub>2</sub> O – Water vapour in the flue gas

## 2.1 Gaseous emissions from complete biomass combustion

The amount and composition of flue gas created during the complete combustion are determined by the proximate analysis of the wood pellets. Table 2 shows the typical result of a proximate analysis of wood pellets, together with the combustion products that each batch creates during complete combustion. Nevertheless, the concentration of gases in the flue gas will depend on the fuel and for some components also on the design of the combustion system.

### 2.1.1 Carbon dioxide

Carbon dioxide (CO<sub>2</sub>) plays a significant role in the greenhouse effect and thus the emission of CO<sub>2</sub> to the atmosphere is problematic. Since wood pellets and other biofuels contain carbon, naturally CO<sub>2</sub> is also created during their combustion. However, when combusting wood fuels there is no more carbon dioxide released than that bound up in the wood as carbon and the only CO<sub>2</sub> attributable to pellets is that emitted during their production and transport. This results in the almost zero CO<sub>2</sub> emissions from biomass fuels shown in Table 3 in comparison with fossil fuels.

Carbon constitutes approximately 50% of completely dry wood, which corresponds to 47% in wood pellets with a moisture content of 7% (Table 2).

### 2.1.2 Nitrogen oxides (NO<sub>x</sub>)

NO<sub>x</sub> is a generic term for the sum of the gases NO and NO<sub>2</sub>. NO<sub>x</sub> is a greenhouse gas that at the same time contributes to the acidification of precipitation. Nitrogen oxides are created partly during the combustion of fuels with a natural nitrogen content including biofuels and partly in the boiler room by the nitrogen that is injected during combustion with the combustion air. The design and size of the boiler combustion chamber is therefore of importance in the emission of nitrogen oxides. It is not possible to give completely plain guidelines for the design of boilers with low NO<sub>x</sub> emission but the following tendencies are certain: high N-content in the fuel increases NO<sub>x</sub> emission and high combustion temperatures generate high NO<sub>x</sub> emissions [13].

Table 3: Gaseous emission key figures for delivered energy [12].

Fuel	CO <sub>2</sub> (g/MJ)	NO <sub>x</sub> (mg/MJ)	SO <sub>2</sub> (g/MJ)	CO (mg/MJ)	TOC (mg/MJ)
Wood pellets	0.108	130–300	0	50–3000	<10
Straw	0.108	130–300	13	500–3000	<10
Oil	0.972	75	94	15–30	0–2
Natural gas	0.72	50–100	0.5	15–20	0–2

NO<sub>x</sub> emissions from biomass combustion applications are mainly a result of complete oxidation of fuel nitrogen, in contrast to fossil fuel combustion applications where nitrogen in the air also contributes, to some extent, to the NO<sub>x</sub> emission level. The possible gas-phase reaction mechanisms for NO<sub>x</sub> formation in biomass combustion applications are as follows:

- *The fuel NO<sub>x</sub> mechanism [14–16]:* Fuel nitrogen is converted to NO (>90%) and NO<sub>2</sub> (<10%) through a series of elementary reaction steps called the fuel NO<sub>x</sub> mechanism. Important primary nitrogen-containing components are NH<sub>3</sub> and HCN. However, significant amounts of NO and N<sub>2</sub> may also be found in the pyrolysis gas. If sufficient O<sub>2</sub> is available, NH<sub>3</sub> and HCN will mainly be converted to NO through different reaction routes. However, in fuel-rich conditions NO will react with NH<sub>3</sub> and HCN, forming N<sub>2</sub>. This is utilized as a primary NO<sub>x</sub> reduction measure. By optimizing the primary excess air ratio, temperature and residence time, a maximum conversion of NH<sub>3</sub> and HCN to N<sub>2</sub> can be achieved.
- *The thermal NO<sub>x</sub> mechanism [17,18]:* Nitrogen in the air starts to react with O radicals and forms NO at temperatures above approximately 1300°C. The amount of NO formed increases with increasing temperature, O<sub>2</sub> concentration and residence time. However, in biomass combustion applications, the combustion temperatures are, in general, lower than 1300°C. Thermal NO<sub>x</sub> is a post-flame problem, meaning that the major formation of thermal NO<sub>x</sub> occurs in the post-flame gases, after the main combustion, due to its dependence on O<sub>2</sub> concentration and residence time.
- *The prompt NO<sub>x</sub> mechanism [14–19]:* Nitrogen in the air may also react with CH mainly forming HCN, which then follows the reaction steps of the fuel NO<sub>x</sub> mechanism. The prompt NO<sub>x</sub> mechanism is less temperature-dependent and much faster than the thermal NO<sub>x</sub> mechanism. However, it is only important in fuel-rich conditions and is very dependent on the CH concentration. The prompt NO<sub>x</sub> mechanism has not been found to be of significant importance in biomass combustion applications, in contrast to fossil fuel combustion applications.

