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A biomass-fired micro-scale CHP system with organic Rankine cycle (ORC) – Thermodynamic modelling studies

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ABSTRACT

This paper presents the results of thermodynamics modelling studies of a 2 kW (e) biomass-fired CHP system with organic Rankine cycle (ORC). Three environmentally friendly refrigerants, namely HFE7000, HFE7100 and n-pentane, have been selected as the ORC fluids. The thermodynamic properties of the selected ORC fluids which have been predicted by commercial software (EES) are used to predict the thermal efficiency of ORC. The results of modelling show that under the simulated conditions (1) the ORC thermal efficiency with any selected ORC fluid is well below (roughly about 60% of) the Carnot cycle efficiency; the ORC efficiency depends on not only the modelling conditions but also the ORC fluid – the highest predicted ORC efficiency is 16.6%; the predicted ORC efficiency follows the following order: n-pentane > HFE7000 > HFE7100 (2) both superheating and sub-cooling are detrimental to the ORC efficiency (3) the electrical efficiency of the CHP system with the selected ORC fluids is predicted to be within the range of 7.5%–13.5%, mainly depending on the hot water temperature of the biomass boiler and the ORC condenser cooling water temperature as well as the ORC fluid, and corresponding to about 1.5 kW and 2.71 kW electricity output (4) the overall CHP efficiency of the CHP system is in the order of 80% for all three ORC fluids although the amount and quality of heating supplied by the CHP system depend on the ORC fluid selected and the modelling conditions.

1. Introduction

It is now almost universally accepted that the greenhouse gases, particularly carbon dioxides (CO_2), resulted from the continual utilisation of fossil fuels have caused the global warming observed over the past decades. Energy saving and renewable energy have now been promoted in many parts of the world via various incentives and legislations. Combined Heat and Power (CHP) Generation has been considered worldwide as the major alternative to traditional systems in terms of significant energy saving and environmental conservation [1]. Energy use in various buildings accounts for nearly half of the UK's delivered energy consumption and half of the UK's CO_2 emissions. Many believe that micro-scale CHP is the most effective way to satisfy the energy demands and to reduce CO_2 emissions of domestic and light commercial buildings such as small office buildings. The heating and power demands of typical domestic buildings and light commercial buildings can be fully met by micro-scale CHP systems within the size range of 1–10 kW (e).

Currently, micro-scale CHP systems within the size range of 1–10 kW (e) are undergoing rapid development, and are

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emerging on the market with promising prospects for the near future commercialisation [2,3]. The UK has been forecast to become one of the three largest markets for micro-scale CHP installations in Europe [4]. In recent years, several fossil fuel-powered micro-scale (1–10 kW (e)) CHP systems, such as the natural gas-fired, Stirling engine-based 1 kW (e) CHP systems of WisperGen [2] and Baxi Ecogen [3], the natural gas or LPG-fired, internal combustion engine-based 5.5 kW (e) Baxi DACHS [3], and the natural gas-fuelled, PEM fuel cell-based 1.5 kW (e) Baxi BETA 1.5 PLUS [3], have been in demonstration/trial operations in the United Kingdom. Although these systems have demonstrated to be able to save a certain amount of primary energy and hence CO_2 emissions comparing with conventional separate heating and power (e.g. a dedicated heat-supply boiler and grid electricity), they still emit significant amount of CO_2 which contributes to the climate change – simply because they are fuelled by fossil fuels. Paepe et al. [5] showed that some fossil fuel-powered micro-scale CHP systems may only have marginal energy and environmental benefits over the separate heating and power by use of modern condensing boilers and grid electricity. To drastically reduce the CO_2 emissions, the energy demands of the buildings have to be supplied by renewable energy-based systems, such as building integrated wind turbines, solar PV, solar thermal and biomass-fuelled micro-scale CHP systems.

