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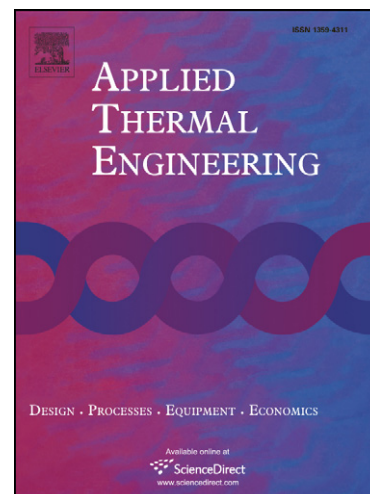
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Development of Small-Scale and Micro-Scale Biomass-Fuelled CHP Systems**– A literature review**

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Abstract

A review is carried out on the development of small- and micro- scale biomass-fuelled combined heat and power (CHP) systems. Discussions have been concentrated on the current application of Organic Rankine Cycle (ORC) in small- and micro-scale biomass-fuelled CHP systems. Comparisons have been made between ORC and other technologies such as biomass gasification and micro-turbine based biomass-fuelled CHP systems. The advantages and disadvantages of each technology have been discussed. Recommendations have been made on the future development of small- and micro- scale biomass-fuelled CHP.

Key words: Biomass CHP; Organic Rankine Cycle

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1. Introduction

Combined Heat and Power Generation (CHP) or cogeneration has been considered worldwide as the major alternative to traditional systems in terms of significant energy saving and environmental conservation [1]. Some researchers argue that heat should always be produced along with the power whenever possible [2]. The most promising target in the application of CHP lies in energy production for buildings, where small-scale and micro-scale CHP is usually installed [3]. Generally speaking, the concept “small-scale CHP” means combined heat and power generation systems with electrical power less than 100 kW. ‘Micro-scale CHP’ is also often used to denote small-scale CHP systems with an electric capacity smaller than 15 kWe.

Small-Scale and micro-scale CHP systems are particularly suitable for applications in commercial buildings, such as hospitals, schools, industrial premises, office building blocks, and domestic buildings of single or multifamily dwelling houses. Small-scale and micro-scale CHP systems can help to meet a number of energy and social policy aims, including the reduction in greenhouse gas emissions, improved energy security, investment saving resulted from the omission of the electricity transmission and distribution network, and the potentially reduced energy cost to consumers [4]. A micro-/small-scale CHP system is also able to provide a higher degree of reliability since the system can be operated independent of the grid if there is a black out [5]. Currently, micro-scale and small-scale CHP systems are undergoing rapid development, and are emerging on the market with promising prospects for the near

future [3, 4]. UK has been forecast to become one of the three largest markets for micro-CHP installations in Europe [6].

2. Application of micro-/small-scale CHP systems to buildings

Bernotat and Sandberg [2] studied the possibilities of using CHP for clustered dwellings and concluded that small-scale CHP has high perspectives if the total heat demand in an area is high enough. Denntice et al. [1] also carried out an investigation on the possibilities of residential micro-CHP systems. They investigated the application of micro-cogeneration (< 15 kWe) to residential and light commercial applications users, conducting an energy analysis of the domestic appliances and evaluating the match between a micro-CHP system and the electrical and thermal requirements of domestic appliances by use of a test facility for micro-CHP modules. They concluded that while the energy saving and the environmental benefits of a micro-scale and on-site cogeneration were undisputed, the technological obstacles still remained against its large diffusion, because a desirable micro-cogeneration system with low price and easy-to-use operation for residential end-users was still being under development at the time. Therefore, future introduction of micro-CHP for domestic applications would subject to available technology, matching of electrical and thermal loads, and the gas and electricity prices. Hawkes and Leach [4] studied the third dispatch mode of a micro-CHP system, i.e., the least-cost mode with which the optimized operation conditions are met, besides the heat-led, which is usually the dominant mode, and the electricity-led. Paepe et al. [7] recently evaluated five micro-CHP systems (< 5 kW) for use in residential applications. They found that that all CHP installations can save the primary energy and reduce CO_2 emission when operated on

heat demand. However, installing a micro-scale CHP in a residential house is not financially favourable at the present time because of high investment cost and long payback period. Therefore, the development of low-cost micro-scale CHP systems with innovative technologies is urgently needed.

