热化学过程中生物电能的产生

A V Bridgwater

（阿斯顿大学 生物能源小组，英国 伯明翰）

Power Generation from Biomass by Thermochemical Processes

A V Bridgwater

（Bio-Energy Research Group，Aston University，Birmingham，UK）

ABSTRACT: Bioenergy is now accepted as having the potential to provide the major part of the projected renewable energy provisions of the future as biofuels in the form of gas, liquid or solid fuels or electricity and heat. There are three main routes to providing these biofuels—thermal conversion, biological conversion and physical conversion — all of which employ a range of chemical reactor configurations and designs. This paper focuses on thermochemical conversion processes for their higher efficiencies, lower costs and greater versatility in providing a wide range of energy, fuel and chemical options. In particular the so-called advanced technologies of gasification and fast pyrolysis are described and discussed. The primary products that can be derived as gas, liquid and solid fuels are characterised, as well as the secondary products of electricity and/or heat, liquid fuels and a considerable number of chemicals. The main technical and non-technical barriers to the market deployment of the various technologies are summarised.

KEY WORDS: thermochemical processes；bio-energy；fast pyrolysis

摘要：目前，生物能被视为在未来有潜力提供大部分可再生能源的储备，它可以以气体、液体或固体燃料形式提供生物燃料或者用于发电和供热。有三种主要的提供生物能的途径，即热转换、生物转换和物理转换，这些方法都需要配置和设计各种各样的化学反应器。文章重点研究能高效、低成本、高度通用地提供大量能量、燃料和化学产品的热化学转换过程。特别研究和讨论了所谓的先进的气化和快速热解技术，其主要产品可以是气体、液体或固体燃料，而其副产品则是电能和/或热能、液体燃料及大量的化学品。文章还对阻碍不同技术的市场配置的主要技术性和非技术性壁垒进行了概述。

关键词：热化学过程；生物能；快速热解

0　INTRODUCTION

Biomass fuels and residues can be converted to energy via thermal, biological and mechanical or physical processes. Thermal processing currently attracts the most interest in Europe, and gasification and pyrolysis receives the most RD&D support as it offers higher efficiencies compared with combustion, Although fast pyrolysis is still at a relatively early stage of development it offers the major advantage of producing a liquid fuel with concomitant advantages of easy storage and transport as well as comparable higher power generation efficiencies at the smaller scales of operation that are likely to be realised from bio-energy systems compared to fossil fuelled systems. The high efficiency of gasification systems arises from high efficiency in converting to a fuel gas (up to 98% hot gas efficiency is realisable), and higher efficiencies in utilising heat from combustion of the gas. This includes larger scale power generation of up to 100 MWe with Integrated Gasification Combined Cycle (IGCC) processes when electricity production efficiencies of up to 45% to 50% are predicted compared with 25% to 35% via combustion; and small scale power generations systems of up to 5 MWe using engines that offer up to 30% efficiency compared to 10%-20% using combustion and a steam cycle. Both of these thermochemical conversion processes offer high conversion efficiencies as explained above, potentially competitive costs and considerable flexibility in scale of operation and range of products. These processes are summarised in Fig. 1.

1　FAST PYROLYSIS

Pyrolysis is thermal decomposition occurring in the absence of oxygen. It is always also the first step in combustion and gasification, but in these processes
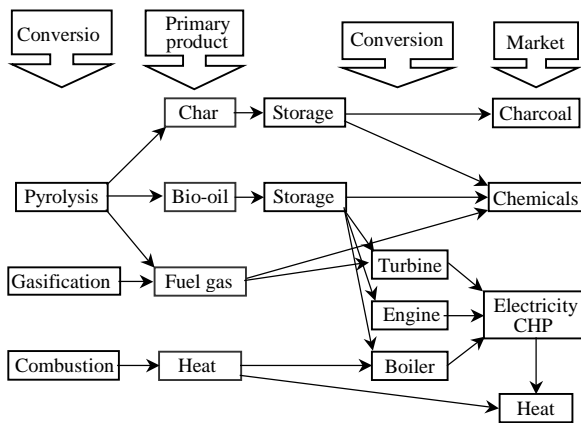
Fig. 1   Thermal processing routes and products

it is followed by total or partial oxidation of the primary products. In pyrolysis, lower process temperatures and longer vapour residence times favour the production of charcoal. Higher temperatures and longer residence times increase biomass conversion to gas, and moderate temperatures and short vapour residence time are optimal for producing liquids. Tab.1 indicates the product distribution obtained from different modes of pyrolysis.

Tab. 1   Typical product yields (dry wood basis) obtained by different modes of pyrolysis of wood

Mode	Conditions	Liquid	Char	Gas
Fast	moderate temperature, around 500°C, short hot vapour residence time 1 s	75%	12%	13%
Intermediate	moderate temperature, around 500°C, moderate hot vapour residence time 10-20 s	50%	20%	30%
Slow (carbonisation)	low temperature, around 400°C, very long residence time	30%	35%	35%
Gasification	high temperature, around 800°C, long residence time	5%	10%	85%

Fast pyrolysis for liquids production is currently of particular interest as the liquid can be stored and transported, and used for energy, chemicals or as an energy carrier. Thorough reviews have been published on the technology applications and status.

Many reactor configurations have been shown to assure this condition and to achieve yields of liquid product as high as 70%-80% based on the starting dry biomass weight. They include bubbling fluid beds, circulating and transported beds, cyclonic reactors and ablative reactors. In the 1990s several fast pyrolysis technologies reached near-commercial status and subsequently, DynaMotive (Vancouver, Canada) built the first commercial plants in West Lorne and Guelph in Ontario, Canada at 100 t/d and 200 t/d biomass feed rate respectively. BTG (The Netherlands) operates a rotary cone reactor system at 50 t/day in Malaysia and Pytec operates a 50 t/day ablative pyrolysis plant in northern Germany. The yields and properties of the generated liquid product, bio-oil, depend on the feedstock, the process type and conditions, and the product collection efficiency. Though primarily biomass pyrolysis oils have been expected to become alternative liquid fuels, other potential applications have also emerged and are reviewed. Typical product distributions are shown in Fig. 2 from a research project.
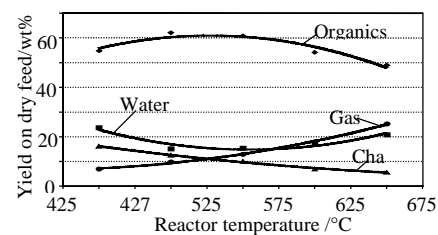

Fig. 2   Typical fast pyrolysis product distributions

2 PROPERTIES OF BIOMASS PYROLYSIS OILS

Bio-oils, also known under the names of pyrolysis oils, pyrolysis liquids and others, are usually dark brown, free-flowing liquids having a distinctive smoky odour. The physical properties of bio-oils are described in several publications [4-6]. These properties result from the chemical composition of the oils, which is significantly different from that of petroleum-derived oils. Bio-oils are multi-component mixtures comprised of different size molecules derived primarily from depolymerization and fragmentation reactions of three key biomass building blocks: cellulose, hemicellulose, and lignin. Therefore, the elemental composition of bio-oil resembles that of biomass rather than that of petroleum oils. Basic data for bio-oils and conventional petroleum fuels are compared in Tab. 2 . There is a comprehensive literature such as fuel-related characteristics which are provided in [7].