Generating electricity from biomass based on combustion combined with a steam Rankine turbine cycle is the most developed technology at the present time. However, the steam-driven Rankine turbine power generation is not suitable for biomass-fired CHP systems smaller than 100 kW (e) because of its inherent low electricity generation efficiency and high capital costs. Development of biomass-fuelled CHP systems with size in the order of 100 kW (e) based on other concepts of power generation, such as gasification combined with internal combustion engines or gas turbines, combustion combined with Stirling engines or indirectly-fired turbines, has been the focus of a number of R&D projects in Europe over the past decade [6–8]. The majority of these biomass-fuelled CHP systems are at under development stages and their electricity generation efficiencies and capital costs are likely to deteriorate significantly when scaled-down to 1–10 kW (e) which are the typical size range for building applications. The market demand for biomass-fuelled CHP systems with the size range of 1–10 kW (e) is expected to increase significantly in the future as the price increases sharply, while the supply becomes less secure, of fossil fuels, particularly natural gas and petroleum oil. However, there have been very few studies which have concentrated on the development of biomass-fuelled CHP systems sized for building applications.

2. The proposed 2 kW (e) biomass-fired CHP system with organic Rankine cycle

Organic Rankine Cycle (ORC) is one of the power generation concepts which have recently been applied to biomass-fuelled CHP systems [9,10]. Biomass-fired CHP systems based on the ORC with the size in the range of 200 kW–1.5 MW (e) have been successfully demonstrated and now they are commercially available from several manufacturers with typical electrical efficiency of in the order of 15–20% [9,10].

The principle of the ORC-based power generation is similar to that of the steam-driven Rankine turbine cycle, except that an organic working fluid which has favourable thermodynamic properties (the boiling point, the critical point, the latent heat, the slope of the saturation vapour T-s line, the maximum stability temperature, etc.), is used as the working medium for the turbine [11]. The ORC-based power generation has been widely applied to the power generation from low temperature heat sources, such as the recovery of industrial waste heat, geothermal heat and solar heat, with the size of the generator ranging from a fraction of 1 kW to over 1 MW (e) [11]. An ORC turbine is more economical than a steam-driven turbine in terms of capital and maintenance costs due to the use of non-eroding, non-corrosive and low temperature working fluid vapour. In addition, the ORC-based power generation offers advantages in electricity generation efficiency over the steam-driven Rankine cycle power generation at small- and micro-scale systems.

Over the past years, the Department of Architecture and Built Environment, Faculty of Engineering, University of Nottingham, UK, has carried out several research projects on the ORC-based micro-scale power generation using different heat sources, such as solar energy and a gas-fired boiler [12,13]. Results from these research projects prove that the ORC-based power generation can be successfully applied to 1 kW (e)-scale CHP systems using various heat sources including hot-water generated from a biomass boiler.

The proposed 2 kW (e) biomass-fired CHP system is schematically shown in Fig. 1. It consists of two cycles: the water cycle and the organic Rankine cycle. The heat released from the combustion of biomass inside the biomass boiler is used to heat the water via the boiler heat exchangers, while the hot water is used as the heating source of the organic Rankine cycle. The ORC working fluid is closely circulating within the organic Rankine cycle: the condensed ORC working fluid is pumped through the evaporator where it is heated by the circulating hot water to generate organic working fluid vapour which expands in the turbine to generate electricity; the working fluid at the turbine exhaust is condensed in the condenser and flows back to the circulation pump to begin a new cycle. Depending on the ORC working fluid used, the

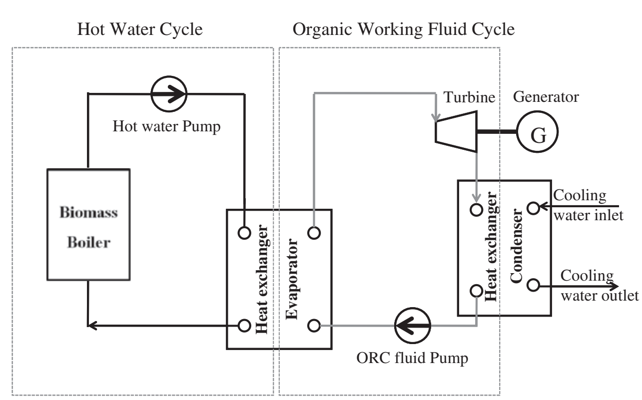

Fig. 1 – Schematic of the proposed 2 kW (e) biomass-fired CHP system.