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Development and Experimental Validation of a New Off-Grid Thermoelectric Fancoil for Domestic Heating

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Conventional heating systems are based either on radiators or on fan coils and the heat transfer process is carried out by convection phenomena in both cases, but with some fundamental differences. Traditional radiators can be considered less efficient compared to fancoils due to the fact that their performance relies on natural convection, a less efficient heat transfer process than forced convection. However, in contrast to fan coils, conventional radiators can operate without the need for mains supply. In this paper, a new heating device based on thermoelectricity, that combines the advantages of both radiators and fancoils, is presented. This new system exploits the heat coming from the heating system to generate electricity, which is consumed in situ to power a fan, eliminating the need for a nearby wall outlet. For this purpose, a laboratory prototype has been built and experimental characterization has been carried out.

Key words: Thermoelectric generator, power generation, energy harvesting, domestic heating, energy efficiency

INTRODUCTION

Conventional heating systems such as radiators and fan coils are mainly based on convective heat transfer. The operating principle of both systems is conceptually the same; that is, in both cases, the heat coming from the heating system (boiler, heat pump…) is transferred to the environment through radiators or fan coils. The main difference is that radiators are passive elements through which heat is transferred to the room thanks to natural convection phenomena and fan coil units are fitted with a fan, which forces the air into the heat exchanger (forced convection) in such a way that a greater heat transfer to the room is achieved, allowing a more rapid homogenisation of the room temperature. In return, in contrast to radiators, fan coils require some electricity consumption and a nearby wall outlet.

The fact of forcing the heat transfer process, reducing the time to homogenize the room temperature, results in a shorter operating time of the boiler or heat pump and, therefore, in an increase of the overall efficiency of the heating system.[1–3] In other words, if homogenisation time is maintained, the required water temperature will be lower with the consequent reduction in energy consumption. Codecasa[4] states that the use of a fan convector to force air through the heat exchanger can increase comfort, reduce temperature stratification, and improve heating efficiency from 85% to 91%.

One way to generate electricity from heat or from a difference of temperature is the use of the thermoelectric effect. Thermoelectric generators are devices that use the Seebeck effect, converting heat (temperature differences) directly into electrical energy. As the heat flows from hot side to cold side, free charge carriers (electrons or holes) in the material are also driven to the cold end. The

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resulting DC voltage is proportional to the temperature difference via the Seebeck coefficient. The beauty of a thermoelectric device is that it has no moving parts, making it extremely durable and easy to produce compared to conventional generation technologies.

In the study of the state of the art carried out to date, an interesting market niche has been identified, since no heating systems have been found that try to combine the advantages of the two mentioned technologies and that is directly installable in a household heating system replacing conventional radiators. RadFan[5] and Radiator Booster[6] are innovative gadgets that redirect the heat and blow it out towards the room in order to improve the room temperature homogenization. But both need a mains supply to power a fan. Codecasa[4] introduce a thermoelectric cogenerator device integrated into a self-standing natural combustion gas stove; however, it has not been conceived for replacing conventional radiators. For that reason, this work is focused on the development of a new concept of a heating device, an off-grid thermoelectric fancoil for domestic applications to replace the conventional radiator (Fig. 1).

In this paper, a new heating device based on thermoelectricity, that combines the advantages of both radiators and fancoils is presented. This new system exploits the heat coming from the heating system to generate electricity, which is consumed in situ to power a fan, eliminating the need for a nearby wall outlet. Montecucco et al.[7] consider this kind of system, where all the heat flowing through it is used for household purposes, 100% efficient, despite the low efficiency of thermoelectric generators. For this purpose, a laboratory prototype has been built and experimental characterization has been carried out.

MATERIALS AND METHODS

Laboratory Prototype

The laboratory prototype consists of a liquid to liquid thermoelectric generator integrated into a commercial fancoil (Fig. 2) which has an AC fan and a heat exchanger. The hot water coming from the heating system enters the hot side of the thermoelectric generator. The heating system is composed of a water tank and an electrical resistance, which is powered by means of a PID temperature controller and tries to simulate a conventional heating system such as a conventional boiler. This way, it has been

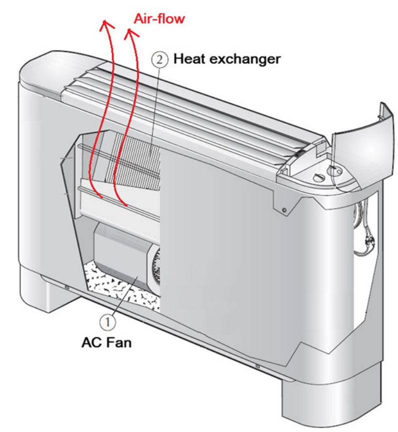

Fig. 2. Commercial fancoil from Aermec company.