3. Biomass-fuelled micro-scale and small-scale CHP systems

In the current stage, micro-CHP systems are emerging on the market with a promising prospect for the near future [3]. With the introduction of more and more stringent environmental legislations and the increasing urgency to address climate change, renewable energy resources play crucial role in replacing fossil fuels that power the traditional CHP systems. Renewable energy including biomass has received more and more research interests due to the rising energy price and the efforts needed to address the current climate change. Biomass has already been used extensively within the Europe for heating and/or power generation. In Austria, the contribution of biomass for district heating has increased 6-fold and in Sweden, 8-fold, during the last decade, largely due to positive stimulation at federal and local levels [8]. In France, direct combustion of wood represents almost 5% of the primary energy use [9] and in Finland, 18% of the total energy production has been bio-energy, and this figure is foreseen to reach as high as 23% by 2025 [10]. Therefore, there is a very large market potential for biomass-fuelled small- and micro- CHP systems within the Europe.

Of all the renewable energy resources, biomass is plentiful and prominent [11-13]. Wind energy and solar energy have the limitation of intermittent nature and therefore, they can only be used in the diversified systems to contribute where fossil fuel-based

power generation provides base-load power when the sun is not shining or the wind is not blowing. Biomass is the world's fourth largest energy source, contributing to nearly 14% of the world's primary energy demand. For many developing countries, the contributions of biomass to their national primary energy demands are much higher, from ca. 20% to over 90%. Biomass energy systems contribute to both energy and non-energy policies. The life cycle of a sustainable biomass energy system has a nearly neutral effect on the atmospheric carbon dioxide concentration. Therefore, sustainable biomass utilisation has been considered as one of the most attractive options for addressing CO₂ concerns [12-15]. Lineback et al. [16] compared the CO₂ emission from coal combustion to those from the biomass consumption with different conversion technologies and concluded that the use of biomass energy was a positive strategy for mitigating greenhouse gas emissions. In addition, combustion of biomass likely produces less carbon monoxide and particulates than an average coal-fired boiler. The sulphur dioxide produced during combustion of fossil fuels, particularly coal and fuel oil, that is one of the main precursors of acid rain, is not a major problem for biomass combustion systems due to the low sulphur content of biomass (<0.1 - 1% compared to 1 to 5% for coal) [12].

Biomass is best suited for decentralized, small-scale and micro-scale CHP systems due to its intrinsic properties [17]. On one hand, small-scale and micro-scale biomass CHP systems can reduce transportation cost of biomass and provide heat and power where they are needed. On the other hand, it is more difficult to find an end-user for the heat produced in larger CHP systems [18]. With the continual rise in gas and electricity prices and the advances in the development of biomass technologies and biomass fuel supply infrastructure, biomass-fuelled CHP systems will become more economically

competitive. In developing countries, small-scale and micro-scale biomass-fuelled CHP systems have a particular strong relevance in the life quality improvement, especially in remote villages and rural communities. The development of small-scale and micro-scale biomass-fuelled CHP systems has been supported and funded by the governments of many industrialised nations, albeit at different levels. For example, the National Renewable Energy Laboratory of the United States was funding a small modular bio-power project, aiming to develop biomass systems that are fuel flexible, efficient, simple to operate, have minimum negative impacts on the environment, and provide power between 5 kW and 5 MW [19]. Pavlas et al. [20] studied the retro-fit of a fossil fuel-based micro-CHP system in a hospital. Of all the alternatives considered, they found that a biomass-fuelled micro-scale CHP could achieve the highest CO₂ reduction. Uddin and Barreto [21] studied the techniques to capture CO₂ from a biomass-fired CHP system to achieve negative CO₂ emissions, despite the side-effects of reduced energy efficiency, higher investment costs and increased costs of end products.

In spite of all the research efforts, small-scale and micro-scale biomass-fuelled CHP systems still suffer from undesirable economics and technical uncertainties which require considerable technical advances [22]. Small-scale and micro-scale biomass-fuelled CHP systems which are commercially available are very limited. In addition, the long term economical and technological viability of the very few commercial systems has yet to be proven. Therefore, further research is needed to overcome the existing economical and technical obstacles, and to demonstrate and commercialize energy-efficient and low-cost small-scale and micro-scale biomass-fuelled CHP systems. This is of particular urgency and importance when it comes to developing,

demonstrating and sharing a feasible, sustainable energy-consumption style for the developing countries to bypass the fossil-fuel-based development models which the developed countries have and which are mainly responsible for the current climate change.

3.1 Energy conversion technologies of biomass-fuelled CHP systems

Various technologies have been developed for energy conversion in biomass-fuelled CHP systems. Basically, these include a primary conversion technology that converts biomass into hot water, steam, gaseous or liquid products and a secondary conversion technology that transforms these products to heat and power. The major biomass energy conversion technologies are listed in Table 1.