Additionally, fuel nitrogen is retained in the char and is largely oxidized to NO in the char combustion phase but may subsequently be reduced to N<sub>2</sub> by a fast

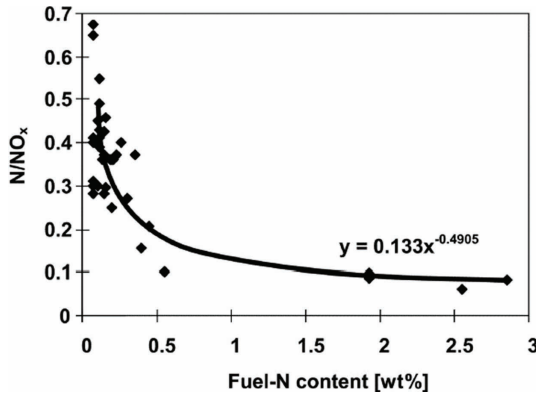


Figure 1: Fraction of fuel nitrogen converted to  $\text{NO}_x$  for various wood fuels in various wood combustion applications, as a function of fuel nitrogen content, together with a trend line [22].

heterogeneous reaction with the char [20]. The amount of fuel nitrogen retained in the char relative to the amount of fuel nitrogen released in the devolatilization phase is determined in part by the thermal exposure of the fuel [21]. The fuel  $\text{NO}_x$  emissions increase with increasing nitrogen content in the fuel, excess air ratio and combustion temperature, up to a point where all fuel nitrogen intermediates have been converted to either  $\text{NO}_x$ ,  $\text{N}_2\text{O}$  or  $\text{N}_2$ . However, the fraction of fuel nitrogen converted to  $\text{NO}_x$  decreases with increasing nitrogen content in the fuel (Fig. 1). Figure 2 illustrates the relative importance of the fuel, thermal and prompt  $\text{NO}_x$  mechanisms as a function of combustion temperature.  $\text{NO}_x$  emissions may be reduced by both primary and secondary emission reduction measures.

### 2.1.3 Nitrous oxide

Nitrous oxide ( $\text{N}_2\text{O}$ ) emissions are a result of complete oxidation of fuel nitrogen. The  $\text{N}_2\text{O}$  emission levels from biomass combustion are very low but they do contribute to some degree to the greenhouse gas effect because of the high global warming potential factor of  $\text{N}_2\text{O}$  [24].

### 2.1.4 Sulphur oxides

Sulphur oxides ( $\text{SO}_x$ ) are a result of complete oxidation of fuel sulphur. It is mainly  $\text{SO}_2$  (>95%), but some  $\text{SO}_3$  (<5%) may be formed at lower temperatures. The emission of  $\text{SO}_2$  can be significantly reduced by means of pellet firing in comparison with those emissions produced from fossil fuels systems (Table 3).