2.1 Water Content

Water in bio-oils [8] results from the original moisture in the feedstock and as a product of the dehydration reactions occurring during pyrolysis. Therefore, the water content can vary over a wide range（15%-35%）depending on the feedstock and process conditions. The presence of water has both

Tab. 2　Bio-oil properties and characteristics

Physical property	Typical value	Characteristics
Moisture content/%	25	Liquid fuel
pH	2.5	Ready substitution for conventional fuels in many stationary applications such as boilers, engines, turbines
Specific gravity	1.20	
Elemental analysis C/%	56	
H/%	6	Heating value of 17 MJ/kg at 25% wt. water, is about 40% that of fuel oil / diesel
O/%	38	
N/%	0-0.1	
HHV as produced/MJ/kg	17	Does not mix with hydrocarbon fuels
Viscosity(40°C and 25% water)/cp	40-100	Not as stable as fossil fuels
Solids (char)/%	0.1	Quality needs definition for each application
Vacuum distillation residue/%	up to 50	

negative and positive effects on the oil properties. It lowers its heating value, especially the LHV and flame temperature. It also contributes to the increase in ignition delay and in some cases to the decrease of combustion rate compared to diesel fuels. On the other hand, it reduces the oil viscosity and leads to a more uniform temperature profile in the cylinder of a diesel engine and to lower NOx emissions.

2.2　Volatility Distribution

Bio-oils cannot be evaporated or distilled because they contain substantial amounts of non-volatile materials such as sugars and oligomeric phenolics. In addition, the slow heating during distillation results in polymerization of some reactive components. Consequently, the oils start boiling below 100°C but the distillation stops at 250-280°C leaving up to 50% of the starting material as residue. Thus, bio-oils cannot be used for applications requiring complete evaporation before combustion.

2.3　Oxygen Content

The oxygen content of bio-oils is usually 45-50 wt.%. The presence of oxygen in many oil components is the primary reason for differences in the properties and behaviour seen between hydrocarbon fuels and biomass pyrolysis oils. The high oxygen content results in a low energy density (heating value) that is less than 50% of that for conventional fuel oils and immiscibility with hydrocarbon fuels. An even more important consequence of the organic oxygen is the instability of bio-oil, which will be discussed later.

2.4　Viscosity and "Aging"

The viscosity of bio-oils can vary over a wide range (35–1000 cp at 40°C) depending on the feedstock and process conditions, and especially on the efficiency of collection of low boiling components. A significant reduction in viscosity can also be achieved by addition of polar solvents such as methanol or acetone. An undesired effect, especially observed when the oils are stored or handled at higher temperature, is the viscosity increase with time [9]. This is believed to result from chemical reactions between various compounds present in the oil leading to the formation of larger molecules.

2.5　Corrosiveness

Bio-oils contain substantial amounts of organic acids, mostly acetic and formic acid, which results in a pH of 2-3. For this reason the oils are fairly corrosive to common construction materials such as carbon steel and aluminium [10] and can affect some sealing materials. The corrosiveness is more severe at elevated temperature and at higher water contents. The oils are essentially non-corrosive to stainless steels. Polyolefins are usually an acceptable material of construction where other circumstances permit.

2.6　Combustion Behaviour

All of these properties have an impact on the combustion behaviour of bio-oils. In particular, bio-oils are combustible but not flammable; because of the high content of non-volatile components bio-oil requires significant energy for ignition but once ignited, it burns with a stable self-sustaining flame. Combustion tests performed on both fast and slow pyrolysis oil did not indicate fundamental differences in combustion behaviour of wood pyrolysis oil and No. 2 fuel oil and confirmed that bio-oil could be burned with steady, self-sustaining flames similar to those from petroleum-based fuel oils. Emissions from bio-oil combustion, in general, showed higher particulate and CO levels than for petroleum fuels with NOx concentration less than for No. 6 but higher than for No. 2 fuel oil. More details can be found in [2].

3　FUEL APPLICATIONS OF BIO-OILS

The interest in use of fast pyrolysis liquid was initially driven by the growing interest in using biomass-derived fuels to satisfy greenhouse gas warming and security of supply concerns. Biomass fuels can be considered essentially CO_2 neutral and have a very low sulfur content compared to many fossil fuels. In addition, being a liquid, bio-oil can be easily transported and stored. However, the properties of bio-oil also result in several unusual requirements

during its use as fuel in boilers, engines, and gas turbines constructed for combustion petroleum-derived fuels. Poor volatility, high viscosity, tendency for coking, and corrosiveness are probably the most challenging and have so far limited the range of bio-oil applications. In addition, bio-oil is not yet a commercial product and it lacks the quality standards necessary for commercial application.

The variability of composition due to different feedstocks, reactor configurations, and recovery systems that results in differences in physical and chemical properties as well as combustion behaviour also currently makes large-scale applications more difficult to design and control. However, bio-oil presents a much better opportunity for high-efficiency energy production and significant effort has been spent on research and development directed to the application of bio-oil for the generation of heat and power and for use as a transport fuel both directly and indirectly.

3.1　Combustion in Burner/furnace and Burner/Boiler Systems

Furnaces and boilers are common devices used for heat and power generation. They are usually less efficient than engines and turbines but they can operate with a great variety of fuels ranging from natural gas and petroleum distillates to saw dust and coal/water slurries. Bio-oil seems thus to be a suitable boiler fuel as long as it has consistent characteristics, provides acceptable emissions level, and is economically viable.

The only commercial system that is known to regularly use bio-oil to generate heat is at the Red Arrow Products pyrolysis plant in Wisconsin [11] and has been operated for many years. Most research on bio-oil combustion in boilers has been carried out in Finland. The main findings of these tests, which were consistent with those of Neste Oy, can be summarized as follows [2]:

（1）Some modifications of the burner and boiler sections were required to improve combustion.

（2）The flame from bio-oil combustion was longer than that from burning standard fuel oil.

（3）A support fuel was necessary during start up and, in cases of lower quality bio-oils, even during operation.

（4）There were clear differences in combustion behavior and emissions for different bio-oils tested-

high viscosity, water and solids content gave worse performances.

（5）Emissions generally were lower than from burning heavy fuel oil except for particulates.

An attractive option can be co-firing of bio-oil with fossil fuels. Large-scale tests have been carried out at the Manitowac power station [12], where pyrolysis liquids from the Red Arrow operation were successfully co-fired with coal for the commercial production of electricity.