Of all the technologies listed in Table 1, ‘combustion’ and ‘steam turbine’ technologies is the most widely used combination, particularly for large-scale and medium-scale biomass-fuelled CHP systems [23]. In the mean time, the combination of ‘combustion’ and ‘organic Rankine cycle (ORC)’ technologies is receiving more and more attention in the development of small-scale biomass-fuelled CHP systems. The cost of an ORC system is far less than that of a Stirling engine, with less than 60% of that of a Stirling engine, and is the similar to that of gasification technology and steam turbine/engine [17]. Instead of water, ORC uses organic chemicals with favourable thermodynamic properties as working fluids [24]. The organic working fluid evaporates requiring a lower heat amount than water, and therefore, ORC operates at lower temperatures and pressures than the conventional steam process [25-26]. For this reason, ORC is particularly suitable for small-scale and micro-scale

biomass-fired CHP systems. For traditional steam engine or steam turbine systems, the typical electrical efficiencies are ca. 6-8% for small-scale CHP systems with a size of less than 30 kW_e [16], which results in the steam-based CHP systems no longer attractive and applicable at such a small scale. In contrast, ORC-based systems are able to produce about 15% of electricity and 60 – 70% of heat [23]. To increase the economic feasibility of the small-scale and micro-scale CHP plant investments, more electricity should be extracted from the process per produced heat unit [26]. In addition to the higher electricity production, the increased power-to-heat ratio could also reduce the fuel consumption and the CO₂ production per produced energy unit. The factors that are limiting the power-to-heat ratios in the small-scale and micro-scale CHP plants are mostly material properties and economical issues. Many other process features that are commonly used in larger plants are often considered to be too expensive for smaller size ranges. Thus, the trade-off between costs, the complexity of the process, and the increased power production is an important factor when defining the most profitable process for a small-/micro-scale biomass-fired CHP system investment [26]. In addition, as most small-scale and micro-scale CHP systems are operated according to the heat demand, the electricity production can be considered as the by-product of the heat production. To maximise the environmental and economical benefits of a small-scale or micro-scale biomass-fuelled CHP system, the electricity efficiency of the system has to be at acceptable levels both at the nominal load and partial load. It should also be noted that the operation mode of a small-scale or micro-scale CHP system based on the heat demand may not be the best choice in terms of CO₂ reductions and cost savings [4].

Except the direct biomass combustion technology, other technologies utilizing sustainable energy for micro-CHP have been carried out in previous studies including biomass gasification and micro-turbine etc. Moreover, these technologies have been available for nearly a decade [27].

The development of biomass gasifiers dated back to the early 20th century. Generally, comparing to coal gasification systems, most of the available biomass gasifiers are still in the development or early demonstration process. Among the small number of commercially viable biomass gasification systems in operation, there are only a few systems that have been economically demonstrated at a small-scale. Biomass gasification is a thermal conversion technology where a solid fuel is converted into a combustible gas. The product gas mainly consists of carbon monoxide, carbon dioxide, hydrogen, methane, water, nitrogen, but also contaminants such as small char particles, ash and tars. The gas can be used by boilers, internal combustion engines or gas turbines to produce heat and power in CHP systems after proper cleaning and conditioning. Advanced gasification technology to produce clean product gases is essential for its success in many practical applications. In a recent research, an advanced two-stage gasifier to produce clean and tar-free fuel gas has been explored and tested by Cao et al. [28]. The schematic of this gasifier is illustrated in Fig. 1. In general, five types of gasifiers can be classified, i.e., updraft, downdraft, fluid bed, circulating fluid bed and entrained flow. The schematics of these five gasifiers are shown in Fig. 2. The comparison of the product gas from different gasifiers is shown in Fig. 3.

A gasification-based CHP system can potentially have higher electricity efficiency than a direct combustion-based CHP system. The gas obtained by gasification can be combusted in a diesel, gas or “dual fuel” engine, or in a gas turbine [22]. So far, many efforts have been made to commercialize biomass gasification-based CHP system. CPC has developed modular micro-scale biomass gasification-based CHP systems with size ranging from 5 kW to 50kW [30]. CPC has reported the systems have the advantages of fully automatic operation and control and with no harmful emissions and liquid effluents. One of the CPC’s micro-modular biopower systems is shown in Figs. 4-5. CPC also developed a Biopower Battery Charger which is a unique product that uses the CPC biomass gasification technology to operate a free-piston Stirling engine generator (Fig. 5). Despite all the efforts made over the past decade, a large market share of small-scale biomass gasification systems for electricity production has yet to achieve [31]. This is probably due to two main reasons. The large variation in the key parameters determining the quality of biomass gasification product gases can cause extreme engine wear due to tar contamination and unstable operation. On the other hand, automatic measurement and control measures are rarely used (to keep the system cost down) and this often results in variable system performances [23]. Therefore, further research is certainly needed to improve and optimize the biomass gasification technology-based CHP systems.

