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A study of selected aspects of the operation of thermoelectric generator incorporated in a biomass-fired stove

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Abstract. High demands in the field of energy efficiency and clean combustion make it necessary to looking for the new developments in the field of stoves, fireplaces and stove-fireplaces with accumulation. An interesting idea is to use the thermoelectric modules, which receive a heat from flue gas and convert it to the electricity. Electricity generated in this way may be used to power combustion optimizers and other components. This paper shows results of studied carried out to determine the possibility of combined heat and power generation using the stove-fireplace with accumulation. Thermoelectric generator with maximum hot side temperature at a level of 150°C was placed on the surface of the exchanger. Cooling down was realized using the dedicated water exchanger as well as the heat sink without and with an air fan. The experimental results allowed to define the effect of the different cooling systems on the output TEG voltage. Moreover, dependence of the current-voltage characteristics and generated power from the temperature was obtained.

1 Introduction

Thermoelectric generators (TEGs), which are a subject of many worldwide conducted studies, are well suited to recover energy from the low grade waste heat. Among the advantages of TEGs, it can be mentioned e.g. direct transfer heat to electrical energy, light weight, silent operation and not mechanical vibration. With current efficiencies at a level of 5-10%, the heat rejected from the TEG may go back to room heating [1,2].

From a number of carried out investigations, there are several studies, where thermoelectric generators operated with different kinds of stoves. In one of them, the prototypical thermoelectric generator was equipped with two Hi-Z TE modules cooled by an air fan and fitted to a wood stove. This unit was installed in Scandinavian house and produced up to 10 W in the cold mornings, and 4-7 W during the day (when house became warmer). The generated power was sufficient to operate the cooling air fan and charge four 6 V batteries (connected in series/parallel to maintain a 12 V output) using DC/DC converter [3]. Another studies devoted to continuous electric power generation using waste heat from the wood stoves were presented in [4]. TE modules were fitted to the side of a domestic woodstove and were cooling by natural convection using heat sink. The maximum steady state matched load power was achieved at a level of 4.2 W per module. The more advanced power generating system produced up to 9.5 W (the maximum power of electricity available for the end users was around 7.6 W) has been studied in [5]. It was a complete system from the heat source up to the end users. In addition to energy performance, an environmental efficiency of the cook stove equipped with TEGs were considered in [6]. Since obtained a maximum level of 4.5 W from the TEG and less than 1 W was needed to power the blower to provide a clean combustion and reduce indoor air pollution.

One of the moist important aspect in the air cooling systems is electricity demand for power the fans. This problem was considered in studies presented in [7], where the cold side of the TEG was connected to heat pipe heat sink, normally used in CPU cooling. The typical fan supplied with this heat sink operated at 12 V and consumed up to 2.2 W of electricity. To improve the energy performance, the low power DC motor was used instead. It could run the fan from 0.3 V and consumed up to 0.5 W with voltage not exceeded 5 V. Since the fan started from very low TEG voltage, the necessity to use an additional battery was eliminated.

The example of usage forced water cooling system instead of the air cooling systems, is presented in [8]. In this case the electric heater was simulating heat source and heating TE modules. The maximum power generating in modules was obtained at the level of 10 W. It should be noted, that continuous operation of a pump certainly decreased the available output power. The advanced, multifunction device capable to produce a considerable amount of electricity and hot water, was designed by [9]. They used together 21 TE modules divided into seven groups of three, each connected electrically in series. The hot sides of modules were connected to a 50 mm-long aluminium pieces which was attached to the stove body. In this way the upper temperature limited by the TEGs was not exceeded. TEGs were cooling via a water-filled

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aluminium block, through which the water flow rate could be adjusted. The average electricity generation was at a level of 7.9 W for each module when charging with 9 kg of firewood per hour.

Taking into account above mentioned studies we can conclude, that from technical and an economic point of view, there is huge potential to development of TEG technology. It would constitute an option of sustainable electricity generation that could be developed in the own regional economies where it is used [9] showed, that simple installation and operation for the own users, would give TE modules some comparative advantages respect to e.g. conventional PV solar arrays. Its low operating costs, feature shared with PV systems, becomes thermoelectric generators an attractive option for low-income rural houses. As TEG are destined both to the high and low income houses, the cost is also an important issue. Many studies, including studies performed by [10, 11] have shown that the price per watt may be really close or equal to the price of photovoltaic systems.