In conclusion, a constant and better quality bio-oil available at attractive price is necessary for commercial, large-scale applications. There are not believed to be any insoluble problems of handling, storage, pumping, filtration, atomization or burner/boiler design.

3.2　Combustion in Diesel Engines

While boilers are mostly used to produce heat, Diesel engines offer a high efficiency (up to 45%) in power generation and can also be adapted to the combined heat and power process (CHP). Medium and slow speed engines are known for fuel flexibility and can operate on low-grade fuels. The main concerns for operating diesel engines on bio-oils are some specific properties of these liquids such as difficult ignition (resulting from low heating value and high water content), corrosiveness (acids), and coking (thermally unstable compounds). However, potential advantages of using bio-oils for power generation have led to valuable research activities in several countries that have been comprehensively summarised in [2].

3.3　Combustion in Turbines

Gas turbines are used in a wide range of applications, most important of which are driving electric power generators and providing power to aircraft. Accordingly, the two main categories of turbines in use are industrial and aircraft types. However, both types of turbines are used in power plants. Although at present most gas turbines operate on petroleum distillates or gas fuels, gas turbines can be modified or redesigned to accommodate some of the unusual properties of biomass pyrolysis oils. Also very important issues to address are compatibility of bio-oils with the materials used in fuel systems (acid corrosion) and in blades (erosion, alkali hot corrosion).

The first gas turbine tests on biomass slow

pyrolysis liquids were carried out at Teledyne CAE (USA) by Kasper et al. [13] in early1980s using a J69-T-29 gas turbine combustor rig. Emissions of CO were higher but CH and NOx were within the limits observed for petroleum fuels. Also a slag buildup in the exhaust section resulting from ash in bio-oil was identified as a potential problem. Since 1995 Orenda Aerospace Corporation (Canada) has been actively working on the application of bio-oil in gas turbines combustion in a 2.5 MWe class GT2500 engine that was designed and built by Mashproekt in Ukraine. The main advantage of this engine is its "silo" type combustion chamber located above the turbine that can be easily modified and optimized for any fuel. Also, advanced coating of the whole hot section provides protection against contaminants (alkali). The engine was tested throughout the whole operational range, from idle to full power, and the NOx and SO_2 emissions from combustion of bio-oil were found to be less while particulates were higher than those from diesel fuel [14]. Additional work carried out at the University of Rostock in Germany on a dual fuel operation in a test rig. Compared to the operation on diesel fuel, CO and HC emissions were significantly higher and NOx less for dual fuel operation. The use of bio-oil in the turbine resulted in deposits in the combustion chamber and on the blades and finding a solution to prevent fouling of the turbine is a priority requirement [15].

4 PYROLYSIS PROCESS SYSTEM

A fast pyrolysis system consists of an integrated series of operations starting with delivery of a roughly prepared feedstock such as whole tree chips from short rotation coppice, wood waste from furniture manufacture, energy crops such as miscanthus or sorghum, or agricultural residues such as straw. A complete integrated fast pyrolysis process for power generation consists of three major stages: feedstock reception, storage and pre-treatment; fast pyrolysis; and power generation is shown in Fig. 3 [3]. The main steps and their characteristics are summarised below.

4.1 Reception and Storage

Low capacity systems of up to around 3 t/h feed typically consist of a concrete pad for tipping delivered feed and a front-end loader to move it between reception, storage and handling steps. Larger
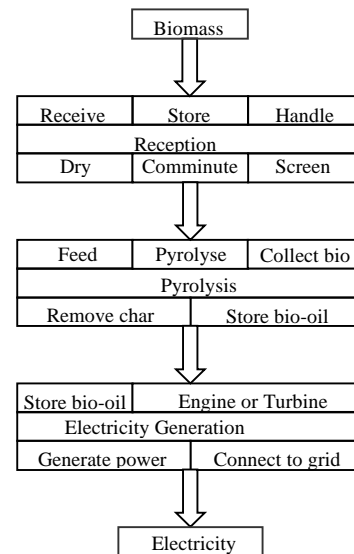
Fig. 3 Fast pyrolysis to power system

size plants will increasingly require more sophisticated systems like those employed in pulp and paper mills. These will include weighbridge, tipping units, conveyors and bunker storage.

4.2 Feed Drying

This is usually essential unless a naturally dry material such as straw is available. Sources of heat for drying include waste heat from combustion of by product char for pyrolysis process heat, combustion of by-product gas, combustion of biomass, waste heat from engine or turbine if power generation is on site, combustion of wastes from chemicals recover or bio-oil refining. Equipment and processes for drying have been reviewed [16].

4.3 Comminution

As explained earlier, particles have to be very small to allow rapid heating and achieve high liquid yields. This is costly and reactors, such as ablative pyrolysers, that can use larger particles have an advantage.

4.4 Reactor Configuration

As described above, a wide variety of configurations that show considerable diversity and innovation in meeting the basic requirements of fast pyrolysis have been tested. However, the "best" method is not yet established.

4.5 Char + Ash Separation

Some char is inevitably carried over from cyclones and collects in the liquid. Almost all of the ash in the biomass is retained in the char, so successful char removal gives successful ash removal. The char may be separated and exported if there is a

viable market; otherwise it would be used to provide process heat either directly as in circulating fluid bed reactors or indirectly as in fluid bed systems.

4.6 Liquids Collection

To collect the bio-liquids, quenching with an immiscible liquid such as a hydrocarbon or a cooled liquid product would usually be used in larger scale processes. Although collection of aerosols is difficult, there has been considerable success with electrostatic precipitators. This technology is widely used on very large scales, so at least in principle this should not be a problem. Careful design is needed to avoid blockage from differential condensation of heavy ends. Light ends collection is important in reducing liquid viscosity.

4.7 Storage and Transport

The bio-oil will require some local storage before local or remote use. A tank farm will provide storage and blending facilities. Both storage and transport are features unique to fast pyrolysis and permit economies of scale to be realised from building as large a conversion plant as possible as well as offering economic supplies of bio-oil for distributed or decentralised small-scale power and heat applications.

5 GASIFICATION

5.1 Introduction

Biomass gasification has been practised for over 100 years, but with little commercial impact due to competition from other fuel sources and other energy forms. In the last 20 years, there has been a renewed interest world wide with many instances of substantial demonstration and commercial scale plants. In particular, the last few years have seen a major resurgence of interest in large scale biomass gasification processes mostly due to environmental and political pressures required by CO_2 mitigation measures. Although the technology has progressed steadily over the last 25 years, very few processes have proved economically viable mostly due to the relatively high cost of biomass fuels and lack of a biomass supply chain as discussed earlier. There is sufficient expertise and knowledge now available to have a very high level of confidence in modern gasification processes. The comments below refer to potential problem areas where concerns have been expressed or where special attention should be directed.

