

WOOD WOULD BURN

J SWITHENBANK, V N SHARIFI, Q CHEN AND X ZHANG
Energy and Environment Engineering Research Group
University of Sheffield, UK

Summary

In view of the world-wide problem of energy sustainability and greenhouse gas production, it is timely to review the issues involved in generating heat and power from **wood fuel**. The combustion properties of this material are significantly different from traditional coal, oil and gas fuels and the pertinent emissions that we have studied include fine particles.

This paper discusses some of the more innovative wood fuel combustion system options, and associated technical factors, which must be considered before their implementation.

One of the most important characteristics of raw wood fuel is its high moisture content of up to 60%. This could be removed by utilising low grade waste heat that is widely available in industry to dry the fuel and thus reduce transport costs. Burning the dried wood also increases the energy available from combustion and acts as a **thermal transformer** by upgrading the low grade heat when it is used for power generation.

The alternative approach is to recover the latent heat by condensing the extrinsic moisture and the water formed during combustion. For atmospheric combustion, the temperature of the condensed products is below the dew point at about 55°C to 65°C and is suitable for an efficient district heating system.

In order to generate **power** from the latent heat, the condensation temperature must be increased to the level where the heat can be used in the thermodynamic power cycle. This can be achieved by increasing the combustion pressure to about 80bars, resulting in the recovered latent heat being available at more than 200°C. It can then be used to increase the cycle efficiency by about 15% by pre-heating the boiler water and/or combustion air etc. The high pressure also reduces the super-heater tube stress.

A further advantage of this high pressure flue gas is that it is above the pressure at which carbon dioxide ‘condenses’ to a liquid at atmospheric temperature. Thus when used with oxy-fuel combustion, the carbon dioxide flue gas from which the moisture has been condensed can be cooled to atmospheric temperature and the supercritical CO₂ fed directly into the pipes leading to the sequestration site. An important consideration of these strategies is to ensure that non-condensable gases in the exhaust, including oxygen and nitrogen, do not adversely affect the ‘condensation’ processes.

When oxy-fuel combustion is used, the flame temperature must be moderated by a cool diluent. Recycled carbon dioxide is often proposed for this duty. However, since the latent heat is recovered, the moisture or even additional water can fulfil this role. This latter option may be advantageous since it can be more efficient to pump wood slurry into the high pressure zone rather than feed solid wood particles.

Bearing in mind that it is much more efficient to pump a liquid to high pressure than to compress the same material as a gas, indicates that cryogenic oxygen is a suitable material to use for an efficient power station that generates energy from biomass (or coal).

Finally, combustion of the hydrogen from the water gas reaction with oxygen allows the steam temperature in the turbine to be increased to the ‘gas-turbine engine’ range of 1000 to 1400°C and hence the biomass and/or coal cycle efficiency can be well over 60%!

Introduction

Large quantities of wood are burned world-wide for cooking and heating using combustion systems varying from three stones to support a cauldron to large systems such as a 400MW fluidised bed boiler burning wood chips. Recent plans include the construction of wood fired boilers of 700MW_e output and the scale of

equipment generating power using wood is clearly increasing.

It is timely to review the issues involved in generating power from wood fuel since the properties of this material are significantly different from traditional coal, oil and gas fuels. The aim of this paper is to discuss some of the options with an innovative open mind,

rather than to carry out a detailed comparative analysis of the many technical factors that must be considered before actual plant construction.

Wood Fuel Characteristics

Conventional fossil fuels consist almost exclusively of carbon, hydrogen and inert ash. On the other hand, wood is largely composed of cellulose, hemi-cellulose and lignin, materials that include about 30% oxygen within their structure. Table 1 shows that the effect of this oxygen is to reduce the calorific value of the wood to about one half that of fossil fuels. The oxygen is included in the water and carbon dioxide in the combustion product gases.

Table 1 Properties of coal, wood and RDF samples [Ref 1, Ref2]

		Coal	White Oak	Pine bark	RDF
Proximate analysis (%)	Fixed Carbon	55.8	17.2	33.9	9.8
	Volatiles	33.9	81.3	54.7	67.6
	Ash	10.3	1.5	0.4	18.9
Ultimate analysis (%daf)	C	84.2	50.2	56.5	61.2
	H	5.6	5.5	5.6	8.2
	O	5.5	43.8	37.9	26.6
	N	1.3	0.4	0.0	1.3
	S	3.5	0.0	0.0	0.2
HHV (MJ/kg)		31.75	19.42	21.78	22.30

Furthermore, raw wood can contain more than 50% moisture; hence the combustion products generally contain a much higher fraction of moisture than would be obtained from conventional fuels.