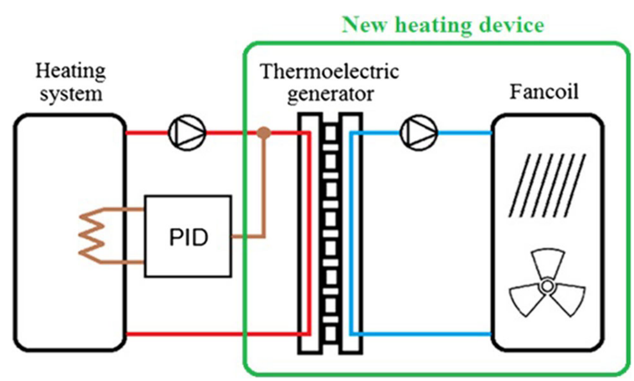

Fig. 3. Scheme of the new heating device: a thermoelectric generator integrated into a fancoil.

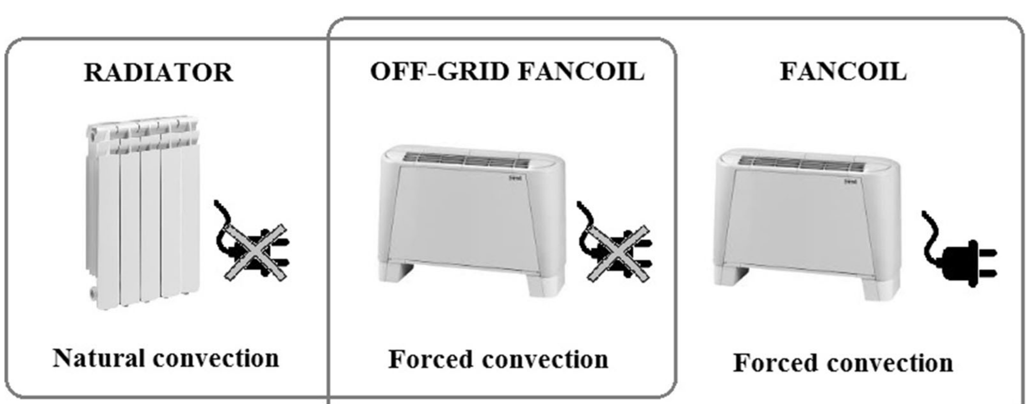

Fig. 1. Graphic representation of the new concept.

possible to set up different values for inlet water temperature for the thermoelectric generator.

An independent cooling circuit is responsible for transferring the heat from the cold side of the thermoelectric generator to the room thanks to a commercial fancoil and, an auxiliary pump. The commercial fancoil is shown below, and it includes a heat exchanger and an AC fan. Also shown is the air flow direction (Fig. 3).

K-type thermocouples have been used for measuring water inlet and outlet temperatures for both circuits, hot and cold.

The thermoelectric generator is made up of 16 Bi-Te based modules with 241 thermoelectric pairs and dimensions of 55 mm × 55 mm per module.

Characterization Test Bench and Laboratory Tests

The prototype has been mounted into a laboratory test bench. Voltage and cold side temperature have been measured for different hot water inlet temperatures, cooling circuit flow rates, and different electrical loads. Variations of these parameters have been continuously recorded and monitored by means of a DAQ system and a tailor-made Labview program.

First of all, several tests have been carried out in order to characterize the thermoelectric system. For that, the AC fan has been powered by an external power supply. Once the characterization has been done, a proper DC fan has been selected and integrated into the new system. The performance with the new fan has been analyzed by means of several heating–cooling tests.

EXPERIMENTAL RESULTS AND DISCUSSION

Characterization of the Thermoelectric Generator

Hot water flow rate coming from the domestic heating system is an independent variable that cannot be controlled by the thermoelectric heating device. However, the flow rate of the cooling system depends directly on the selected pump and the pressure drop along the cooling circuit. For that reason, first of all, the influence of cooling water flow rate and hot side temperature on the output power have been analyzed.