Although the worldwide studies consider many configurations of TEGs with different types of stoves and other heat appliances, there are no studies devoted directly to the stove-fireplaces with accumulation (which combine fireplaces and traditional accumulative stoves). Such studies were performed at AGH UST in Krakow and presented in the further part of this paper.

2 Experimental rig

Stove-fireplaces with accumulation (SFA) combine fireplaces and traditional accumulative stoves. Heat produced during wood combustion is stored in the accumulative heat exchanger and dissipated up to 12 hours after the fire has died out. As a result, the thermal efficiency of SFA is high and close to 90% [12,13]. The idea of such device was shown in Fig. 1.

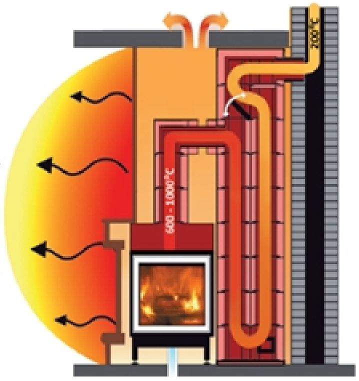

Figure 1. The idea of stove-fireplace with accumulation.

Studies were carried out on the test rig equipped with a stove-fireplace with accumulation composed with a 550 kg furnace and a 1050 kg accumulation exchanger located next to the furnace. Based on a number of previous works, heat exchanger dedicated for TEG was located at the beginning of the accumulative exchanger. The illustration of the tested system is shown in Fig. 2

Figure 2. The location of thermoelectric generator in the flue gas channel.

The structure of the heat exchanger dedicated for TEG was made in the form of the rectangular channel with the dimensions of 30 x 16 x 11.5 cm (length x width x height). The exchanger's surface is insulated by a 5 cm layer of mineral wool. Inside the exchanger, a special reducer and radiator were used. Reducer allowed to increase the gas flow in the boundary layer and radiator allowed to intensify the heat exchange between exhaust gas and hot side of TE module (only one module was fitted to the radiator during the tests) [14]. The structure of the heat exchanger with TE module is present in Fig. 3.

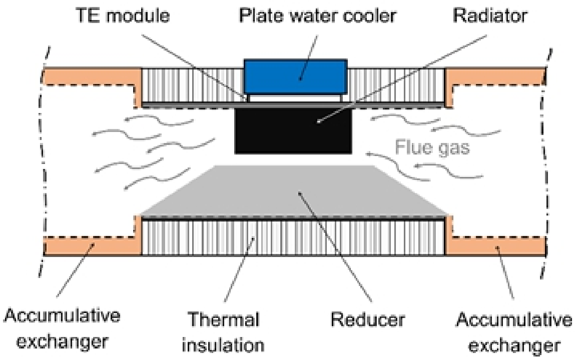

Figure 3. The construction of thermoelectric generator.

Thermoelectric module used in the carried out studies was a Bi_2Te_3 module with a dimensions of 40 x 40 x 3.2 mm and maximum differential temperature at a level of 150°C. It contained 199 thermocouples. Ceramic plates were made from Al_2O_3, and their thermal conductivity was about 15 W/mK.

Hot side of TE module (during described studies only one module was tested) was heating by a flue gas flown through the heat exchanger. Flow and temperature of flue gas was controlled by changing the amount of the air blown to the furnace area. Cooling the cold size of TE module was realized using the dedicated water exchanger and the heat pipe heat sink with or without a fan.

The operation of the stove-fireplace with accumulation was controlled using advanced control and measurement system based on the WAGO PLC controller combined with the set of measurement elements and actuators:

- thermocouple and resistance temperature sensors placed inside the furnace, heat exchanger dedicated for TEG, accumulative mass and chimney;
- resistance temperature sensors placed on the external side of accumulative mass and heat exchanger dedicated for TEG;

- thermoanemometers with a range of 0-2 m/s to measure the flow rate of the air blown into the furnace area;
- flue gas analyser uses the electrochemical method of O_2 concentration measurement and the NDIR method for measuring the concentrations of CO, CO_2, NO, NO_2 and SO_2;
- servo-mechanisms controlled via analogue signals 0-10 V to control the air throttles positions;
- electronic load.