It has to be highlighted that the sulphur in the fuel will not be completely converted to  $\text{SO}_x$ : a significant fraction will remain in the ashes while a minor fraction is emitted as a salt ( $\text{K}_2\text{SO}_4$ ) or as  $\text{H}_2\text{S}$  at lower temperatures. Measurements at two district heating plants in Denmark using straw as a fuel showed that 57%–65% of

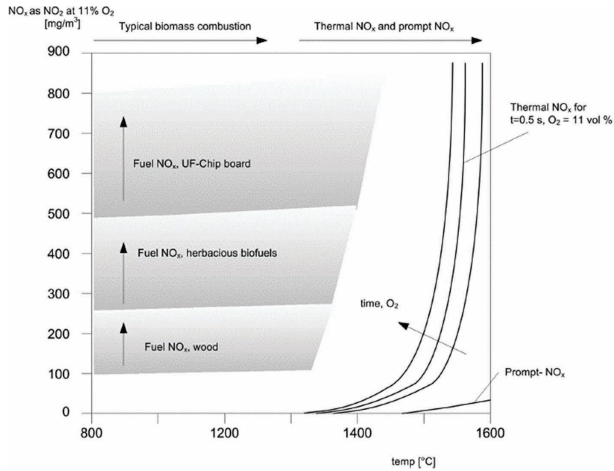


Figure 2: Fuel- $\text{NO}_x$  emission levels as a function of temperature and fuel type (fuel-N content) and comparison with thermal and prompt  $\text{NO}_x$  formation [23].

the sulphur was released into the flue gas, while the remainder was bound in the ashes [25]. Houmøller and Evald [26] reported nine closed sulphur balances from several full-scale measurements in Denmark, four straw-fired units, three wood-chip-fired units and two pellet-fired units and they found similar results.

Special consideration needs to be given to wood pellets made with additives as binding agents. The lignin-based binders that are sometimes used in wood pellets manufacturing are mostly either Wafolin or lignosulphonate, which contain approximately 6 mass percentages of sulphur. The amount of binder is usually <1% of the finished wood pellet. With a binder content of 1%, the content of sulphur in the pure wood pellet is quadrupled to approximately 0.08% compared with the content of sulphur in the pure wooden raw material at approximately 0.02%. This corresponds to a content of sulphur of 45 mg/MJ fuel, which should be compared with the sulphur content in heating oil of <25 mg/MJ [24].

### 2.1.5 Hydrogen chloride

Significant amounts of hydrogen chloride (HCl) may be formed from biomass fuels containing higher amounts of chlorine, such as miscanthus, grass and straw [27]. Part of the chlorine content in the fuel will be released as HCl. The fuel chlorine will not be completely converted to HCl; the main fraction is retained in salts (KCl, NaCl) by reaction with K and Na, while traces are emitted as dioxins and organic chlorine components. HCl emissions may be reduced by washing of the fuel, which is utilized to some extent for straw due to its high chlorine content [28].

## 2.2 Gaseous emissions from incomplete biomass combustion

Emissions caused by incomplete combustion are mainly a result of either:

- Too short residence times.
- Too low radical concentrations, in special cases, for example in the final stage of the combustion process (the char combustion phase) in a batch combustion process.
- An overall lack of available oxygen.
- Inadequate mixing of combustion air and fuel in the combustion chamber, which produces local fuel-rich combustion zones.
- Too low combustion temperatures.

These variables are all linked together through the reaction rate expressions for the elementary combustion reactions. However, in cases in which sufficient oxygen is available, temperature is the most important variable due to its exponential influence on the reaction rates. An optimization of these variables will, in general, contribute to reduce the levels of all emissions from incomplete combustion described below:

### 2.2.1 Carbon monoxide (CO)

Conversion of fuel carbon to  $\text{CO}_2$  takes place through several elementary steps, and through several different reaction paths. CO is the most important final intermediate. It is oxidized to  $\text{CO}_2$  if oxygen is available, so CO can be regarded as a good indicator of the combustion quality. CO emission is unwanted because of being an indicator of an incomplete combustion process, being toxic and combustible (a health and safety risk), and finally because CO destroys the ozone layer.

In addition, a high CO emission is often an indicator of the presence of other unwanted and dangerous matters in the flue gas. In practices, it is not possible to entirely avoid the creation of a little carbon monoxide during combustion, but its minimization is of vital importance.