Micro-turbine technology can also be combined with direct biomass combustion technology for applications in small- and micro-scale biomass CHP systems. Talbott’s Heating Ltd has developed and reported a biomass combustion-turbine system with the electrical efficiency of 17% and the overall efficiency of 80-85% [16]. The turbine engine assembly that was evaluated by Talbott’s Heating Ltd is shown in Fig. 6.

Compower reported its development of externally-fired micro-CHP systems in the range of 1 – 15kW electricity that can operate on biogas and biomass [5]. Compower's first micro-CHP system was based on the reuse and reconfiguration of commercially off the shelf components and rated 7kW electricity and 17kW heat. The main modules include a burner, a turbogenerator and a set of heat exchangers, which are shown in Fig. 7. Despite all the efforts on the development of micro-turbine technology, gas turbine technology is only widely used in CHP systems larger than 100kWe with the electrical efficiency generally higher than 25%. To increase the electrical efficiency of micro-turbine technology-based CHP systems remains to be a research focus in the near future.

3.2 ORC-based biomass-fuelled CHP systems

As an advanced power generation technology for low-temperature heat source applications at various scales from a fraction of kW_e to over 1 MW_e, ORC is robust and advantageous in many ways. At low temperatures, organic working fluids lead to higher cycle efficiency than water. ORC power generation systems have been used successfully in geothermal power plants for decades [32]. In small-scale and micro-scale CHP systems, organic working fluids are preferable because the fluid mechanics leads to high turbine efficiency in both full and partial load. This is one of the main reasons that ORC power generation is adopted for small-scale and micro-scale biomass-fuelled CHP systems. Another advantage of ORC in small-scale and micro-scale CHP systems is a legal and economic one. Water shows good efficiency at high pressure requiring increased safety measures, which are not economically feasible for

small-scale and micro-scale systems [33]. With an appropriately selected organic working fluid, the vapour can expand in the turbine in its saturated and superheated states. Therefore, there is no danger of droplet erosion on turbine blades [34]. Although the specific investment cost of an ORC system is higher than conventional steam cycle, the operating cost is considerably lower due to its good controllability, high degree of automation, and low maintenance cost [17].

Biomass-fired CHP plants based on the ORC with the size in the range of 400 kW_e to 1.5 MW_e process have been successfully demonstrated [34] and now they are commercially available from several manufacturers with typical electrical efficiency of ca. 20%. The thermodynamic cycle of an ORC-based CHP system is shown in Fig. 8. The main module and the turbine system are shown in Fig. 9 and 10, respectively. The scale effects with biomass conversion systems are significant for both their energetic and economic performance. Up-scaling increases the relative primary energy savings of the CHP systems. While up-scaling and further optimization of the ORC technology for biomass-fired CHP systems have never been stopped, limited interest and research in small-scale and micro-scale biomass-fired CHP systems over the last decade lead to little development of the technology [17, 35]. As a consequence, the implementation of the ORC in small-scale and micro-scale biomass-fired CHP systems is encountering many technical and economical obstacles comparing to the relative mature technology in the medium- to large-scale systems. Two prominent obstacles are the relatively high specific investment cost and limited electrical efficiency [16-17]. The conflicting nature of these two factors makes the solution more complicated and difficult to find. Based on economic reasons, some researchers argued that small-scale and micro-scale CHP systems should be simplified comparing to the medium- to large-scale CHP

plants, because of low annual operating hours typically varying between 4000 – 5000 hours, most of which are on partial load [36]. But a cost reduction in small-scale and micro-scale biomass-fired CHP systems has to be achieved without sacrificing too much the electrical efficiency. Further development of existing technologies and implementation of new technologies are inevitably required in order to achieve higher electrical and CHP efficiencies under the constraint of a specific investment cost [37].