The environmental pressures for renewable energy has created interest in many organisations who have the resources to thoroughly develop and market suitable technologies that meet these environmental and political requirements. The result has been consolidation of interest at an industrial level and substantial speculative investment in these technologies of the future.

Fuel gas can be produced from biomass and related materials either by partial oxidation to give a mixture of carbon monoxide, carbon dioxide, hydrogen and methane with nitrogen if air is used as the oxidant, or by steam or pyrolytic gasification. Tab. 3 summarises the main products in each case. The process of gasification occurs in a number of sequential steps:

（1）Drying to evaporate moisture．

（2）Pyrolysis to give gas, vaporised tars or oils and a solid char residue．

（3）Gasification or partial oxidation of the solid char, pyrolysis tars and pyrolysis gases.

There are several types of gasifiers that can all in principle operate in different modes as summarised in Tab. 3. There is an extensive literature on gasification including several reviews e.g. [17] from which the following summary is derived.

Tab. 3　Modes of gasification

Gasification	Characteristics
Partial oxidation with air	The main products are CO, CO_2, H_2, CH_4, N_2 and tar, giving a low heating value gas of ~5MJ/m³. Utilization problems can arise in combustion, particularly in gas turbines.
Partial oxidation with oxygen	The main products are CO, CO_2, H_2, CH_4 and tar (no N_2), giving a medium heating value gas of ~10–12 MJ/m³. The cost of providing and using oxygen is compensated by a better quality fuel gas. The trade-off is finely balanced.
Steam (pyrolytic) gasification	The main products are CO, CO_2, H_2, CH_4 and tar giving a medium heating value gas of ~15–20 MJ/m³. The process has two stages: the primary reactor produces gas and char, and the sand and char is passed to a second reactor where the char is burned with air to reheat the sand, which is then re-circulated to the first reactor to provide the heat for reaction. The gas heating value is maximised due to a higher methane and higher hydrocarbon gas content, but at the expense of lower overall efficiency due to loss of carbon in the second reactor.

5.2 Types of Gasifiers

Atmospheric downdraft gasifiers are attractive for small-scale applications up to about 1.5 MW as there is a very big market in both developed and developing economies. However, the difficulty of

efficient tar removal is still a major problem and a higher level of automation is needed, especially for small-scale industrial applications. Nevertheless, recent progress in catalytic conversion of tar gives more credible options and these systems can therefore be considered of average technical strength.

Atmospheric updraft gasifiers seem to have little market attractiveness for power applications. While this may be due to the high tar levels in the fuel gas, recent developments in tar cracking have shown that very low levels can be achieved from dedicated thermal/catalytic cracking reactors downstream of the gasifier (BTG, 2000). Another possible reason is that the upper size of a single unit is around 2.5 MWe so larger plant capacities require multiple units.

Atmospheric bubbling fluidised bed gasifiers have proven to be reliable with a variety of feedstocks at pilot scale and commercial applications in the small to medium scale, up to about 25 MW$_{th}$. They are limited in their capacity size range as they have not been significantly scaled up and the gasifier diameter is significantly larger than that of circulating fluid beds for the same feedstock capacity. On the other hand, they are more economic for small to medium range capacities. Their market attractiveness and technology strength are thus relatively high.

Atmospheric circulating fluidised bed gasifiers have proved very reliable with a variety of feedstocks and are relatively easy to scale up from a few MW$_{th}$ to 100 MW$_{th}$. Even for capacities above 100 MW$_{th}$, there is confidence that the industry would be able to provide reliable gasifiers. These gasifiers appear to be the preferred system for large-scale applications and most industrial companies use them; these systems therefore have high market attractiveness and are technically well proven.

Atmospheric cyclonic gasifiers have only recently been tested for biomass feedstocks and although they have medium market attractiveness because of their simplicity, they are still unproven. Finally, atmospheric entrained-bed gasifiers are still at a very early stage of development and since they require feedstock of a very small particle size, their market attractiveness is very low.

Pressurised fluidised bed systems, either circulating or bubbling, are considered of more limited market attractiveness because of their more complex installation and the additional costs of construction of pressurised vessels. However,

pressurised fluidised bed systems have the advantage in integrated combined cycle applications as the need to compress the fuel gas prior to utilisation in the combustion chamber of the gas turbine is avoided. No company is known to be developing pressurised systems for downdraft, updraft, cyclonic or entrained-bed gasifiers for biomass feedstocks, and it is difficult to imagine that such a technology could ever be developed into a commercial product due to the inherent problems of scale, tar removal and cost. The relative merits of pressure vs atmospheric pressure gasifiers are summarised in Tab. 4.

Tab. 4　Features of pressure and atmospheric gasifiers

Pressurised gasifiers	Atmospheric gasifiers
Feeding is more complex and very costly, and has a high inert gas requirement for purging.Capital costs of pressure equipment are much higher than atmospheric equipment, although sizes are much smaller (Bridgwater and Evans, 1993).Gas is supplied to the turbine at pressure, removing the need for gas compression and also permitting relatively high tar contents in the gas. Hot gas clean-up also reduces energy losses and in principle is simpler and has lower overall costs than scrubbing systems.Overall system efficiency is higher owing to retention of sensible heat and chemical energy of tars in the product gas.	For gas turbine applications, the product gas is required to be sufficiently clean for compression prior to the turbine. For engine applications the gas quality requirements are less onerous and pressure is not required.Atmospheric systems have a potentially much lower capital cost at smaller capacities of below around 30 MWe (Bridgwater and Evans, 1993).Gas compositions and heating values are not significantly different for either system.

In conclusion, for large-scale applications (above 25–50 MWe) the preferred and most reliable system is the circulating fluidised bed gasifier, while for small-scale applications (up to 0.5 MWe) downdraft gasifiers are the most extensively studied. Bubbling fluidised bed gasifiers can be competitive for medium-scale applications. Large-scale fluidised bed systems have become commercial by reason of successful co-firing projects (see below), while moving-bed gasifiers are still trying to achieve this. An overall summary of the range of applications for each technology and representative efficiencies for power generation is shown in Fig. 4.
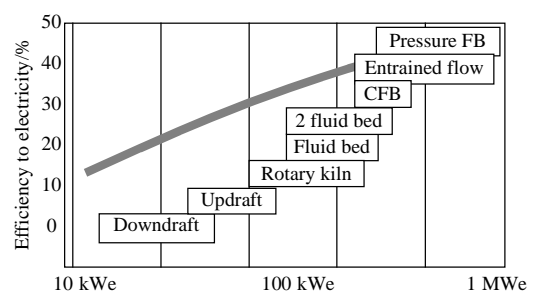

Fig. 4　Typical efficiencies of different biomass gasification systems for power generation

5.3 Gas Cleaning

Gases formed by gasification will be contaminated by some or all of the constituents listed in Tab. 5. The level of contamination will vary depending on the gasification process and the feedstock. Gas cleaning must be applied to prevent erosion, corrosion and environmental problems in downstream equipment.