Hot water flow rate is 4.5 L/min for every test, and cooling water temperature is a result of thermal balance. Output voltage has been measured for open circuit and electrical loads of 10 Ω, 22 Ω, 50 Ω and 100 Ω. The results are shown below:

Figures 4, 5, 6 and 7 show power-current diagrams obtained for different tests. Both, the output power and the current, are obtained analytically by means of Ohm's law considering the measured value of the output voltage and the value of the electrical load, which is known. These results confirm that the output power increases with the temperature difference between the hot and cold side of thermoelectric modules. It is also demonstrated that the cooling water flow rate has an important influence on the output power. However, it seems that the lower the cooling water flow rate, the lower the influence.

Considering the most realistic working conditions for a domestic heating installation (hot water temperature between 60°C and 80°C), it is possible to conclude that the maximum output power could range from 3 W to more than 5 W depending on the cooling water flow rate.

The definition of the fan and its operating conditions are directly conditioned by the required time to homogenize the room temperature and the required thermal comfort level, which depends, among others, on the air flow rate and its temperature. For that reason, in the present study, the influence of fan speed and therefore, the influence of the air flow through the fan coil heat exchanger, in the output power has been also analyzed. Comfort parameters will be studied in future works (Fig. 8).

The AC fan included in the commercial fancoil can run at three different speed levels, I, II and III, driving 80 m^3/h, 120 m^3/h and 180 m^3/h of air, respectively, and the maximum input power is 18 W. Although the results above show that the thermoelectric system would not be able to power the AC fan in any of the studied regimes, it has been used and powered with an external power supply, with the only purpose being the thermoelectric system characterization. The output power for these three levels of speed have been measured. The cooling water flow rate has been maintained constant to 3 L/min for every test. Results are shown below:

Obtained results (see Figs. 9 and 10) show that the power output is similar for the three speed levels. However, if the fan is switched off, it is drastically reduced. This happens because the heat transferred to the room is interrupted with its subsequent increase of cooling water temperature and therefore, decrease of temperature difference between hot and cold side of thermoelectric modules.

Performance of the System with a DC Fan

Characterization results show that the thermoelectric system is not able to power the AC fan of the fancoil unit in any of the studied regimes. For that reason, in this stage, a new DC fan has been selected and integrated into the system. Thus, there is avoided the need for a DC–AC converter which would make the system much more expensive and less competitive in the market.

First, the DC fan has been powered by an external DC power supply in order to compare the power-