The monitoring and process (measurement) data acquisition system has been developed in the CoDeSys environment on the PC computer. It was possible to observe the real time variations of the measured values, archive measurement data (in the internal memory of the PLC controller or in the PC) and control the SFA operation. Measurements were recorded in the 1s time interval. The location of control and measurement elements is shown in Fig. 4 (only elements used during the described tests were marked).

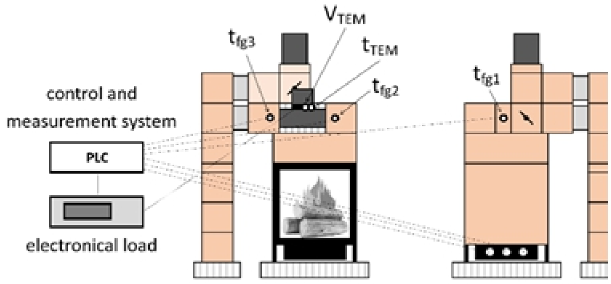

Figure 4. Scheme of the experimental rig.

The investigations were divided into two parts. At the beginning different cooling methods and their impact on the TE module performance have been tested. First, it was used only heat pipe heat sink, in the second approach heat pipe heat sink with an air fan, and finally the water heat exchanger (temperature of the cold water was equal to 22°C). Further experiments were aimed to determine the specific characteristics of the tested TE module. In each of measurement series 10 kg of beech wood briquette has been burned. The shape of briquette was rectangular and its caloric value was in the range of 14 – 17 MJ/kg.

The first tested configuration of TEG contained a heat pipe heat sink typically using in the PC processors cooling (see Fig. 5). The alumina heat sink had four heat pipes with cross-section of 6 mm, which received heat directly from the TE module surface. Dimensions of the whole heat sink was 125 x 52 x 152 mm (length x width x height).

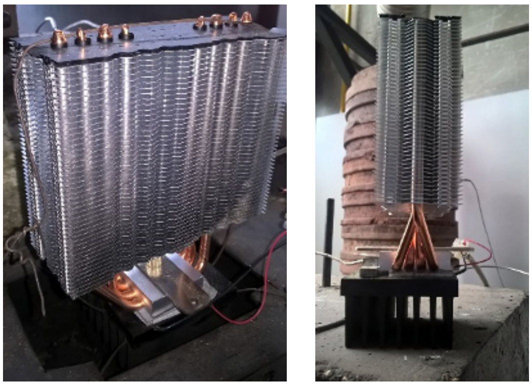

Figure 5. Cooling of the TEG using the heat sink.

In the second approach, in addition to the heat sink, an air fan with dimensions of 120 x 120 x 25 mm was used (see Fig. 6). The operation voltage of the fan was 12 V and current was 0.12 A – what means, that maximum taken power was less than 1.5 W. The fan provided the air flow at a level of 1.7 m^3/h, when the number of rotates per minute was 1400 +/-10%.

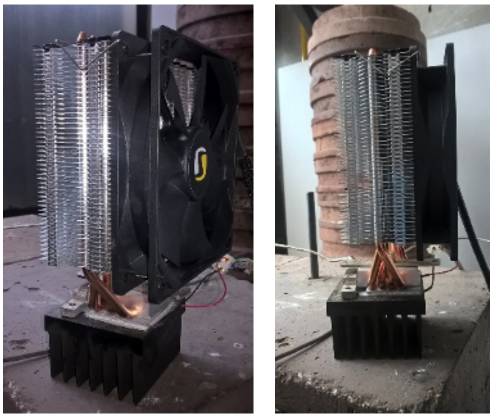

Figure 6. Cooling of the TEG using the heat sink with air fan.

The third configuration of TEG was equipped with the dedicated alumina water heat exchanger (see Fig. 7). The size of exchanger was suited for the size of TE module's ceramic plate. Water was flown via steel pipes connected with exchanger via inlet and outlet localized at the wall of exchanger.