Due to the fact that wood pellets are homogeneous and have very low moisture content, very low CO emissions can be achieved if the combustion conditions and the design of the boiler are the adequate ones, but huge differences can be found when the CO emissions range are observed (Table 3). Large-scale biomass combustion systems usually have better opportunities for the optimization of the combustion process than small-scale biomass combustion applications [29]. Figure 3 shows the CO emission level as a function of combustion temperature, whereas Fig. 4 shows the CO emission level as a function of excess air ratio for various biomass combustion applications. For a given system, higher excess air ratios will result in a decreased combustion temperature while lower excess air ratios will result in inadequate mixing conditions. In addition, sufficient residence time is important to achieve low CO emission levels, mainly because CO is generally a later intermediate than hydrocarbons.

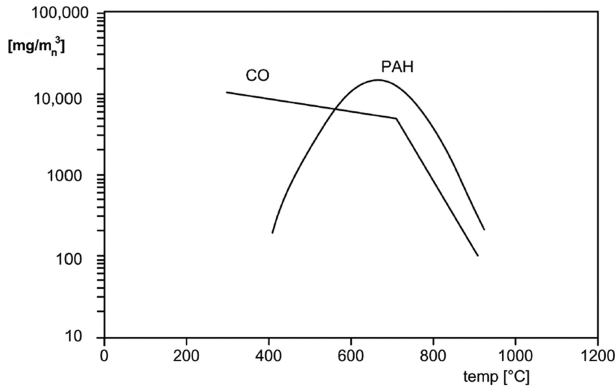


Figure 3: CO and PAH emissions in  $\text{mg}/\text{m}_n^3$  as a function of combustion temperature [30].

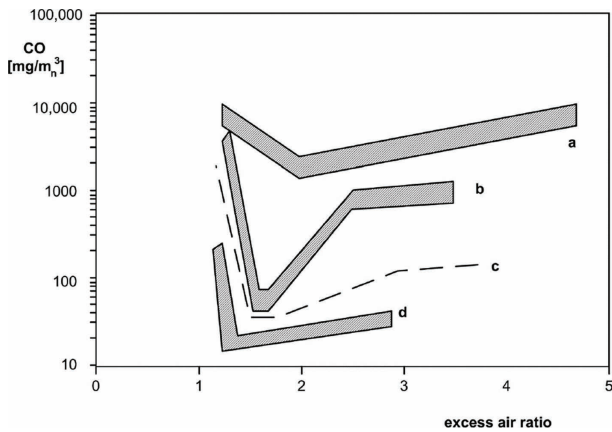


Figure 4: CO emissions in  $\text{mg}/\text{m}_n^3$  as a function of excess air ratio  $\lambda$  [23]. (a) A simple, manually charged wood boiler. (b) A down-draught log boiler. (c) An automatic furnace with combustion technology as of 1990. (d) Automatic furnaces with appropriate combustion process control can be operated under optimum conditions.

**2.2.2 Total organic compounds**

Total organic compounds (TOCs) are the unburned hydrocarbon combinations in the flue gas, and their emission is undesirable because many of the organic combinations are toxic and some of them are carcinogenic [29]. Though TOC emissions are very low when biomass is combusted (Table 3), the requisites for low TOC emission are the same as for CO emissions.



### 2.2.3 Methane

Methane ( $\text{CH}_4$ ) is usually mentioned separately from the other hydrocarbons since it is a direct greenhouse gas. In biomass combustion applications, it is an important intermediate in the conversion of fuel carbon to  $\text{CO}_2$  and fuel hydrogen to  $\text{H}_2\text{O}$ . As for CO, emissions of  $\text{CH}_4$  are a result of too low combustion temperatures, too short residence times or lack of available oxygen. Hydrocarbons are, in general, earlier intermediates than CO, which means that they have lower emission levels.

### 2.2.4 Polycyclic aromatic hydrocarbons

Polycyclic aromatic hydrocarbons (PAHs) are usually mentioned separately from other hydrocarbons due to their carcinogenic effects. They are all intermediates in the conversion of fuel carbon to  $\text{CO}_2$  and fuel hydrogen to  $\text{H}_2\text{O}$ . As for CO emissions, PAHs are a result of too low combustion temperatures, too short residence times or lack of available oxygen. A comparison of the combustion temperature influence on the PAH and CO emission level is shown in Fig. 3.