The effect of the moisture on wood fuel can be very dramatic. First of all, when raw wood fuel is transported, whether by road, rail or sea, it is apparent that more than 50% of the cargo is water. This obviously has an impact on the cost, fuel efficiency and emissions of transportation. Analysis of the potential production of wood in the UK shows that it would not be feasible to produce enough wood fuel to satisfy our total power needs. The import of sustainable wood supplies by sea from Africa or South America etc. will be carried out in huge 'wood tankers' whose fuel consumption to deliver the load is a tiny fraction of the energy of the cargo. [Ref 3]

The impact of the water on combustion is also dramatic. This can be seen from its effect on the calorific value (CV) of the fuel since every 10% increase in the moisture content reduces the CV of the fuel by about 2MJ/kg. Thus the lower CV of the raw fuel is about

8MJ/kg whereas that of dry wood fuel is about 18MJ/kg. It is not necessary to dry wood completely to obtain an advantage, as can be seen from the following argument. Simply reducing the moisture from 50% to 30 % would increase the CV from 8MJ/kg to 12MJ/kg. This represents a 50% increase in calorific value for a modest amount of drying. Clearly, determination of the optimum level would require a detailed economic analysis for any specific case.

Dry wood fuel is thus a value added product and drying could provide an energy efficient means of using the huge amount of low grade heat that is currently discharged to the atmosphere by industry. Not only could this result in reducing transport costs, but it is thermodynamically remarkable since although the low grade heat is unsuitable for generating power, the drier wood regenerates the energy at flame temperatures, when it can be used to generate power. Thus drying can be regarded as part of a thermal transformer.

The option of using solid recovered fuel (SRF) as an alternative to wood could be considered since it consists of more than 50% biomass, and huge quantities are now becoming available from material recycling facilities (MRF). Its morphology depends on the process used for production and may vary from damp flock to rigid cylindrical pellets. Many of the points discussed below are applicable to such fuels.

Condensing Boilers

An alternative means of recovering energy from moisture is to use a condensing boiler. These are used widely in the UK on domestic water heating systems but rarely used in industry. They recover the latent heat of the moisture in addition to the sensible heat and thus exploit the higher CV, thus increasing the efficiency of the boiler by about 15%. The condensation of moisture from the flue gases requires that the gases be cooled below the dew point of the gases. In the case of natural gas combustion products, this temperature is about 55°C to 65°C and it follows that the temperature of the water returned from the central heating system, (or from the hot water heating system), must be well below this temperature. This requires a high surface area of the radiators in the building. Similar considerations apply to district heating schemes if the latent heat of the moisture is to be recovered from the flue gases. Most district heating schemes presently use delivery and return water temperatures of about 120°C and 70°C respectively.

However, if wood is to be used for a combined heat and power (CHP) or district heating scheme, then there will be a significantly larger amount of latent heat that could be recovered by condensing the flue gases. This

requires that the district heating return temperatures be reduced to about 30°C. This temperature is still well above the temperature required in the rooms, and established under-floor heating technology would be well suited to this requirement.

The high pressure also reduces the super-heater tube stress and by inverting their load from tension to compression could allow novel materials such as silicon carbide/nitride to be used. The thermal conductivity of these materials is four times higher than stainless steel and their temperature capability is much higher. This potential extension to the proposed system would allow steam temperatures to be increased resulting in a substantial enhancement in power generation efficiency.

High Pressure Combustion Systems

Bearing in mind the fact that energy in the form of electricity is more highly valued than low grade heat, it is worth considering whether recovery of the latent heat of the flue gas moisture from wood firing is practicable in power generation systems. Thermodynamic considerations show that heat available at less than 50°C is not significantly useful for power generation, either within the steam cycle or for pre-heating boiler water or combustion air. However, if the combustion takes place at high pressure, Figure 1 shows that the dew point increases to more than 200°C and the latent heat is then available to increase the efficiency of the electrical power production by about 10%. A coal fired system utilising such a system has been investigated analytically by CANMET [Ref 4].