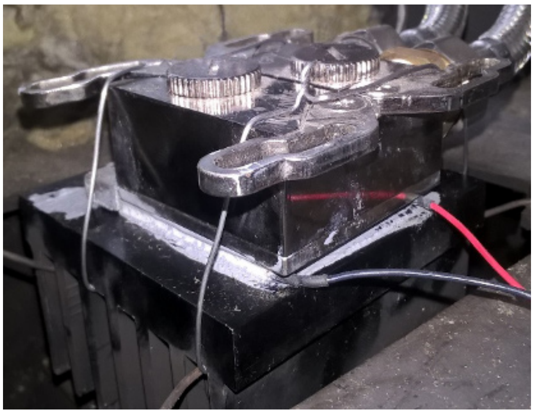

Figure 7. Cooling of the TEG using the water heat exchanger.

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3 Results and discussion

3.1 The impact of the cooling method on the TE module performance

The results of conducted studies show, that the use of proper cooling method has a great impact on the performance of TEG operation. Due to higher heat capacity of water (in comparison to air), water cooling is generally more efficient than air cooling. It can be observed in Fig. 8, where variations of voltage in each of studies cases were presented.

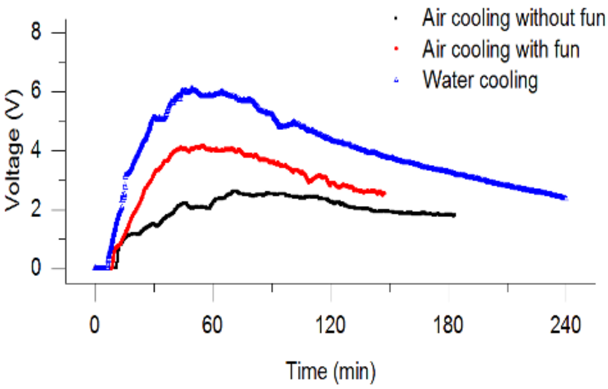

Figure 8. Histogram of TE module voltage (depending on the cooling method).

As we can see in Fig. 8, there is a huge difference between the output voltage obtained in the three considered series. Definitely the most efficient cooling method is water cooling, which allowed to obtain the maximum voltage value above 6 V (there is three times more than using air cooling without fan). On the other hand, during performed tests, temperature of water was constant over time and equal to 22°C. The increase of its temperature in the cooler was less than 4 K (with the flow rate of 5 l/min). In practical solutions it is hard to provide so good conditions. The use of water cooling may be connected with the use of the return water from hot water or heating system.

However, also in the case of using heat sink with air fan, there is necessary to take into account the power taken by the fan. It is about 1.44 W in the studied situation (the operation voltage of the fan is 12 V and current is 0.12 A). The solution is to use one air fan for few TE modules and modulate its rotation speed (depending on the hot side temperature of TE modules). It will allow to minimize the share of power taken by air fan.

In addition to data presented in Fig. 8, in Tab. 1 were shown the maximum and the average voltage values obtained during each of studies cases. The average value was calculated for the range from 10 to 150 minute of combustion process.

Presented above results are in general true for the studied cooling methods. Moreover, to eliminate the possible impact of the variations of combustion process on the output voltage from TE module, it can be introduced a comparative voltage and temperature coefficient (CVTC), calculated as follows:

$$CVTC = \frac{\sum_i^n (V_{TE,i}/t_{ex,i})}{n} \qquad (1)$$

where:
$V_{TE,i}$ – output voltage of TE module, V
$t_{ex1,i}$ – temperature of the flue gas measured on the outlet from the furnace, °C
n – a number of the measurements

The values of CVTC calculated for the range from 10 to 150 minute of combustion process, were presented in Tab. 2.

Table 1. The maximum and average voltage values obtained from tested TE module.

Cooling method / Parameter	The maximum voltage	The average voltage
	[V]	[V]
Air cooling (heat sink without fan)	2.64	2.07
Air cooling (heat sink with fan)	4.17	3.21
Water cooling	6.10	4.82

Table 2. The values of comparative voltage and temperature coefficient.

Cooling method / Parameter	CVTC value
	[-]
Air cooling (heat sink without fan)	0.0064
Air cooling (heat sink with fan)	0.0089
Water cooling	0.0144

Data included in Tab. 1 confirms, that the most efficient cooling is connected with the use of water heating system. The relative differences between calculated values are quite lower than in the case of direct voltage values, but still significant. The variations of output voltage of TE module to temperature of the flue gas measured on the outlet from the furnace ratio was presented in Fig. 9.