Tab. 5 Fuel gas contaminants and their problems

Contaminant	Examples	Problems
Particulates	Ash, char, fluidised bed aterial	Erosion
Alkali metals	Sodium, potassium ompounds	Hot corrosion
Fuel-bound nitrogen	Mainly ammonia and HCN	NOx formation
Tars	Refractive aromatics	Clogs filters Difficult to burn Deposits internally
Sulphur, chlorine	HCl, H_2S	Corrosion emissions

5.4 Gasification Process System

A gasification system consists of the following elements:

（1）Feed reception, storage and handling.

（2）Feed preparation for size and moisture control.

（3）Gasification.

（4）Gas cleaning.

（5）Power generation.

5.5 Engines and Turbines

While turbine and turbine fuel specifications are imperfectly defined, experience from plants such as Varnamo provide reassurance of success [18-20]. Engines are more tolerant of biomass derived fuel gas and engines close coupled to gasifiers are more common and are now routinely and successfully used up to 2 MWe in plants including Güssing [21-22], Wiener Neustadt [23], Harboore [24] and DTU [25].

5.6 Gasification System Efficiency and Cost

There are several ways of producing electricity by gasification of biomass: pressurised gasification with a gas turbine in a combined cycle mode, atmospheric gasification with a turbine or an engine and a range of more innovative technologies such as gasification and fuel cells. The efficiency of these different biomass power generation systems is compared in Fig. 4 from biomass delivered to the conversion plant to power exported to the grid. The specific capital costs of two of the current major opportunities for power generation are shown in Fig. 5 and electricity generation costs are shown in Fig. 6 for different capacities.
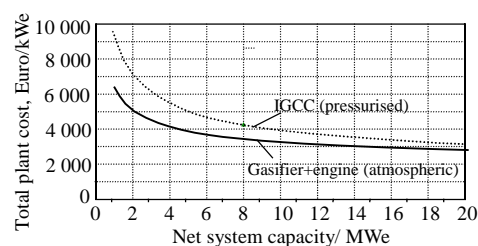
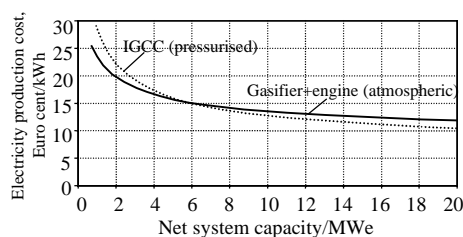**Fig. 5 Typical specific capital costs of gasification to power systems (updated to 2005 from [26])**

Fig. 6 Typical cost of electricity from different biomass power generation systems against capacity (updated to 2005 from [26])

6 DESIGN AND COST CONSIDERATIONS IN AN INTEGRATED PROCESS

Biomass is prepared in the forest usually as chips, although bundles from short rotation forestry and whole logs from conventional forestry may be delivered in some circumstances. Annual crops would be delivered in bundles (for example from arundo, miscanthus or sorghum), as bales (for example from straw or miscanthus), as billets (for example from arundo or miscanthus) or possibly chopped (for example from any crop). This material has to be received, handled, stored and processed prior to gasification and this front-end system is described later. The technology is well established and available for chips although there is little experience with either large scale or long term production of short rotation coppice for energy purposes.

There is a clear difference in costs between pressurised and atmospheric gasification systems which may be accounted for by the significantly higher equipment and construction costs of pressure equipment. Although pressurised systems have a lower volume, there is relatively little reaction kinetics or thermodynamic advantage resulting from pressurised operation as biomass is so reactive, unlike coal gasification when higher pressures offer considerable performance advantages.

A study carried out about 10 years ago found that pressurised gasifiers (prepared feed storage to cold

clean gas) cost about three times as much as atmospheric gasifiers on an installed plant basis at higher plant capacities of around 50 to 100 MWe and four times as much at smaller plant capacities of 5 to 20 MWe [26].

The relative advantages and disadvantages in terms of cost and performance of pressurised gasification systems have not been fully resolved, but a brief analysis is given below.

Pressurised gasifiers have the following significant features:

（1）Feeding is more complex and very costly, and has a high inert gas requirement for purging.

（2）Capital costs of pressure equipment are much higher than atmospheric equipment, although equipment sizes are much smaller. This was discussed in section 2 which includes data showing that pressurised gasification systems can cost up to four times as much as atmospheric systems at power outputs up to 20 MWe. This disadvantage is countered by the higher efficiency and this becomes significant around 30-50 MWe above which pressure systems are believed likely to be more economic than atmospheric systems.

（3）Gas is supplied to the turbine at pressure removing the need for gas compression and also permitting relatively high tar contents in the gas which need to be completely burned in the turbine combustor [20].

（4）Hot gas clean-up with mechanical filters (such as sintered metal or ceramic candles) is usually employed which reduces thermal and pressure energy losses and in principle is simpler and lower cost than scrubbing systems [27].

（5）Overall system efficiency is higher due to retention of sensible heat and chemical energy of tars in the product gas and the avoidance of a fuel gas compression stage prior to the turbine. The only significant energy losses are to the environment and provision of inert gas to the pressure feeders and these can be as low as 5%-8% giving an energy conversion efficiency for the gasifier itself of 92%-95%. A corresponding atmospheric gasifier with water scrubbing and product gas compression would have an analogous efficiency as low as 80%-85% depending on capacity and design.

Atmospheric gasifiers have the following significant features:

（1）For gas turbine applications the product gas is required to be sufficiently clean for compression prior to the turbine. For engine applications the gas quality requirements are less onerous and pressure is not required.

（2）Atmospheric systems have a potentially much lower capital cost at smaller capacities.

（3）Gas compositions and heating values are not significantly different for either system.

Twin fluid beds or steam or pyrolytic gasifiers require two reactors, one to produce the gas and the second to combust the char to reheat the fluidising sand to provide the process heat for gasification. While there is an additional cost of providing two reactors, the increased heating value of the gas from absence of nitrogen results in smaller equipment sizes for all gas handling downstream of the gasifier resulting in lower costs. The overall cost effect appears to be neutral from studies carried out on published data [26] and [28].

It is important to appreciate that the gasifier typically comprises around 15% of the total installed cost of a gasification plant and even substantial variations in specific gasifier costs will not have a significant effect on system cost. Since even detailed capital costs estimates are rarely better than +30% /-10% of achieved cost, the uncertainty associated with lack of specificity of gasification technologies at early stages of project development is negligible. At later stages of project approval, when a technology has been selected and formal tenders offered for supply, there is usually a clearer picture of probable costs, but any expectation of a high level of accuracy in predicting capital costs even after signing contracts is probably misplaced. This is discussed further in uncertainties below.