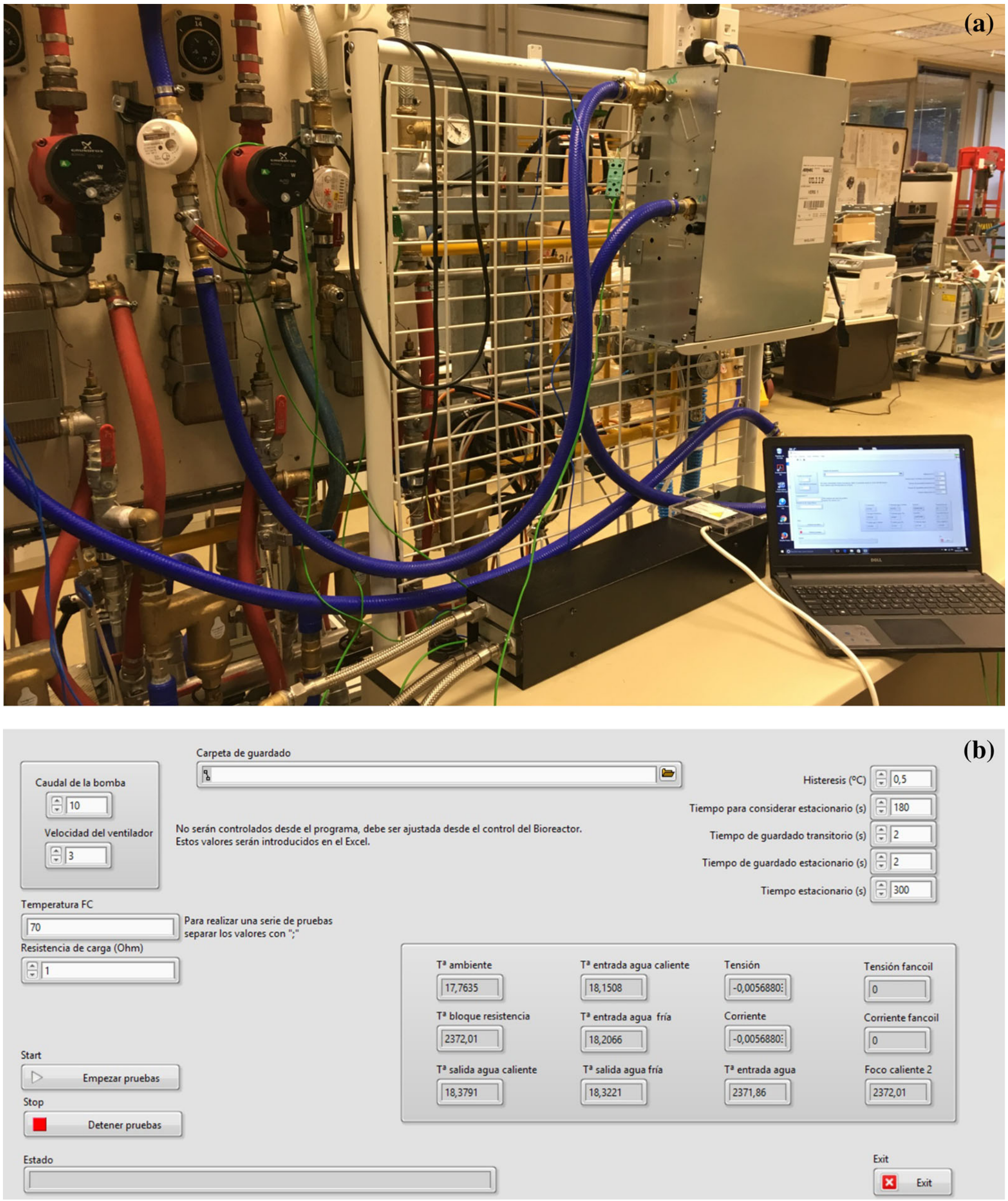

Fig. 4. (a) Test bench and (b) tailor-made measurement system.

current diagrams with those obtained with the AC fan. The selected fan is an axial 12 V-DC axial fan with a maximum power consumption of 5.4 W, 3100 rpm and maximum flow rate of 184 m^3/h.

Tests for 70°C and 65°C for hot water mean temperature and 3 l/min for cooling water flow rate have been performed and plotted together with previous results for comparison.

Due to the lower flow rate driven by the DC fan, the thermal balance is achieved for higher cold side water mean temperatures: 37°C instead of 35°C for results shown in Fig. 11 and 39°C instead of 34°C for results shown in Fig. 12. Thus, the temperature difference between the hot and cold side of thermoelectric modules is lower with DC fan than with AC fan, which justifies the lower output power. It is also shown that the maximum output power of the thermoelectric generator decreases around 15% for the 70°C test and 28% for the 65°C test, but maximum power consumption of the fan is reduced to more than the third part, from 18 W to 5.4 W (reduction of 70%).

After this comparison the DC fan has been powered directly through the thermoelectric generator and several heating–cooling tests have been carried out in order to analyze the behavior of the overall system. The test consisted of a heating process up to 70°C of hot side mean temperature, a

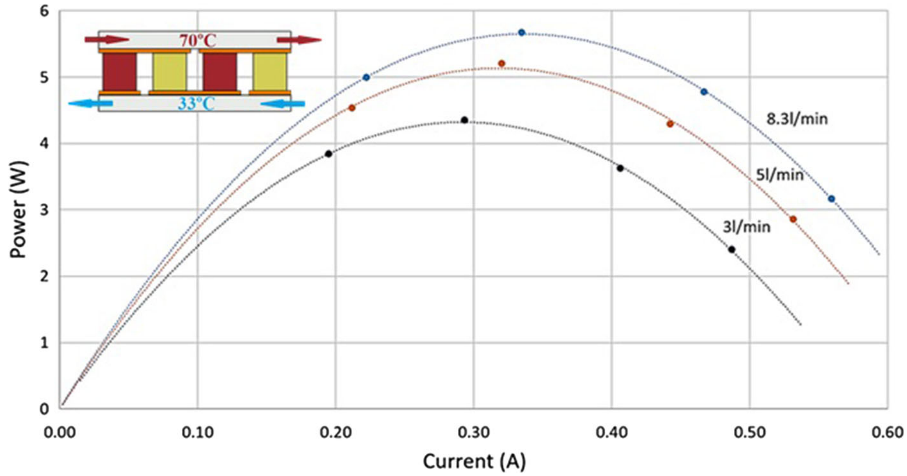

Fig. 5. Analysis of the influence of flow rate on power generation for a hot side mean temperature of 70°C.