### 2.2.5 Non-methane volatile organic components

This group includes all hydrocarbons except  $\text{CH}_4$ , PAH and other heavy hydrocarbons, which condense and form particle emissions. They are all intermediates in the conversion of fuel carbon to  $\text{CO}_2$  and fuel hydrogen to  $\text{H}_2\text{O}$ . As for CO, emissions of Non-methane volatile organic components (NMVOC) are a result of too low combustion temperatures, too short residence times or lack of available oxygen.

### 2.2.6 Polychlorinated dioxins and furans

Polychlorinated dioxins and furans (PCDD/PCDF or PCDD/F) are a group of highly toxic components. They are found to be a consequence of the *de novo synthesis* in the temperature range within  $180^\circ\text{C}$  and  $500^\circ\text{C}$  [23]. Carbon, chlorine, catalysts (Cu) and oxygen are necessary for the formation of PCDD/F, so PCDD/F can be formed in very small amounts from all biomass fuels containing chlorine. The emissions of PCDD/F are highly dependent on the conditions under which combustion and flue gas cooling take place; therefore, wide variations are found in practice. Although herbaceous biomass fuels have high chlorine contents, their PCDD/F emissions are usually very low. This may be explained by their high alkali content, which leads to the formation of salts (KCl, NaCl) and thus to a lower level of gaseous chlorine for the *de novo synthesis*. Because of the many factors influencing PCDD/F formation, wide variations may appear even within the same biomass combustion installation, but in general, the PCDD/F emission level from biomass combustion applications using virgin wood as a fuel is well below the health risk limit.

### 2.2.7 Ammonia

Small amounts of ammonia ( $\text{NH}_3$ ) may be emitted because of its incomplete conversion to oxidized nitrogen-containing components. This occurs in special cases in which the combustion temperature is very low. Additionally, secondary  $\text{NO}_x$



reduction measures utilizing  $\text{NH}_3$  injection may contribute to the  $\text{NH}_3$  emission level due to  $\text{NH}_3$  slippage.  $\text{NH}_3$  emissions can be reduced by general primary emission reduction measures for emissions from incomplete combustion, and by optimizing the  $\text{NH}_3$  injection process.

### 2.2.8 Ozone

Ozone ( $\text{O}_3$ ) is a secondary combustion product formed from photochemical atmospheric reactions including  $\text{CO}$ ,  $\text{CH}_4$ , NMVOC and  $\text{NO}_x$ . It is a direct greenhouse gas and also influences the local and regional environment. As such, it is a highly unwanted by-product of biomass combustion applications.  $\text{O}_3$  emissions can be reduced indirectly by reducing emissions from incomplete combustion, and by  $\text{NO}_x$  emission reduction measures.

## 3 Emissions Thresholds in the European Union

The European legislation regarding the control of emissions has been derived from the guidelines for Large Combustion Plants (LCP) (2001/80/EG, PB L 309) as well as from the Waste Incineration Directive (WID) (2000/76/EG, PB L 332). Guideline 2001/80/EG applies for biomass, whereas guideline 2000/76/EG applies to the incineration of all other types of waste. The emission guidelines are listed in Table 4.

Table 4: Overview of LCP and WID (data in  $\text{mg}/\text{m}^3$ ) [31,32].

	LCP (clean biomass, at least 50MW <sub>th</sub> )		Waste incineration directive	
	Co-firing (6% O <sub>2</sub> )	Stand-alone (6% O <sub>2</sub> )	Co-firing (6% O <sub>2</sub> )	Stand-alone (11% O <sub>2</sub> )
NO <sub>x</sub> (measured as NO <sub>2</sub> )	200*	200–400	200*	200
SO <sub>2</sub>	200*	200	50*	50
Dust	30*	30–50	10*	10
Cd + Tl			0.05	0.05
Hg			0.05	0.05
Sum heavy metals			0.5	0.5
HCl			10*	10
HF			1*	1
Dioxins/ furans (ng/m <sup>3</sup> )			0.1	0.1
VOC			10*	10
CO			50*	50

\*Mixing rule applies for composition of total flue gas.