7　POWER GENERATION INTERFACING REQUIREMENTS IN GASIFICATION SYSTEMS

7.1　Definition

The product gases form gasification of biomass may be used in either gas turbines or engines for the generation of electricity. This section considers gas quality requirements and control techniques that are required to make the use of gas turbines or engines a feasible and viable proposition. The gas quality requirement for a gas turbine is known to be very demanding in that extremely low levels of any solid or

liquid contaminant can be tolerated and extremely low levels of some gaseous contaminants such a sulphur and chlorine compounds [29], but there are no specifications available for design of gas cleaning systems. A common response to a question on tolerance levels to any contaminant is either zero or the same as natural gas. Results from ongoing and planned large scale tests will provide better data.

7.2　Gas Quality Requirements

There is an improving understanding of the specifications for biomass derived fuel gas driven gas turbines. Known major problems are alkali metals and sulphur.　Sulphur is not normally associated with biomass, but what are often viewed or claimed as "trace" levels of, for example, 0.1 % weight, can lead to levels of sulphur in the fuel gas of up to 100 ppm. This level is not acceptable and will require reduction. Alkali metals are a major component of the ash of many biomass forms and their effect on turbines is well known, although the particular nature of the biomass derived alkali metals and their association with other contaminants such as sulphur is not known.

Solids such as char and fluid bed material will clearly have a deleterious effect on any moving parts and will require almost total removal. Tars are a potential problem if the gas has to be compressed as in an atmospheric gasifier since they will deposit in the compressor. Pressurised gasifiers overcome this problem by removing the need for a fuel gas compressor as the gas can be filtered hot and burned hot with the tars remaining in the gas phase and combusted. Tars otherwise will require cracking and/or removal as discussed below.

Chlorine is a difficult contaminant as it interacts with most metals at the temperatures involved in gasification and combustion.　Changing from a reducing (as in the gasifier) to an oxidising environment (as in the combuster) exacerbates the potential problem.　The reactions between chlorine and most metals are well known and the operating regimes well understood. Biomass often contains nitrogen, particularly from bark and some special biomass forms. NOx generated from fuel bound nitrogen may cause problems and gas cleaning should, therefore, reduce traces of HCN and NH_3 to a minimum. This is adequately dealt with in a water scrubbing system, but in pressurised system with hot gas filtration, a post-combustion catalytic process (SCR) would be required.

There will be a trade-off between increasing the gas cleaning to a high standard and increasing the maintenance cost of the turbine. This interaction has not been studied and no data is available.

Engines have the advantage of higher tolerance to contaminants than turbines (e.g. up to 30 ppm tars can be tolerated as long as no condensation takes place in the engine inlet). If the gas is compressed in a turbocharger there will be similar but possibly less demanding quality requirements on the gas. No firm or reliable data on the gas quality specifications is published, but there is sufficient evidence and information available to provide a high level of assurance of successful operation.

7.3　Control Requirements

In gas turbine applications, if the gasifier operates at atmospheric pressure, the product gas will require compression prior to combustion as well as the air.　This imposes severe gas quality requirements to avoid damage to the compressor. The air supply to the gasifier would probably be provided independently, although a bleed from the air compression loop could be used. This latter choice would, however, require extensive compressor modifications and impose severe control problems on the system analogous to those for a pressure gasifier. A pressurised gasifier would either use compressed air from the compressed air loop on the turbine set or would have an independent air compressor. The latter solves some of the potential control problems that arise from integration of the gasifier operation with the turbine, but at the expense of higher cost and lower system efficiency.

Engines present a more tolerant control requirement through the use of conventional fuel mixing devices and orthodox engine management systems. They will tend to react positively and quickly to variations in gasifier output without adversely affecting the gasifier operation. There is extensive practical experience of such systems from small scale gasifier operations as well as landfill gas operations.

8　TECHNICAL UNCERTAINTIES

8.1　Pretreatment

The pretreatment steps are relatively well established with a high level of reliability from experiences gained in the pulp and paper industry.

The need to minimise capital cost with the lower quality specifications for a fuel product than paper feed permit a less demanding design.

Wood as forestry waste or short rotation coppice would normally be delivered in bulk as whole tree chips. Some wood may require comminution. There are no perceived problems in handling or storing wood. This is common practice in pulp and paper mills throughout the world and in many smaller biomass combustion systems that operate in many countries.

Use of annually harvested energy crops such as miscanthus, arundo, grasses etc will require specialist reception, storage and handling systems, for which there is good experience available from straw handling systems in Denmark and the UK.

The drying requirement depends on the gasifier feed specification. Wet wood at typically 50% moisture wet basis is generally considered too wet, giving rise to a much dirtier gas, condensation problems and lower efficiencies. Drying to 15%-25 % is considered acceptable in energy and cost terms. Drying may be carried out in the field and in the storage pile, but this is slow, unreliable, causes loss of material from biological degradation and can cause fires. Rotary kilns are widely specified as dryers using waste heat and/or combustion of biomass feed, perhaps as screenings or fines, again depending on the gasifier feed specification. Fluid bed, silo and steam dryers have all been used successfully for biomass. None is very efficient, however, and the energy and economic costs are high, but these are outweighed by the higher downstream gas cleaning requirements consequent on not drying. The operation is well established with extensive experience to draw on for woody feedstocks, but there is less experience with non-woody energy crops.

Different gasifiers have different feed requirements. Fluid bed and circulating fluid beds are the most tolerant to particle size range, while fixed bed gasifiers require a regularly sized and relatively large particle with a minimum of fines. Entrained flow gasifiers require a smaller particle size which can increase technical and economic problems due to the difficulty in comminuting or grinding wood to small sizes. Comminution and screening are well established operations in the pulp and paper industry and there are minimal uncertainties.

8.2　Feeding

Biomass has a number of peculiar properties that must be considered in designing feeding systems which relate to its grain structure. In devising handling and feeding systems where gas tight seals are required, provision must be made for particles to fall away or be swept aside since blockage will result in major physical deformation. This is well known but poorly understood. Pressurised gasifiers are a special and more extreme example of this problem where a lock hopper based feeding system can cost more than the gasifier, although recent developments on screw and plug feeders have provided much lower cost and more reliable alternatives.

Another problem, particularly with pressure gasifiers is the inert gas requirement which can be considerable from purging feeders due to the high voidage of most bulk biomass. A commercial plant might consider recycling carbon dioxide from gas combustion for example, rather than purchasing inert gas in bulk.

8.3　Particulate Removal

The quantity of ash requiring removal and disposal from a biomass gasifier is relatively small at typically 1%-2 % of the dry feed weight. Removal from the gasifier will vary according to the type of system. Fixed beds will usually have a rotating grate with screw or mechanical discharge from the base of the reactor. Fluid beds may have an overflow arrangement or extraction from the bed as a "bleed", while circulating fluid beds will take a side-stream off from an appropriate place in the circuit. Each process will have its own proprietary system. Reliability is a function of the experience gained by the developer and the mode of ash removal.