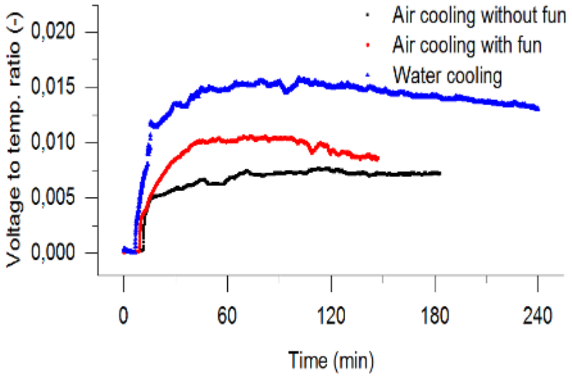

Figure 9. Histogram of the TE output voltage to temperature of the flue gas (measured at the outlet from the furnace ratio).

As we can see in Fig. 9, the courses of presented curves are more stable in time in comparison to output voltage curves presented in Fig. 8. This situation confirms once again a direct correlation between the temperature of the cold side of TE module and its performance.

3.2 Specific characteristics of the tested TE module

The operation parameters of the tested thermoelectric module (voltage, current and power), depends not only on the temperature of its cold side. First of all, there are connected with the variations of the hot side temperature. During the studies carried out in the second part of this investigation, the effect of the hot side temperature variations on the current-voltage characteristic and the output power has been determined. The same amount of the fuel was burned (10 kg of briquette). Cooling of the cold side of TE module was realized using water cooling system (flow rate was the same as before, that is 5 l/min).

The current-voltage characteristics for the three chosen values of TE module hot side temperature (110, 130 and 150 degrees Celsius), were presented in Fig. 10.

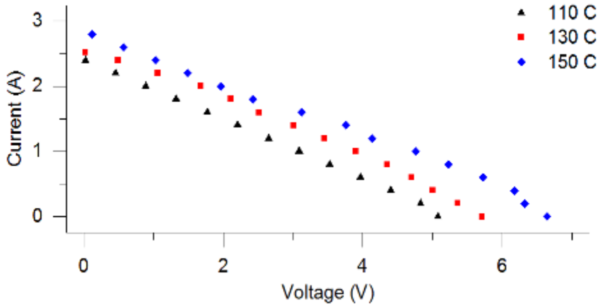

Figure 10. The current-voltage characteristic of the TE module.

The variations of the voltage and current presented in the Fig. 10 depends on the current phase of the combustion process. A great impact is connected also with the velocity of temperature variations of the flue gas and the variations of the flue gas flow (which depends e.g. on the opening degree of the air throttles). As a results the courses of presented curves are non-linear and irregular.

The huge dependence of the power generated in TE module on the temperature was shown also in Fig. 11. This figure illustrates the variations of the power in the function of the voltage and temperature.

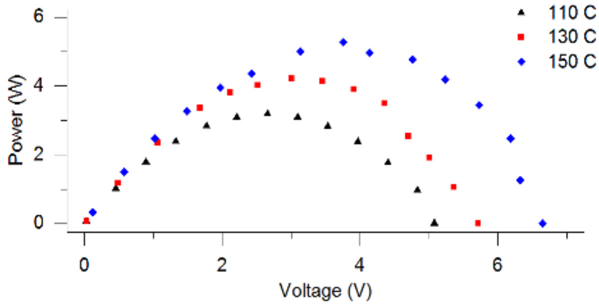

Figure 11. Power generated in the TE module.

As we can see in Fig. 11, the almost literature courses of the power curves in the voltage function were obtained – this illustrates the very good operation of the TE module. Power generated in the tested TE module exceeded 5 W (when temperature of the hot side was at a level of 150 degrees Celsius). In the other cases power was significantly lower – the maximum value measured for the temperature of 110 degrees Celsius was two times lower. However, the voltage obtained under laboratory conditions was about 10.5 V.

The maximum power points (which were marked in the Fig. 11) were also presented in Tab. 3.

Table 3. The maximum power points depending on the temperature.