It has to be mentioned the existence of an European standard EN-303-5 [33] and several quality labels for residential biomass heating devices that also encourage the boilers manufacturers to optimize their products and to minimize the pollutant emissions. In addition, it is important not to forget that the performance of pellet boilers in real-life conditions [34] has to satisfy the emissions and efficiency requirements of existing standards and quality labels, and that in consequence, the standard methods developed in a laboratory have to reproduce the real performance of biomass boilers to be reliable.

## 4 Emissions Data

The amount of pollutants emitted to the atmosphere from biomass combustion is highly dependent on the combustion technology implemented, the fuel properties, the combustion process conditions and the emission reduction measures implemented. When available, such data generally refer to a single fuel–technology combination. To obtain an objective view of emission levels from various biomass combustion applications, it is necessary to collect emission data from a wide range of fuel–technology combinations. However, due to the many parameters involved, the data can still only give an indication of typical emission levels [35].

### 4.1 Domestic furnaces

The results from the analysis of gaseous emissions generated in domestic appliances have shown that the traditional stove had significantly higher levels of emissions from incomplete combustion than the staged-air wood stoves and the catalytic stoves [36]. The emissions usually decrease as the size of the combustion installation increases, due to improved process control possibilities and efficient flue gas cleaning facilities. However, wide variations in the emission levels from the same stove have been reported, depending on operating conditions, characteristics of the fuel and even on the test method (forced or natural draught) [35,37,38]. In many cases, the levels of emissions from incomplete combustion may be many times higher than that reported at nominal load, usually increasing exponentially with decreasing load relative to nominal load [39]. In 1994, the Technical University of Munich performed an extensive measuring programme on emission levels from domestic wood applications [40]: wood stoves, fireplace inserts, heat-storing stoves, pellet stoves and catalytic wood stoves.

### 4.2 Industrial appliances

Several authors [41,42] have compiled and presented typical ranges of emission levels from various automatic wood furnaces (under stoker furnaces, grate firings and dust firings) and different biomass fuels. As in the case of domestic furnaces, the differences among the data obtained made necessary to divide the emissions into two groups: (1) those mainly influenced by combustion technology and



process conditions to compare between poor and high standard furnace design and (2) those mainly influenced by fuel properties.

Some related experiences were developed in the Netherlands [43–45], where different wood-burning installations with a capacity of 30–320 kW were working with the same fuel (clean woodchips), so that the technologies could be compared. It has to be noted that these installations are relatively efficient and that their automatic operation and combustion process control drastically reduced the emission of CO and C<sub>x</sub>H<sub>y</sub> [35]. In this respect, it is known that there are some design and operation parameters that help to reduce the gaseous emissions. Moreover, the correct dimensioning of boilers as well as the user behaviour may have an influence on the emissions.

## References

- [1] Larson, T.V. & Koenig, J.Q., Wood smoke: emissions and noncancer respiratory effects. *Annual Review of Public Health*, **15**, pp. 133–156, 1994.
- [2] Hemminki, K. & Pershagen, G., Cancer risk of air pollution: epidemiological evidence. *Environmental Health Perspectives*, **102**(Suppl), pp. 187–192, 1994.
- [3] Pope III, C.A., Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *Journal of American Medical Association*, **287**, pp. 1132–1141, 2002.
- [4] Andreae, M.O. & Merlet, P., Emission of trace gases and aerosols from biomass burning. *Global Biogeochemical Cycles*, **15**, pp. 955–966, 2001.
- [5] Winiwarter, W., Kuhlbusch, T.A.J., Viana, M. & Hitzenberger, R., Quality considerations of European PM emission inventories. *Atmospheric Environment*, **43**, 3819–3828, 2009.
- [6] ABB, *Emissions and the Global Environment – Statistics and Scenarios*, 1994.
- [7] Karlsvik, E., Hustad, J.E., Skreiberg, Ø. & Sønju, O.K., Greenhouse gas and NO<sub>x</sub> emissions from wood-stoves. In *Energy, Combustion and Environment*, Gordon & Breach, pp. 539–550.
- [8] Magelli, F., Boucher, K., Bi, H.T., Melin, S. & Bonoli, A., An environmental impact assessment of exported wood pellets from Canada to Europe. *Biomass and Bioenergy*, **33**, pp. 434–441, 2009.
- [9] Flyver Christiansen, H., Danish Energy Agency FMW., Center for Biomass Technology at dk-TEKNIK Energy and Environment, “LCA of Procurement and Conversion of Biomass and Fossil Fuels – Used for Energy Production in Denmark 1997,” *Poster presented at the First World Conference and Exhibition on Biomass for En 2000*.
- [10] Sikkema, R., Junginger, M., Pichler, W., Hayes, S. & Faaij, A.P.C., The international logistics of wood pellets for heating and power production in Europe: costs, energy-input and greenhouse gas balances of pellet consumption in Italy, Sweden and the Netherlands. *Biofuels, Bioproducts and Biorefining*, **4**, pp. 132–153, 2010.