Despite the fact that some medium-scale and large-scale biomass-fired CHP plants with ORC are in operation across the Europe and throughout the world, the available technical operating data are much limited due to commercial secrets. Evaluations were reported on two biomass-fired CHP plants installed for demonstration in Austria [34, 37, 38]. On the 400 kWe Admont CHP plant, it was attributed the main innovative component in the biomass-fired CHP system to the ORC process. Silicon oil was selected as the organic working fluid. The condensation of the silicon oil takes place at a temperature level that allows the heat recovered to be utilized with the hot water feed temperature of about 80 to 90°C. It was also reported that installation of a flue gas condensation system results in an evident increase in the total efficiency of the CHP system [37]. On the 1000 kWe Lienz biomass CHP plant, it was claimed that the key innovation was due to the use of an internal heat recovering system along with a thermal oil economizer and a combustion air pre-heater, by which the net electricity efficiency was increased considerably. The net electric efficiency of the ORC plant amounted to 18% at nominal load and about 16.5 at 50% partial load at feed water temperatures of 85°C [30]. This underlines the excellent partial load behaviour of this technology, which is especially relevant for a heat-controlled operation of a CHP plant. The thermal efficiency of the ORC unit was about 80% and was slightly increased at

partial load operation. Sipila et al. [26] carried out a simulation on a small-scale biomass-fired, ORC based CHP system using the 400kWe Admont CHP plant as the basic model plant. Their results indicated that the simplest structure was the best choice for an ORC-based CHP system subjected to power-to-heat ratio. Only the combustion air pre-heater had a positive effect on the electricity efficiency when compared to the basic ORC model plant, although the pre-heater did not affect electricity production but it improved the boiler efficiency. Any changes in the organic Rankine cycle, whether superheating or double cycle structure, only decreased the power-to-heat ratio. It also concluded that turbine expansion from the saturated steam temperature was optimal for the ORC system [26].

Although ORC-based power generation has been applied to power generation units as small as a fraction of kWe, no literature is available on the performance and evaluation of a micro-scale biomass-fired CHP system with ORC. This is mainly due to the limited interest on micro-scale CHP systems and lack of research funding. With growing environmental and political pressures to tackle climate change, and interests in micro-scale CHP systems from the public, more investigations on the performance of micro-scale biomass-fuelled CHP systems with ORC are expected to be carried out in the near future.

4. Conclusions

In summary, the application of micro- or small- scale biomass-fired CHP system has a great market potential in both UK and the rest of the world. This potential is becoming more and more significant as the environmental protection, economical development

and climate change control become more and more urgent. However, despite the fact that small-scale and micro-scale biomass-fuelled CHP systems can play a key role in addressing a series of important issues including energy, environment, and economics, etc., the research and development on small-scale and micro-scale biomass-fuelled CHP systems is still in its infant stage. The relevant technologies in the current stage cannot meet the demands from different industrial sectors. Commercialization of such small scale systems is not yet reached despite of the successful commercial operation of large-scale and medium-scale systems. The development and implementation of small-scale and micro-scale biomass-fuelled CHP systems are still hindered by several technical and economic barriers. Therefore, significant research efforts are urgently needed and should be accelerated in order that the next generation of stand-alone small-scale and micro-scale biomass-fuelled CHP systems can be demonstrated and commercialized in the near future.

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38. Obernberger I., Thonhofer P. and Reisenhofer E., Description and evaluation of the new 1000 kW_{el} organic Rankine cycle process integrated in the biomass CHP plant in Lienz, Austria, *Euroheat & Power*, 10/2002