Secondary and tertiary ash removal will arise from cyclones, hot gas filters and water washing systems. Apart from hot gas filters where little operating experience has been obtained, these are well understood and reliable.

8.4　Heat Recovery

The product gas will usually be hot, ranging from around 800 ˚C up to 1100 ˚C. It will need to be cooled before a hot gas filter to around 500–600˚C, or even lower if water washing is the first gas cleaning step. This provides the opportunity to recover heat as steam for combined cycle operation when up to 10% of the total energy content of the feed might be recovered.

Particular care is needed to avoid tar deposition or fouling of the heat exchanger surfaces with ash, char or any other contaminants. Primary raw gas cleaning is thus very important.

8.5 Gas Cleaning

Gas cleaning is still probably the most uncertain area in biomass gasification. Ii affects both heat recovery systems and downstream applications. The main requirements are summarised in Tab. 6.

Tab. 6   Contaminants in fuel gas from biomass gasification

Contaminant	Examples	Problems
Particulates	Ash, char, fluidised bed material	Erosion
Alkali metals	Sodium, potassium compounds	Hot corrosion
Fuel-bound nitrogen	Mainly ammonia and HCN	NOx formation
Tars	Refractive aromatics	Clogs filters Difficult to burn Deposits internally
Sulphur, chlorine	HCl, H_2S	Corrosion Emissions

Pressurised systems will use hot gas filters that remove solids typically in ceramic or metal candle filters with back-pulsing for cleaning. Temperature is important to ensure that alkali metals are no longer in the vapour phase, and cooling to below 500℃ is considered acceptable, but loss of sensible heat in the hot gas can detract from the overall gasifier efficiency. Temperatures much lower than this may result in tar deposition which must be avoided both from a blockage viewpoint as well as energy loss since tars can be readily combusted in the gas turbine.

Atmospheric systems use either wet cleaning systems which tend to be multi-stage for sufficiently high efficiency and result in an effluent disposal requirement and cost penalty; or cyclones and barrier filters such as bag filters. When a gas turbine is used, the gas has to be compressed prior to the turbine which places a tight gas quality requirement on both gas quality and temperature. In this case a water wash or quench is an efficient process for both cleaning and temperature reduction.

9 ECONOMIC UNCERTAINTIES

9.1 Learning

It is well known that after the first plant of a new technology has been built, subsequent plants will cost less due to learning effects-the knowledge and experience gained in building and operating this first plant will improve the design and operation of subsequent plants. This learning effect has been widely applied to chemicals production costs, for example, when learning effects of 15% to 20% are common [30]. This is defined as the cost reduction when production is doubled. A similar effect is found for capital costs of novel process plant and application of the 20% learning effect results in a potential cost reduction of 50% by the time the tenth plant is built. There is only largely empirical evidence of this effect but it is widely known and is now being increasingly applied to examination of the replication potential of energy from biomass projects.

The full life cycle of capital cost estimates is shown in Fig. 7. Line A is the traditional learning effects for novel technologies, when the actual cost of the first unit built can be as much as 4 or 5 times higher than the first estimates, or many times higher in some cases. Line B shows that as learning occurs, modified technologies that are less innovative can take advantage of previous learning and can start from a more realistic starting point, and this is the case with biomass gasification plants. Similarly, some parts of a gasification plant such as engines and turbines have already benefited from learning over many years on conventional fuels and the benefits of learning are less significant as shown in Line C.
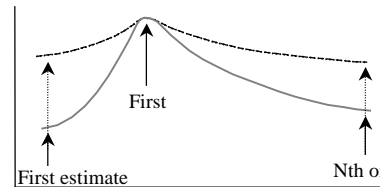

Fig. 7   Capital costs and learning effects

9.2 Contingencies

First of a kind plant also need to provide for contingency. Contingency is a catch-all for uncertainties that arise in the design or construction stages and also include for commercial uncertainties of delivery, exchange rates, taxes, etc. The initial learning curve takes account of contingency but there is no data available on its size. Much has been written about contingency in the process and power industries and a typical figure is often taken to be 10% of the investment costs, since larger figures present less attractive economics. However, any novel technology that has not been proven at comparable scales of operation or under analogous conditions will require higher contingencies and figures of 25% to over 100% of the investment cost have been proposed.

9.3　Location

The effect of location on costs of construction is complex and dependent on many factors including:

（1）Climate–very low temperatures require additional foundation and civils costs and higher insulation costs.

（2）Labour and social costs–higher labour rates are reflected in higher capital costs, subject to local productivity levels.

（3）Labour productivity–this is the most difficult to estimate but higher productivity can outweigh higher labour costs.

（4）Accessibility of site – construction near a major import center reduces or avoids special handling and transport costs. Conversely, construction in remoter areas will cost more in handling, transport and labour relocation costs.

（5）Legislation relating to environment and health and safety. Although there are common European directives on many aspects, interpretation and implementation are not uniform.

10　CONCLUSION

10.1　Pyrolysis

The liquid bio-oil product from fast pyrolysis has the considerable advantage of being a storable and transportable fuel as well as a potential source of a number of valuable chemicals that offer the attraction of much higher added value than fuels. Bio-oil has been successfully used as boiler fuel and also showed promise in diesel engine and gas turbine applications. There are still many challenges to overcome before bio-oil finds large-scale application as fuel, including:

（1）Cost of bio-oil, which is 10% to 100% more than fossil fuel.

（2）Availability of bio-oil for testing remains a problem with only limited supplies available.

（3）Lack of standards for use and distribution of bio-oil and inconsistent quality inhibits wider usage. Considerable work is required to characterize and standardize these liquids and develop a wider range of energy applications.

（4）Incompatibility of bio-oil with conventional fuels and, therefore, need for dedicated fuel handling systems.

（5）Users are unfamiliar with bio-oil.

（6）Environmental health and safety issues need to be completely resolved.

More research is needed in the field of fast pyrolysis and bio-oil testing to develop large-scale applications. The most important issues that need to be addressed seem to be:

（1）Scale-up.

（2）Cost reduction.

（3）Better oil quality.

（4）Norms and standards for producers and users.

（5）Environment health and safety issues in handling, transport and usage.

（6）Encouragement for developers to implement processes; and users to implement applications.

（7）Information dissemination.

10.2　Gasification

The process components involved in an integrated biomass to electricity system have all been individually tested at pilot scale or larger but long term operation and integration can only be achieved in a substantial demonstration plant. Several processes are in hand and more are planned for implementation in the near term. The key conclusions are summarized below:

（1）Biomass gasifiers are sufficiently advanced to justify a substantial pre-commercial plant. There are still areas of uncertainty, but these are relatively minor and will not be resolved until a large integrated plant is built and operated in a commercial environment.

（2）Gas cleaning has been developed to the point where large scale demonstration and long term operating experience is necessary. This area is still considered one of the most uncertain features of biomass gasification, in spite of all the accumulated experience to date.