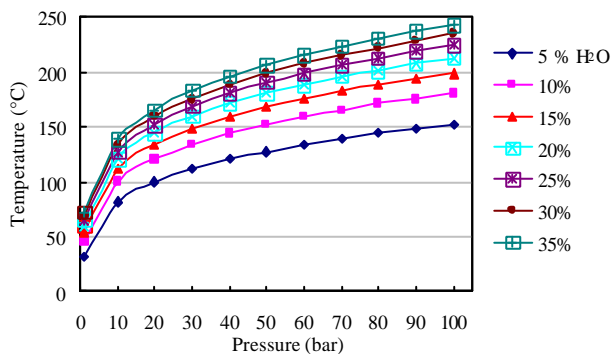


Figure 1 Flue gas dew point temperature as a function of pressure and moisture content

For raw wood with 60% moisture content burning with oxygen, the moisture content of the flue gases is about 20–35%. The high pressure combustion system is well matched to fuels with such high moisture content since the latent heat is recovered. Furthermore, the flow of moisture through the combustion system serves to moderate the combustion temperature and thus reduces

the need for carbon dioxide flue gas recycle than is required with coal fired oxy-fuel systems. It must also be noted that the recycled gases are significantly reactive compared to the nitrogen present with an air-fuel combustion system.

Heat Recovery from the Condensation of Water

As mentioned above, the condensation of water from the high pressure flue gases recovers heat at more than 200°C. This is at a sufficiently high temperature that it can be used within the power generation system and thus increase the plant efficiency. The question of where it should be returned to the power cycle has been considered in the case of coal firing in Ref 5. Possible locations are for heating the oxygen used for combustion or for heating the boiler feed water. It was found that the latter was more beneficial in the case of coal firing.

Although Figure 1 shows the flue gas temperature as a function of pressure, this figure assumes that the gas consists of pure carbon dioxide and water vapour. In practice, other contaminants will be present. These are due to contaminants in the oxygen, particularly nitrogen, and contaminants in the fuel, thus leading to flue gas contaminants including sulphur dioxide and oxides of nitrogen. The actual flue gas condensation temperature must therefore take the effect of these contaminants into account.

The water remaining in the carbon dioxide is an important parameter from its potential contribution to pipe corrosion problems, especially if sulphur oxides are present. However wood is relatively free from sulphur and this problem will be less severe with the biomass combustion. If the carbon dioxide saturated with water at high pressure were to expand to low pressure its humidity would drop remarkably. The market value of the carbon dioxide will obviously depend on its purity.

Carbon Dioxide Recovery

The main advantage of the pressurised combustion system is that carbon dioxide can be recovered for transmission and sequestration. For pure carbon dioxide, the pressure temperature relation for its 'liquefaction' is shown in Figure 2, where the liquid region lies above the curve. Again, it must be noted that this curve applies for pure gas and for a real system account must be taken of the actual composition of the mixture. This issue is discussed in Ref 5 where it is shown that gas impurities can have a profound effect of the phase equilibrium of the carbon dioxide rich stream. One main conclusion from this observation is that high quality oxygen (low N₂) should be used for the process. Also, products of incomplete combustion such as CO

and contaminants such as sulphur compounds may have to be removed at an appropriate point.

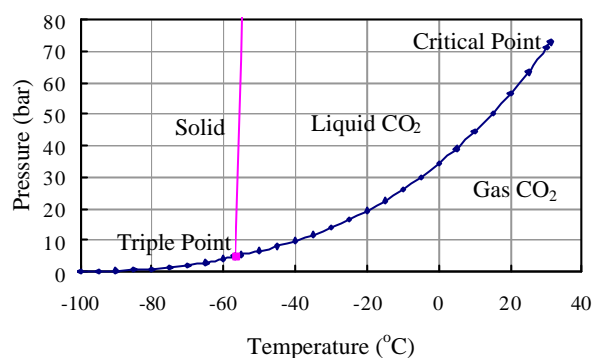


Figure 2 Phase diagram for pure carbon dioxide

The desire to operate with a high flue gas 'condensation' temperature and an output of supercritical liquid carbon dioxide both require high pressure combustion at about 80bars. Detailed design studies are needed to optimise this pressure for the wood combustion; however, this value can be regarded as an approximate value at this stage of the discussion.

