Applied Energy 97 (2012) 667–672

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Integrated thermoelectric and organic Rankine cycles for micro-CHP systems

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ARTICLE INFO

Article history:
Received 11 August 2011
Received in revised form 17 December 2011
Accepted 25 December 2011
Available online 20 January 2012

Keywords:
Thermoelectric
Organic Rankine cycle
Micro-CHP
Dual-cycle

ABSTRACT

Interest in micro-combined heat and power (micro-CHP) for residential homes is growing. Stirling engines, internal combustion engines and organic Rankine cycles (ORC) could be applied for micro-CHP. However, the electrical efficiency of these micro-CHP systems is relatively low. The present paper discusses an integrated system of thermoelectric power cycle and ORC which forms an advanced dual-cycle power system. The integration scheme and the dual-cycle system thermodynamics were studied and a mathematic model was established. Dual-cycle system performance was simulated under various conditions. Overall power output and energy conversion efficiency were calculated using the established model. Experiments were conducted in an experimental setup to investigate the performance of power generation under conditions representative of the dual-cycle system. The thermoelectric modules or converters were found to be well suited for integration with the micro-CHP system.

1. Introduction

Combined heat and power is an effective approach to increasing fuel efficiency while reducing GHG emissions as compared to conventional electrical and thermal energy production. Interest in micro-combined heat and power (micro-CHP) systems for residential applications is growing. Micro-CHP systems are particularly attractive for cold climate areas and remote communities where connection to the grid is not cost-effective. There are several reasons for the growing interest in micro-CHP: first, the liberalization of energy markets is changing the approach to energy production; second, environmental pressures, particularly to minimize CO_2 emissions, are increasing considerably; and third, the technology is becoming available. Rising energy costs, volatile fuel prices, electrical power blackouts and increasing environmental concerns have favoured the acceptance of the micro-CHP concept.

Different technologies can be used for micro-CHP systems, including internal combustion engines (also known as reciprocating engines), stirling engines and organic Rankine cycles. In general, however, the electrical efficiency of such engines suitable for household-scale micro-CHP systems is relatively low. Thermoelectric devices convert thermal energy directly into electricity using solid-state technology based on the Seebeck effect. A thermoelectric generator has no moving parts and is compact, quiet, highly reliable and environment friendly. A thermoelectric power converter can recover engine waste heat in a straightforward manner. Renewed emphasis has been placed on thermoelectric energy conversion in recent years [1–5] and significant progress has been made in producing thermoelectric devices for heat recovery power generation systems.

The energy conversion efficiency of thermoelectric devices is determined by the value of figure of merit (*ZT*) for thermoelectric materials. Since the late 1990s new thermoelectric materials with high *ZT* values have been emerging. Improvements in the *ZT* factor have been demonstrated through nanocrystalline structure manipulation and lower-dimensional configurations, and use of quantum-well structures and nano-composites. The efficiency of thermoelectric generation can also be improved by using segmented thermoelectric elements. Both p-type and n-type thermoelectric materials should be chosen in terms of their highest *ZT* for each temperature range. Established thermoelectric materials include low temperature ($T < 500$ K) materials such as $(Bi, Sb)_2\,(Te, Se)_3$, mid temperature ($550\ K < T < 850$ K) materials such as PbTe and PbSnTe and high temperature ($\sim$1200 K) materials such as SiGe alloys. Each material group has its optimum temperature range for high levels of heat to electricity conversion. The elements can be constructed with a segmented structure to achieve the best average *ZT* over the operating temperature range for a power generation system.

Thermoelectric power generation in heat recovery applications is a major subject in the development of the field. It appears that the application of thermoelectric power conversion to CHP systems has not attracted enough attention. Recently, Chen et al. [6] have evaluated the potential application of thermoelectric generation to CHP energy systems. They discussed three integration modes (Fig. 1). The first is to place a thermoelectric generator between the expander and the waste heat boiler. The second is to place a thermoelectric generator at the outlet of the waste heat boiler, using the temperature difference between the exhaust gas from the boiler and the ambient temperature to produce electricity.

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0306-2619/$ - see front matter
doi:10.1016/j.apenergy.2011.12.072

