Applied Thermal Engineering 62 (2014) 69–79

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Experimental study of a domestic thermoelectric cogeneration system

X.F. Zheng [a], C.X. Liu [a, b], R. Boukhanouf [a], Y.Y. Yan [a, *], W.Z. Li [b]

[a] Energy and Sustainability Research Division, Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK
[b] School of Power and Energy, Dalian University of Technology, Dalian 116024, China

HIGHLIGHTS

- A thermoelectric cogeneration system uses both converted heat and unconverted heat.
- This system can deliver energy utilisation efficiency up to 80%.
- Thermal efficiency varies with operating temperature due to unstable matching load.
- The fluid-filled heat exchanger enables the system to store and spread heat.

ARTICLE INFO

Article history:
Received 14 March 2013
Accepted 4 September 2013
Available online 25 September 2013

Keywords:
Thermoelectric cogeneration
Thermal efficiency
Domestic

ABSTRACT

Thermoelectric application for power generation does not appear to be appealing due to the low conversion efficiency given by the current commercially available thermoelectric module. This drawback inhibits its wide application because of the overall low thermal efficiency delivered by typical thermoelectric applications. This paper presents an innovative domestic thermoelectric cogeneration system (TCS) which overcomes this barrier by using available heat sources in domestic environment to generate electricity and produce preheated water for home use. This system design integrates the thermoelectric cogeneration to the existing domestic boiler using a thermal cycle and enables the system to utilise the unconverted heat, which represents over 95% of the total absorbed heat, to preheat feed water for domestic boiler. The experimental study, based on a model scale prototype which consists of oriented designs of heat exchangers and system construction configurations. An introduction to the design and performance of heat exchangers has been given. A theoretical modelling for analysing the system performance has been established for a good understanding of the system performance at both the practical and theoretical level. Insight has also been shed onto the measurements of the parameters that characterise the system performance under steady heat input. Finally, the system performance including electric performance, thermal energy performance, hydraulic performance and dynamic thermal response are introduced.

1. Introduction

In most developed countries with temperate climate, heat for space heating and domestic hot water is often provided by burning gas or oil in a boiler or furnace. Current condensing boilers are highly efficient achieving thermal efficiencies in excess of 90% with combustion gases rejected at dew point temperature. Despite a growing market for condensing boilers, a large number of old boilers are still being used with thermal efficiency as low as 55%, resulting in large energy loss [1].

Thermoelectric modules, consisting of pairs of p-type and n-type semiconductor materials forming a pair of thermocouple, generate electricity when a temperature difference is established across the module. Thermoelectric devices have found a wide range of applications including power generation, heat recovery and thermal sensing. These applications span a wide range of industries such as transport [2,3], process industries [4–6], medical [7,8] and space [9]. Many efforts have been made in the development of advanced thermoelectric materials with high conversion efficiency to enhance the potential of a wider range of applications [10–13]. According to operating temperature, thermoelectric materials are classified into three categories: low temperature, intermediate temperature and high temperature thermoelectric. The low temperature type, which includes alloys based on bismuth in combinations with antimony, tellurium or selenium, utilises heat from

* Corresponding author. Tel.: +44(0)115 951 3168.
E-mail address: yuying.yan@nottingham.ac.uk (Y.Y. Yan).