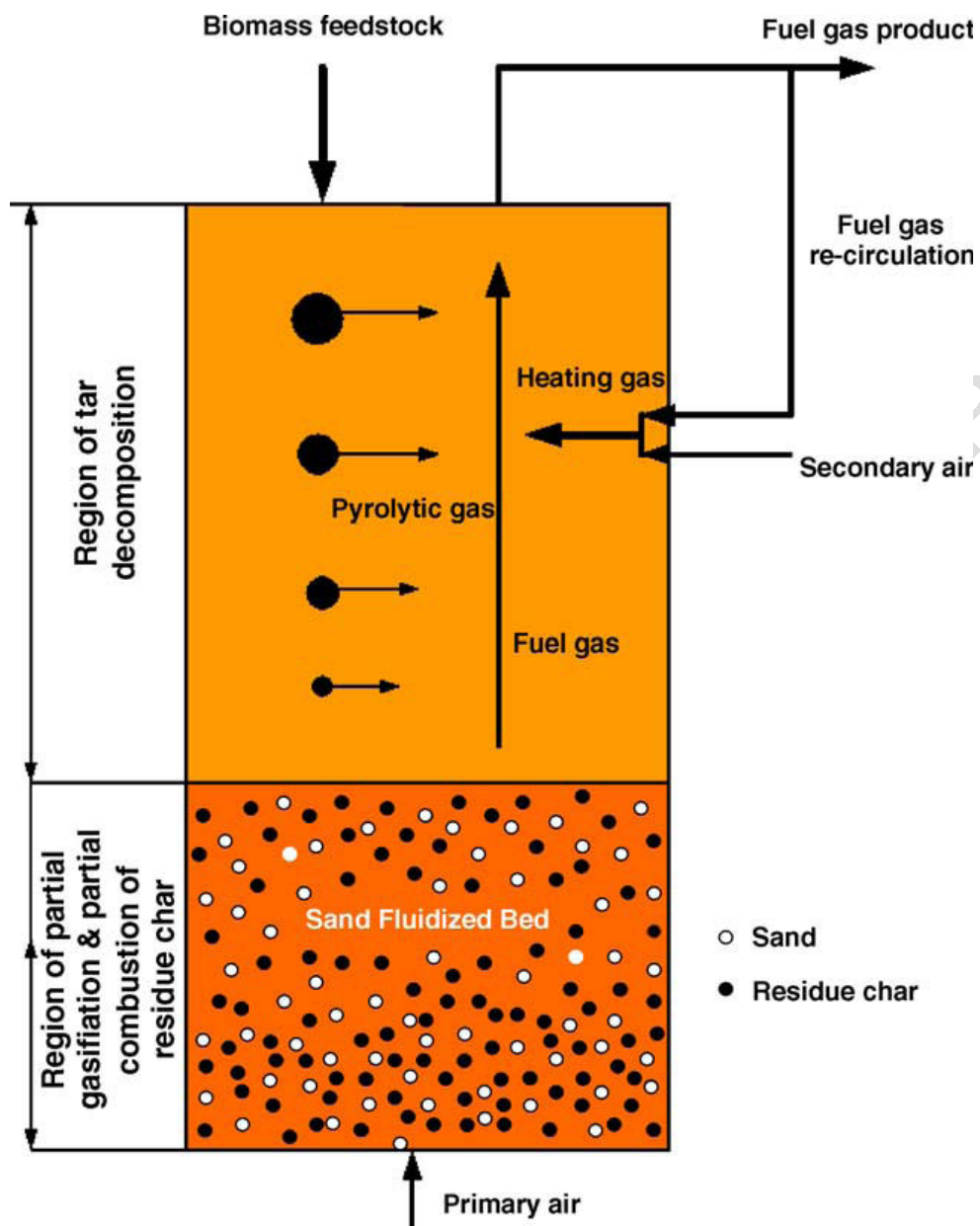


Fig. 1. The concept schematic of the novel two-stage biomass gasifier by air (from Ref. 28)