Fuel Feeding System

The technique used to feed a solid fuel into a high pressure environment poses some interesting problems. If a lock hopper system is used, then the chamber between the two valves will fill with gas as the solids move into the high pressure environment. The gas will then release to the low pressure region and must be discharged, or it must be pumped back up to the high pressure level before being returned. Compressing the solids to high pressure requires very little energy since they are largely incompressible. This problem is usually solved with coal fired gasifiers by using slurry made from the fuel in water. For a combustor operating at high pressure with latent heat recovery, the energy required to evaporate the water added to make wood fuel slurry will be recovered in the condenser. The effect of the amount of water that must be added the wood to make pumpable slurry and the size of the wood particles will obviously have an effect on the combustion as discussed below.

Slurries that contain particles can interfere with the operation of valves in the pump. A valveless system could be devised whereby the particles are fed through the pressure gradient produced in water spinning in a zero liquid flow centrifugal turbine configuration. Such a system would allow the particles to be transferred to the high pressure system with a smaller proportion of water. Nevertheless, the optimum proportion of

moisture in the high pressure combustor still remains to be determined.

The problem of feeding solid recovered fuel (SRF) as an alternative to wood depends on the physical nature of the material. Flock can be fed as a water slurry as above, whilst the energy to feed semi-solid SRF may be minimised by extruding a cylindrical 'worm' of material directly into the high pressure environment.

High Pressure Combustion of Wood

There are several potential combustor configurations that can be considered for the high pressure combustion of wood as follows:

- Burning bed on a moving grate
- Bubbling fluidised bed
- Circulating fluidised bed
- Entrained pulverised fuel
- Shaft combustor
- Rotary kiln

Bearing in mind that the requirement for high pressure means that the whole combustion equipment must be enclosed in a pressure vessel, and thus should be simple to maintain and operate. This suggests that a moving grate or rotary kiln would be unsuitable. A shaft combustor could be used for small scale but would not be suitable for slurry containing wood chips. The entrained wet sawdust would also be generally undesirable. The circulating fluidised bed is quite flexible but tends to be subject to high erosion. The bubbling fluidised bed is regularly used for slurries and for wood chips and at first sight would be the preferred technology for the proposed application. The temperature of the bed must be controlled by in-bed heat loading, fuel-oxygen ratio, flue gas recycle and/or water. Typical bed temperature would be in the range of 800°C – 900°C.

The use of added water to limit the combustion temperature is interesting since it could completely replace the recycle of the carbon dioxide flue gas, but the total flow through the heating section of the boiler would be similar. The overall heat balance for the cycle is almost unchanged since the heat required to evaporate the water would be recovered in the condenser. However, the combustion chemistry would be significantly changed as the flue gases would contain a greater proportion of hydrogen. If then the oxygen were reduced, the heat output would decrease, and obviously the system would approach the role of a gasifier.

Heat transfer in the high pressure system differs significantly from that in conventional boilers since both radiation and convection contributions will

increase with pressure. The radiation increases modestly due to the greater concentration of the emitting species which are largely water and carbon dioxide. Convection heat transfer increases more rapidly with pressure than radiation and account must be taken of this in the design of the heat transfer surfaces in the boiler. The result is that smaller heat transfer surface area will be required in regions such as the super-heater.

Oxygen Production

The improvement of about 15% in the power yield from the proposed high pressure combustion system comes at the expense of high pressure oxygen input. Bearing in mind the fact that pumping gases to high pressure requires an enormous power input, whilst pumping the same flow of ‘incompressible’ liquid requires very little power suggests that the oxygen is preferably required as a liquid. Technology for the cryogenic production of oxygen is well established, but it tends to be rather more expensive than some alternative techniques. The above discussion shows that the quality of the oxygen is also important to the process and the economic choice of oxygen containing a few percent of nitrogen, or a fraction of one percent of nitrogen, will be a key factor in the high pressure wood fired power generation system optimisation.

Emissions

The emission of fine particulates from wood combustion has given particular concern and data from the literature [Ref 6] together with data from our measurements on a boiler converted from coal firing are shown in Figure 3



Figure 3 Mass concentration of particles from a wood boiler and retrofitted boiler

With wood combustion, the amount of bottom ash is likely to be small, and there is considerable experience

in ash removal when operating a fluidised bed system at atmospheric pressure. Reversing the pump system discussed above for fuel feed implies that the ash should be removed suspended in water.