1359-4311/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2013.09.008

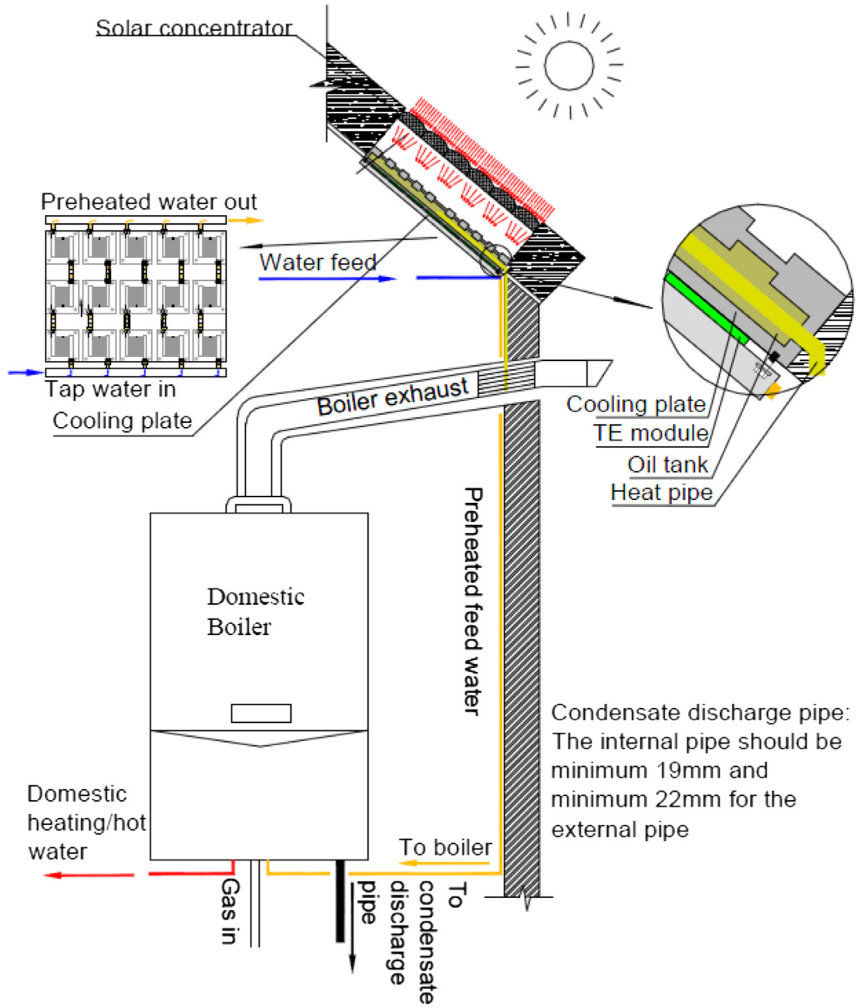

Fig. 1. Concept diagram of domestic thermoelectric cogeneration system.

warm/hot water or general waste heat by operating up to 523 K, while the latter two which include the alloys of lead telluride and silicon germanium are oriented for incineration/steel plants and automobile exhaust, respectively [14]. Their operating temperatures can reach up to 850 K and 1300 K. Suitable application of thermoelectric material is generally referred to large electrical power factor, good cost effectiveness and being environmentally friendly. For high operating temperature, modules with segmented thermoelectric elements have larger average figure-of-merit *ZT* over a large temperature drop compared to those using same alloy in the element [15]. The thermoelectric efficiency reached as high as 20% operating between 300 K and 975 K [16]. For applications in cogeneration for domestic buildings with heat source temperature about 473 K, Bi_2Te_3 has been selected for its high figure of merit, ZT.

The main advantages that boast thermoelectric devices are being static, compact, and low maintenance cost. However, low conversion efficiency has confined their application to specialised niche markets. One of these markets is generating electrical power in buildings located in inaccessible remote areas. For instance, back in 1996, the Swedish Royal Institute of Technology [17] developed a thermoelectric stove to provide small amounts of power to residential houses in the remote northern areas of the country where grid connection is prohibitively expensive. Recent works on thermoelectric stoves include those of Champier [18], Nuwayhid [19] and Mastbergen [20], which recover waste heat from cooking stove to generate electricity to power fan or lamp.

Because domestic boilers rely on grid connection for operation, Daniel [21,22] attempted to develop a self-powered domestic boiler using thermoelectric generators by integrating the thermoelectric modules between the combustion chamber and the water channel in the boiler enclosure. Thermoelectric generators were also thought of as direct contenders to replacing diesel gensets for power generation in off-grid buildings, eliminating noise, and high maintenance that characterise internal combustion engines. Commonly, the heat sink is an assembly of a finned heat exchanger and fan that removes heat via forced convection.

The thermal performance of the thermoelectric devices for power generation-only applications remains, however, poor with maximum efficiency below 5% [14]. This means 95% of the fuel energy content is rejected as low grade heat. Therefore, recovering rejected heat for useful utilisation for space heating and domestic hot water as part of a thermoelectric cogeneration system would make thermoelectric more attractive as overall thermal efficiency could be increased up to 100%, which was discussed by Gao in Ref. [23]. In a later time, this concept was initially proved in a different work by the author at an earlier time [24], which demonstrated a practical achievement of thermal efficiency at up to 80%. Qiu [25] developed a thermoelectric power generation system which generates electricity and hot water by burning natural gas in a furnace. Relying on the supply of natural gas, its operation is suitable for the applications which are purposefully designed for using the natural gas as the primary fuel. In the first stage study [24], the author