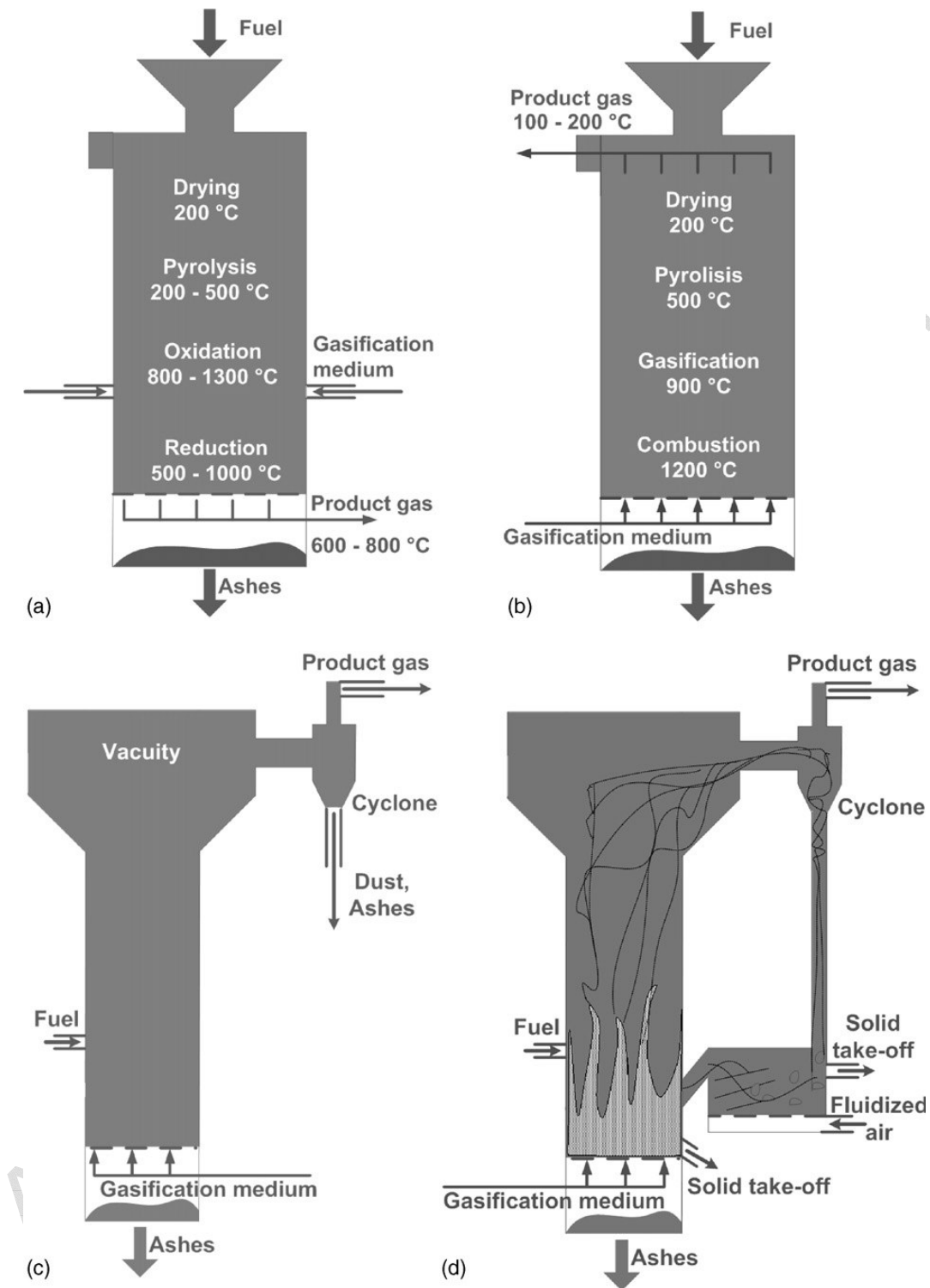


Fig. 2 Diverse gasifiers: (a) Co-Current, (b) Counter Current, (c) Stationary Fluidized Bed, (d) Circulating Fluidized Bed (from Ref. 29)

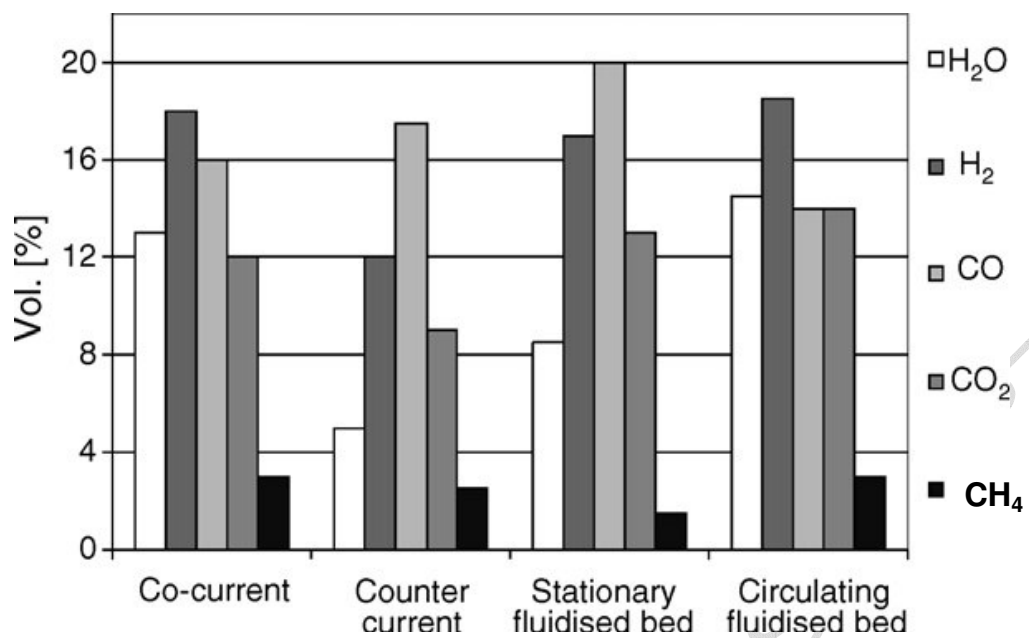


Fig. 3 Composition of product gas in selected gasifiers (from Ref. 29)



Fig. 4 CPC's micro-modular biopower system configured for combined heat and power for an off-grid application (includes battery inverter) (from Ref. 30)

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Fig. 5 CPC's 1 kWe /18 kWt Biomass Stirling Power Generator (from Ref. 30)