Temperature of the hot side / Parameter	**Voltage**	**The maximum power**
	[V]	[W]
110 degrees Celsius	2.65	3.18
130 degrees Celsius	3.00	4.21
150 degrees Celsius	3.76	5.26

Presented values are related to the use of the only one TE module. Connecting in series/parallel more units, it is possible to generate more power with higher voltage and current. Produced power, using DC/DC converter, may be used to charge the battery. Looking further, there is possible to provide self-sufficient operation of the stove-fireplace with accumulation and also use of the generated electricity to power some of the home appliances (radio, lights, hot water circuit pump etc.).

4 Conclusions

The results of conducted study confirm the possibility of power generation using TEG connected to the stove-fireplace with accumulation.

Comparing different cooling methods, it was concluded, that the water cooling system is significantly more efficient that the air cooling system. The maximum measured output voltage of studied TE module was 6.1 V (in the case when the hot side of TE module was heating by the flue gas, and the cold side was cooling by the water). It is good results if we take into account the fact, that theoretically available output voltage of tested module is about 10.5 V (this value is possible to obtain in laboratory conditions). Also a comparative voltage and temperature coefficient CVTC (introduced to eliminate the possible impact of the combustion process variations on the output voltage from TE module) confirmed a direct correlation between the temperature of the cold side and module's performance. On the other hand, water cooling system may be efficiently used in the stove-fireplaces, which are used to heating water in the hot water circuit or central heating system.

The operation of TE module is strongly dependent not only on the cooling parameters, but also on the actual parameters of the combustion process (in particular flue gas temperature and flow). The variations in the current-voltage characteristics and power generated in TE module were considered as a function of voltage and temperature. As we observed, the maximum power was achieved at a level of 5.26 W, when the hot side temperature was 150ºC, voltage – 3.76 V and current – 1.4 A. Connecting together more modules self-sufficient operation of the tested stove-fireplace with accumulation may be provided. On the other hand, some further developments in the construction of the thermoelectric generator are necessary.

Besides technical aspects, also economic reasons are really important and should be taken into account. The expected costs of the power generating system is lower than 30% of the price of tested stove-fireplace with accumulation. On the other hand, the increasing demands in the fields of using renewable energy sources, improvement of energy efficiency and reduce exhaust gas emission to the atmosphere, make such solutions more and more preferred.

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References

1. D.M. Rowe, Proceedings of the institution of electrical engineers, 24 (1978)
2. M. Hodes, IEEE Transactions on Components and Packaging Technologies **28,** 12 (2005)
3. Killander, J.C. Bass, Fifteenth international conference on thermoelectric proceedings ICT '96, 4 (1996)
4. R.Y. Nuwayhid, A. Shihadeh, N. Ghaddar, Energ Convers Menage **46**, 13 (2005)
5. D. Champier, J.P. Bédécarrats, T. Kousksou, M. Rivaletto, F. Strub, P. Pignolet, Energ **36**, 9 (2011)
6. P. Raman, N.K. Ram, R. Gupta, Energ **69**, 13 (2014)
7. S.M. O'Shaughnessy, M.J. Deasy, J.V. Doyle, A.J. Robinson, Appl Energ **156**, 11 (2015)
8. G.F. Rinalde, L.G. Juanico, E. Taglialavore, S. Gortari, M.G. Molina, Int J Hydrogen Energ **35**, 5 (2010)
9. A.M. Goudarzi, P. Mazandarani, R. Panahi, H. Behsaz, A. Rezania, L.A. Rosendahl, J Electron Mater 42, 7 (2013)
10. D. Champier, J.P. Bedecarrats, M. Rivaletto, M. Strub, Energ **35**, 8 (2010)
11. D. Mastbergen, B. Wilson, ETHOS International Stove Research Conference (2005)
12. K. Sornek, M. Filipowicz, L. Kurcz, M. Szubel, M. Rosół, K. Rzepka, J. Ręka, Engineering and Protection of Environment **18**, 16 (2015)
13. K. Sornek, M. Filipowicz, K. Rzepka, Study of clean combustion of wood in a stove-fireplace with accumulation, Journal of the Energy Institute (2016)
14. K. Sornek, M. Filipowicz, K. Rzepka, The development of a thermoelectric power generator dedicated to stove-fireplaces with heat accumulation systems. Energy Convers Manage (2016)