- [11] Thiers, S., Aoun, B. & Peuportier, B., Experimental characterization, modeling and simulation of a wood pellet micro-combined heat and power unit used as a heat source for a residential building. *Energy and Buildings*, **42**, pp. 896–903, 2010.
- [12] Pelletsatlas, *English Handbook for Wood Pellet Combustion*, European Biomass Industry Association, 2009.
- [13] Obernberger, I. & Brunner T., Aerosols in *Biomass Combustion – Formation, Characterisation, Behaviour, Analysis, Emissions, Health Effects*, vol. 6 of Thermal Biomass Utilization Series. BIOS Bioenergiesysteme: Graz, Austria, 2005.
- [14] Gardiner, W.C., *Gas-Phase Combustion Chemistry*, 2nd edn., Springer-Verlag, 2000.
- [15] Miller, J.A. & Bowman, C.T., Mechanism and modelling of nitrogen chemistry in combustion. *Progress in Energy and Combustion Science*, **15**, pp. 287–338, 1989.
- [16] Bowman, C.T., Control of combustion-generated nitrogen oxide emissions: technology driven by regulation. *Proceedings of the 24th International Symposium on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 859–878, 1992.
- [17] Zeldovich, Y.B., Barenblatt, G.I., Librovich, V.B., Makhviladze, G.M., *The Mathematical Theory of Combustion and Explosions*. Consultants Bureau: New York, pp. 30–36, 1985,.
- [18] Zeldovich, Y.B., Sadovnikov, P.Y. & Frank-Kamenetskii, D.A., *Oxidation of Nitrogen in Combustion*. Academy of Sciences of the USSR: Moscow, 1947.
- [19] Fenimore, C.P., Formation of nitric oxide in premixed hydrocarbon flames. *Proceedings of the Thirteenth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, pp. 373–380, 1971.
- [20] Jensen, L.S., Jannerup, H.E., Glarborg, P. & Jensen, A.D.-J.. Experimental investigation of NO from pulverised char combustion. *Proceedings of the Combustion Institute*, **28**, 2000.
- [21] Johnsson, J.E., Formation and reduction of nitrogen oxides in fluidised bed combustion. *Fuel*, **73**, 1994.
- [22] Skreiberg, Ø., Hustad, J.E. & Karlsvik, E., Empirical NO<sub>x</sub> modelling and experimental results from wood-stove combustion. In *Developments in Thermochemical Biomass Conversion*, Blackie Academic & Professional, pp. 1462–1476, 1997,.
- [23] Nussbaumer, T., *Furnace Design and Combustion Control to Reduce Emissions and Avoid Ash Slagging*. Report No. IEA Bioenergy: T13: Combustion, no. 03 1998, International Energy Agency, Biomass Combustion Activity, Final Report of the Triennium 1995–1997.
- [24] Roy, M.M., Dutta, A. & Corscadden, K., An experimental study of combustion and emissions of biomass pellets in a prototype pellet furnace. *Applied Energy*, **108**, 298–307, 2013.