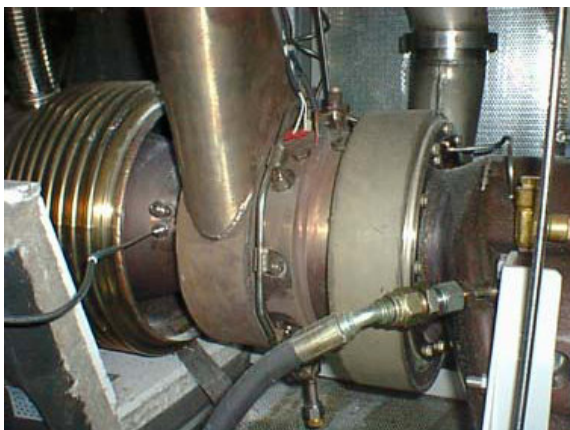


Fig. 6 Turbine Engine Assembly (from Ref. 16)

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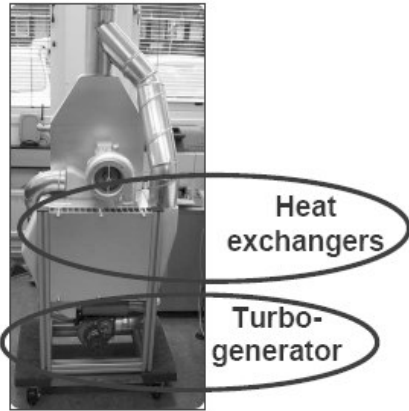


Fig. 7 Main modules of the micro-turbine system (from Ref. 5)

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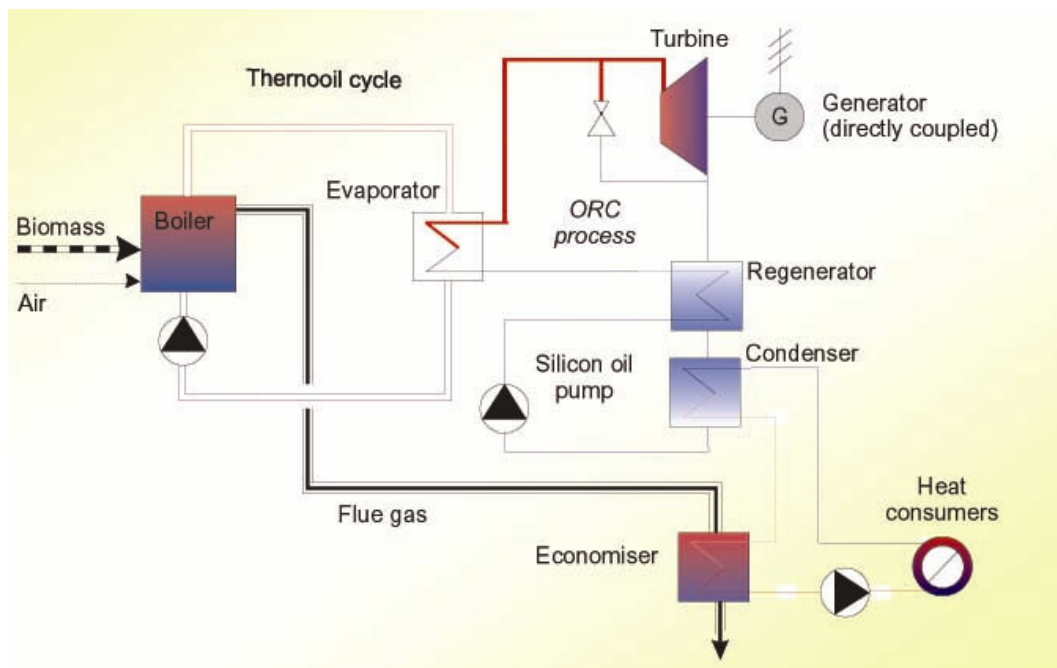


Fig. 8 Schematic of the Biomass-Fired ORC Process (from Ref. 25)



Fig. 9 Overview of the Whole Module of the Biomass-Fired ORC Plant (from Ref. 25)

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Fig. 10 Two-Stage Axial Turbine for the Biomass-Fired ORC Process (from Ref. 25)

Table 1: Major energy conversion technologies of biomass-fuelled CHP systems

Primary Technology	Secondary Technology
Combustion producing steam, hot water	Steam engine; Steam turbine; Stirling engine; Organic Rankine Cycle (ORC)
Gasification producing gaseous fuels	Internal Combustion Engine; Micro-turbine; Gas turbine; Fuel cell
Pyrolysis producing gaseous, liquid fuels	Internal Combustion Engine
Biochemical/Biological processes producing ethanol, biogas	Internal Combustion Engine
Chemical/Mechanical processes producing biodiesel	Internal Combustion Engine