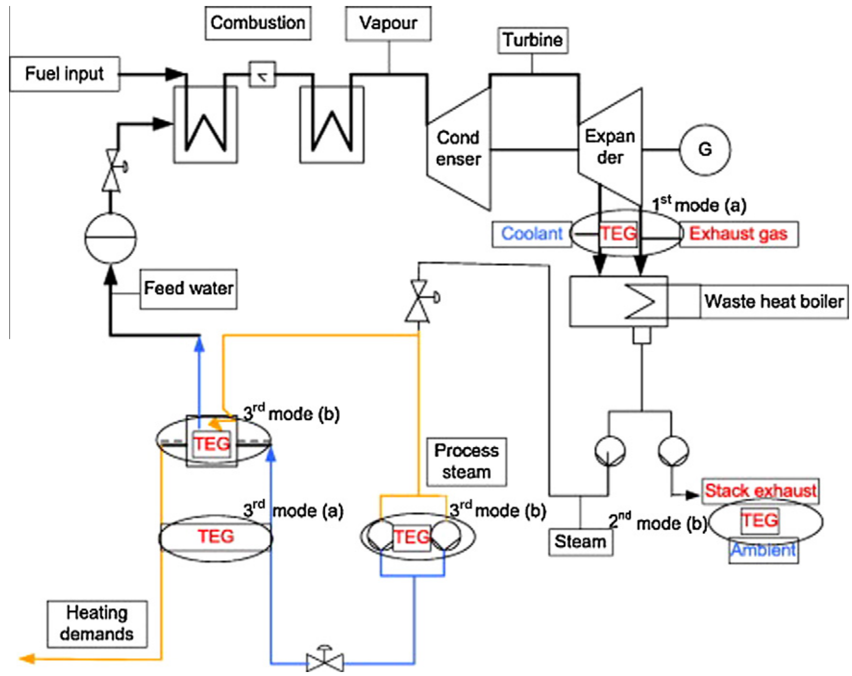

Fig. 1. A typical CHP system and location of thermoelectric generators [6].

The third is to place a thermoelectric generator at the condenser between the inlet fluid and the outlet fluid, or in any other location to substitute the traditional heat exchangers.

Miller et al. [7] proposed a dual-cycle model system for energy recovery using thermoelectric generation integrated with an organic Rankine bottoming cycle. The integrated system consists of a thermoelectric generator to utilize high-temperature waste heat and an organic Rankine cycle (ORC) to recover a large portion of the remaining low-temperature thermal energy.

The straightforward operation of thermoelectric conversion and its other advantages make it a feasible supplement to micro-CHP. In other words, thermoelectric power cycle is suited to being coupled with combustion-driven micro-CHP to improve the overall system performance. In this study, the concept of an advanced thermoelectric and organic Rankine dual-cycle system is developed for micro-CHP applications. In the combined cycle system, the topping cycle consists of a thermoelectric generator, while the bottoming cycle is an ORC. The thermoelectric generator converts combustion heat directly into electricity. The residual heat streams are taken from the thermoelectric converter and applied to the input of the ORC so as to increase the electricity production and the efficiency of the micro-CHP system.

2. Dual-cycle description

Configuration of the thermoelectric and organic Rankine dual-cycle system is illustrated in Fig. 2. The integrated energy system consists of a gas burner, a thermoelectric converter, a cooling device that is also used as a preheater for ORC working fluid, a working fluid evaporator, an expander, a condenser and a working fluid feed pump. The burner generates combustion heat at a rate of Q_{fuel}. Q_h is the heat input rate from the burner to the thermoelectric converter and Q_c is the dissipated heat rate from the converter to the circulating ORC working fluid. Circulating fluid is directed to the cooling system by which the unconverted heat is removed from the thermoelectric module cold junctions and the working fluid is thus preheated. The electric power P_{TE} is generated and supplied to the load. T_1 and T_2 are the temperatures of the hot and cold junctions, respectively. Q_{fg} is the heat remaining in the flue gases after thermoelectric conversion, which flow through a working fluid evaporator. The thermoelectric generator can operate at temperatures up to 600 °C on the hot side (junction).

The ORC has been applied to waste heat recovery for many years. The use of organic working fluids for the realization of the Rankine cycles has proven to be a promising solution for CHP. The problem of high specific investment costs for machinery such as steam boilers are overcome due to the low working pressures in the ORC process. However, so far, only large ORC systems have been commercially available. The ORC process allows the use of various low temperature heat sources in small-scale applications, offering many advantages, especially for micro-CHP. New developments concern small systems with acceptable performance, new working fluids with low environmental impact, scroll expanders and advanced heat transfer components including efficient condensers that are compact and small in size [8].

The ORC uses a circulating organic fluid of high molecular mass which is pumped around the circuit and is heated by the evaporator or boiler to produce a vapor, which rotates a scroll expander. The scroll expander can be designed and made for small-scale ORC systems ($\leqslant$15 kWe). The expander shaft output runs the generator. The organic vapor then passes through a condenser that transfers the fluid's heat content to the central heating circuit. The condensed fluid is returned to the preheater for heating and is then directed to the evaporator. In the dual-cycle system, heat is provided to the working fluid in two separate ways. Reject heat from the thermoelectric converter heats the ORC working fluid in the preheater that also serves as the cooling device for the thermoelectric converter. The working fluid then evaporates and the vapor is slightly superheated in the evaporator through which the hot flue gases from the thermoelectric generator flow in the normal fashion. As mentioned above, the thermoelectric generator constitutes a topping cycle, while the ORC process is a bottoming cycle in this integrated system. The dual-cycle structure couples the thermoelectric converter with the ORC compactly.