- [25] Technology CFB., *Straw for Energy Production, Technology – Environment – Economy*, 2nd edn., [www.videncenter.dk/](http://www.videncenter.dk/), 1998.
- [26] Houmøller, S. & Evald, A., Sulphur balances for biofuel combustion systems. *Presented at the 4th Biomass Conference of the Americas*, 1999.
- [27] Vassilev, S.V., Baxter, D., Andersen, L.K. & Vassileva, C.G., An overview of the chemical composition of biomass. *Fuel*, **89**, pp. 913–933, 2010.
- [28] Said, N., Bishara, T., García-Maraver, A. & Zamorano, M., Effect of water washing on the thermal behavior of rice straw. *Waste Management*, **33**, 2250–2256, 2013.
- [29] Win, K.M., Persson, T. & Bales, C., Particles and gaseous emissions from realistic operation of residential wood pellet heating systems. *Atmospheric Environment*, **59**, 320–327, 2012.
- [30] Nussbaumer, T., Emissions from biomass combustion, IEA Biomass Agreement, Task X – Biomass Utilization, Activity 1: Combustion, Final Report of the Triennium 1992–1994, 1994.
- [31] European Union, Directive 2001/80/EC, PB L 309, Guidelines for Large Combustion Plants (LCP), n.d.
- [32] European Union, 2000/76/EG, PB L 332, Guidelines for Waste Incineration Directive (WID), n.d.
- [33] EN303-5, Heating boilers for solid fuels, manually and automatically stoked, nominal heat output of up to 500 kW. Terminology, requirements, testing and marking, 2012.
- [34] Verma, V.K., Bram, S., Vandendael, I., Laha, P., Hubin, A. & De Ruyck, J., Residential pellet boilers in Belgium: standard laboratory and real life performance with respect to European standard and quality labels. *Applied Energy*, **88**, pp. 2628–2634, 2011.
- [35] Van Loo, S. & Koppejan, J., *Biomass Combustion and Co-firing*, Earthscan: London and Sterling (VA), 2004.
- [36] Skreiberg, Ø., Theoretical and experimental studies on emissions from wood combustion. *PhD Thesis*, Norwegian University of Science and Technology, 1997.
- [37] Skreiberg, Ø., Karlsvik, E., Hustad, J.E. & Sønju, O.K., Round robin test of a wood-stove: the influence of standards, test procedures and calculation procedures on the emission level. *Biomass and Bioenergy*, **12**, pp. 439–452, 1997.
- [38] Skreiberg, Ø. & Saanum, Ø., Comparison of emission levels of different air pollution components from various biomass combustion installations in the IEA Countries. Supplemental Report to IEA Report Emissions from Biomass Combustion, IEA Biomass Agreement, Task X – Biomass Utilization, 1994.
- [39] Karlsvik, E., Hustad, J.E. & Sønju, O.K., Emissions from wood-stoves and fireplaces. In *Advances in Thermochemical Biomass Conversion*, Blackie Academic & Professional, pp. 690–707, 1993.
- [40] Strehler, A., *Emissionsverhalten von Feuerungsanlagen für feste Brennstoffe*, Technische Universität München-Weihenstephan, Bayerische Landesanstalt für Landtechnik, Freising, 1994.

- [41] Nussbaumer, T. & Hustad, J.E., Overview of biomass combustion. In *Developments in Thermochemical Biomass Conversion*. Blackie Academic & Professional, pp. 1229–1243, 1997.
- [42] Obernberger, I., Stand und Entwicklung der Verbrennungstechnik. VDI Berichte 1319, *Thermische Biomassenutzung, Technik und Realisierung*, April, VDI Verlag GmbH: Düsseldorf, Germany, 1997.
- [43] Landentechnik, P.B.F., Wieselberg/Erlauf Prot. Nr. 033/94, 32/94,024/95, 025/94, 035/95, 023/93, n.d.
- [44] Wildeburger, J.M.F., Staatlich befugter und beeideter Zivilingenieure für Technische Chemie, Polten (Aus), Prüfberichte PZ 1304/ZJW 920, 1996.
- [45] Sulilatu, W.F., *et al.*, Kleinschalige verbranding van schoon resthout in Nederland, NOVEM rapport, November, 1992.