The main gaseous contaminants of the flue gases are likely to be O₂, N₂, CO, NO_x, SO_x, HCl, fly ash, organics and other minor species. The oxygen arises from the need to burn out the fuel, whilst the nitrogen is the main impurity in the feed oxygen. Other contaminants will be at the ppm level. It is anticipated that most gas cleaning equipment such as scrubbers, activated charcoal and bag filters will be fitted in the high pressure system. Due to the high density of the gases, these will be significantly smaller than their atmospheric equivalents, but the need to contain the very high pressure will undoubtedly pose special problems. It is also expected that the condensation of water in the proposed system will be effective in removing fly ash, including sub-micron particles.

It is particularly noteworthy that there will be little or no atmospheric emissions from the plant and the power industry will no longer require chimneys.

Issues of Scale

The proposed pressure in the plant is about half that in a conventional high pressure gas cylinder and this clearly leads to critical features of the plant design. It is likely that parts of the equipment with a thermal load, such as the fluidised bed, will be placed within a separate pressure vessel. It follows that the pressure vessel construction material must be chosen for its strength rather than its thermal properties and it will be lined with insulation.

The economics of most process plants follow the rule that their cost increases at the 0.6 power of their scale. This leads to the well known ‘economy of scale’, and the result is often a very large power plant. However, high pressure systems require a large amount of metal and many parts such as valves need an amount of material that scales as the cube of a linear dimension, whilst the valve port area only increases as the square. This property can result in the specific material cost per unit of throughput increasing with scale. The overall result is likely to be that there is an optimum size for the final power plant.

Ultra-high Efficiency Prospects

The potential to increase steam temperature and hence cycle efficiency by using new super-heater materials that exploit the inverted pressure load on the heat transfer tubes was presented above. Nevertheless, the temperatures are then still well below the established technology temperatures used with cooled turbine

blades on aircraft gas turbines. This gives us scope to dramatically increase the efficiency as follows:

The intrinsic and extrinsic water present in the combustion chamber will lead to the production of substantial quantities of hydrogen, principally through the water gas reaction. A number of studies are investigating the separation of this H₂ fuel from the carbon dioxide. For several years, we have been producing ultra-super-heated steam at temperatures of 1500°C to 2000°C by burning such fuel in a steam-oxygen mixture. Finally, utilising this established technique to burn the hydrogen with some oxygen allows the steam temperature in the turbine to be increased to the established ‘gas-turbine engine’ range of 1000°C to 1400°C and hence the biomass and/or coal cycle efficiency for electrical power generation can be increased to well over 60%!

Conclusions

- Decarbonise the atmosphere with advanced wood burning technology
- Particles emitted by wood combustion for CHP must be controlled
- Moisture in Wood: Dry wood using low grade heat, or condense after combustion to recover latent heat of water
- Burn and Condense at High Pressure: Recovers latent heat >200°C for energy generation and allows ‘condensation’ of CO₂ for sequestration;
Pump liquid wood chip slurry efficiently to high pressure;
Inverted heat transfer tube stress (compression) allows advanced materials.
- Oxy-fuel Combustion:
Control flame temperature with water (forms H₂ by water-gas reaction) or recycled CO₂.
Pump oxygen as liquid to high pressure.
- Raise power generation efficiency for biomass and/or coal fuel > 60% by oxy-hydrogen superheating steam to ~1400°C

References

1. Gaur S and Reed T. Thermal Data for Natural and Synthetic Fuels. Marcel Dekker, 1998
2. Hernandez-Atonal F D, Ryu C, Sharifi V N and Swithenbank J. Combustion of refuse-derived fuel in a fluidised bed. Chemical Engineering Science. 62, 627 – 635, 2007
3. Drax Ltd, Private Communication
4. Carbon Capture and Storage – High Pressure Oxy-fuel (HiPrOx), http://canmetenergy-canmetenergie.nrcan-rncan.gc.ca/eng/clean_fossil_fuels/carbon_capture_storage/hi_pr_o_x.html Accessed 19 Jan 2009
5. Zheng L, Pomalis R and Clements B. Technical and Economic Feasibility Study of a Pressurised Oxy-fuel Approach to Carbon Capture, http://www.thermoenergy.com/userfiles/File/TIPS_Feasibility_Study_Mar_2007.pdf Accessed 19 Jan 2009
6. Ehrlich C, Noll G, Kalkoff W D, Baumbach G and Dreiseidler A. PM10, PM2.5 and PM1.0 – Emissions from industrial plants – Results from measurement programmes in Germany. Atmospheric Environment. 41, 6236 – 6254, 2007