（3）Biomass handling, storage, drying, comminution and screening are well established in the pulp and paper industry as well as in combustion systems and present no uncertainties in operation and performance. There is a need to optimise both the cost and performance of the front end of the plant in relation to the gasifier performance and requirements, and the availability of heat and power energy from the clean-up and power generation stages.

（4）Fuel specifications for both engines and turbines are now quite well understood, although only really long term tests will confirm current specifications.

（5）Biomass gasification is likely to be able to compete in the future with combustion based

technologies. Gasification has higher electricity production costs than hydropower and wind power, although as technology advances and larger scales of operation can be implemented, it is expected that the gap will reduce.

（6）Biomass offers significant advantages over wind power from the reliability of supply and over hydropower by being more widely available as an energy resource across Europe.

REFERENCE

[1] Bridgwater A V，Peacocke G V C. Fast pyrolysis processes for biomass, Sustainable and Renewable Energy Reviews[J]. Elsevier，1999，4 (1)：1-73.

[2] Czernik S，Bridgwater A V. Applications of biomass fast pyrolysis oil[J]. Energy and Fuel，2004，(18)：590-598.

[3] Bridgwater A V. The production of biofuels and renewable chemicals by fast pyrolysis of biomass[J]. International Journal of Global Energy Issues，2007，27(2)：160-203.

[4] Elliott D C. 1986, analysis and comparison of biomass pyrolysis/ gasification condesates–final report[R]. PNL-5943, Contract DE-AC06-76RLO 1830.

[5] Peacocke G V C，Russel P A，Jenkins J D，et al. Physical properties of flash pyrolysis liquids[J]. biomass &Bioenergy，1994，(7)：169-178.

[6] Fagernäs L. Chemical and physical characterisation of biomass-based pyrolysis oils. literature review[Z]. Espoo 1995，Technical Research Centre of Finland.

[7] Oasmaa A，Czernik S. Fuel oil quality of biomass pyrolysis oils- state of the art for the end-users[J]. Energy & Fuels，1999，13，914-921.

[8] Elliott D. Water，alkali and char in flash pyrolysis oils[J]. Biomass and Bioenergy，1994，(7)：179-185.

[9] Czernik S，Johnson D，Black S. Stability of wood fast pyrolysis oil[J]. Biomass and Bioenergy，1994，(7)：187-192.

[10] Soltes E J，Lin J C K. Hydroprocessing of biomass tars for liquid engine fuels[Z]. In Progress in Biomass Conversion，Tillman，D.A. and Jahn，E C，Eds，Academic Press，New York，1984，1-69.

[11] Freel B A，Graham R G，Huffman D R. Commercial aspects of rapid thermal processing (RTMTM)[Z]. In Bio-oil Production and Utilization，Bridgwater，A V and Hogan，E，Eds；CPL Press 1996.

[12] Sturzl R. The commercial co-firing of RTPTM bio-oil at the Manitowoc Public Utilities power generation station，available at http://www.ensyn.com.

[13] Kasper J M，Jasas G B，Trauth R L. Use of pyrolysis-derived fuel in a gas turbine engine[Z]. ASME Paper No. 83-GT-96，1983.

[14] Andrews R G，Fuleki D，Zukowski S，et al. Results of Industrial Gas Turbine Tests Using a Biomass-Derived Fuel. In Making a Business from Biomass in Energy, Environment, Chemicals, Fibers, and Materials，Overend，R P and Chornet，E Eds；Elsevier Science Inc，New York，1997，425-435.

[15] Strenziok R，Hansen U，Künster H. Combustion of bio-oil in a gas turbine[Z]. In Progress in Thermochemical Biomass Conversion；Bridgwater，A V，Ed；Blackwell Science，Oxford，2001.

[16] Brammer J，Bridgwater AV. A review of biomass drying technologies for thermal conversion[J]. Renewable and Sustainable Energy Reviews，3(4)：243-289.

[17] Bridgwater A V，Maniatis K. The production of biofuels by the thermochemical processing of biomass[Z]. Molecular to Global Photosynthesis，2004.

[18] Stahl K. Värnamo demonstration plant-Construction and commissioning[Z]. Skogs Sätteri AB and Skogs Boktryckeri AB，Trelleborg，1998.

[19] Stahl K，Neergaard M，Nieminen J. Värnamo demonstration program - Final report[Z]. In S. Kyritsis，A. Beenackers，P. Helm，A. Grassi, D. Chiaramonti: 1st World Conference on Biomass for Energy and Industry，Sevillia，Spain，2000.

[20] Stahl K. Värnamo Demonstration-The Demonstration Program[Z]. Skogs Sätteri AB and Skogs Boktryckeri AB，Trelleborg，2001.

[21] Hofbauer H，Rauch R. B. K. Biomass CHP plant Güssing-A success story[Z]. In A. V. Bridgwater，CPL Press，Newbury，UK: Expert Meeting on Pyrolysis and Gasification of Biomass and Waste，Strasbourg，France，2002，527-536.

[22] Bolhar-Nordenkampf M，Hofbauer H，Bosch K，et al. Biomass CHP plant Güssing-Using gasification for power generation[Z]. In K. Kirtikara：2nd RCETCE，Phuket，Thailand，2003，567-572.

[23] Bolhàr-Nordenkampf M，Jörg K，Baaske W，et al. Extension of a biomass district heating plant with a twin-fire fixed bed gasifier [Z]. Proceedings of the 2nd World Conference and Technology Exhibition on Biomass for Energy，Industry and Climate Protection，Rome，Italy，2004，1679-1682.

[24] Teislev B. Harboore wood chips updraft gasifier and 1500 kW gas engines operating at 32% power efficiency in CHP configuration [Z]. 12th European Conference on Biomass for Energy，Industry and Climate Protection，Amsterdam，The Netherlands，2002，1027-1030.

[25] Goebel B，Bentzen J D，Hindsgaul C，et al. High performance gasification with the two stage gasifier[Z]. 12th European Conference on Biomass for Energy, Industry and Climate Protection, Amsterdam，The Netherlands，2002，389-396.

[26] Bridgwater A V. The technical and economic feasibility of biomass gasification for power generation[J]. Fuel，1995，4 (5)：631-653.

[27] Andries J，Unal O，De Jong W，et al. Hot gas clean up downstream of a coal/biomass fuelled pressurized fluidized bed gasifier using ceramic channel flow filter [J]. J Filtr Soc，2000，(1)：10-11.

[28] Hofbauer H，Rauch R B K. Biomass CHP Plant Güssing - A Success Story[Z]. Pyrolysis and Gasification of Biomass and Waste，Strasbourg，France，2002，527-536.

[29] Hofbauer H，Kaltschmitt M. Kaltschmitt M，et al. Energie aus Biomasse[Z]. Springer: Berlin，Heidelberg，2001，427-505.

[30] Taylor J A，Craven P J. Process Economics International，1979，1 (1)：5-28.