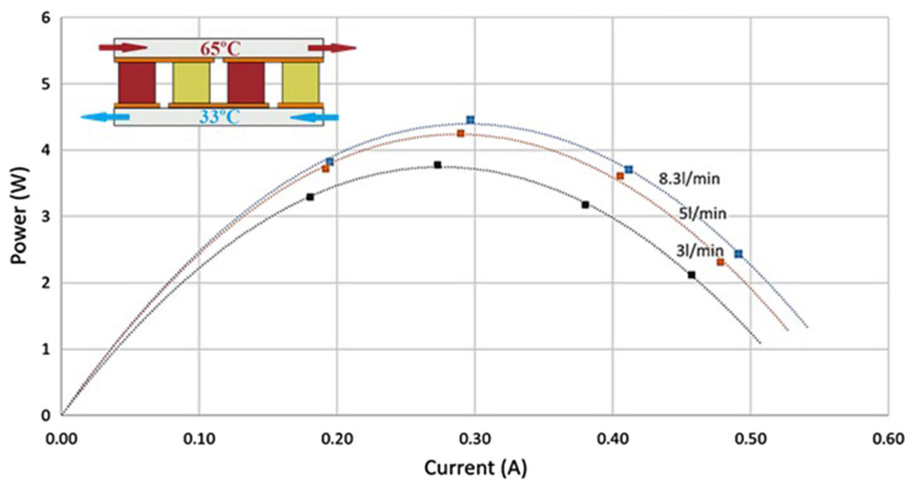

Fig. 6. Analysis of the influence of flow rate on power generation for a hot side mean temperature of 65°C.

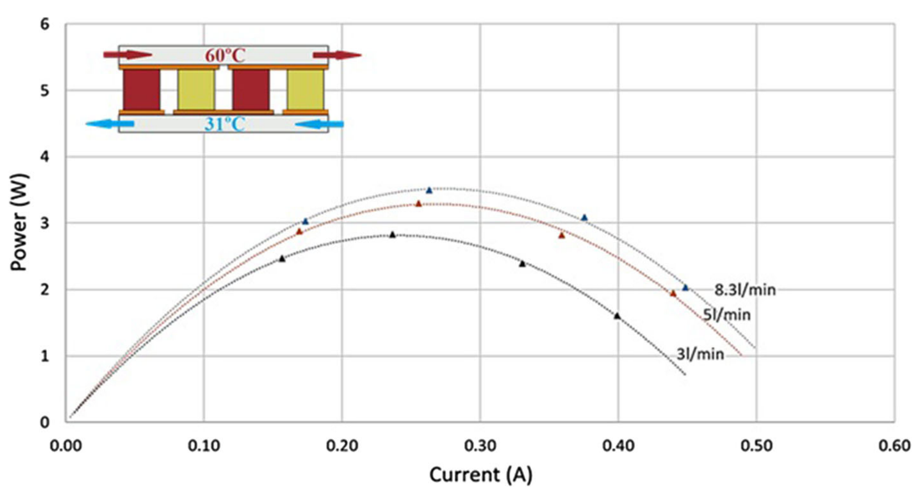

Fig. 7. Analysis of the influence of flow rate on power generation for a hot side mean temperature of 60°C.

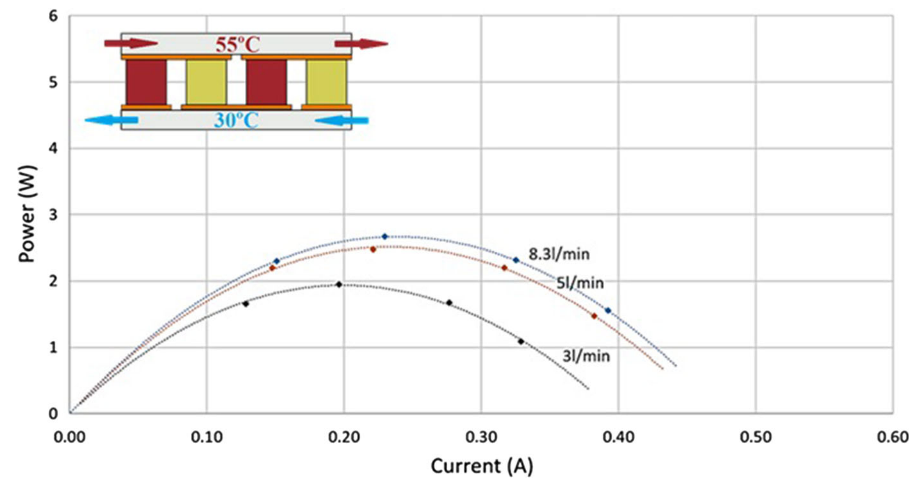

Fig. 8. Analysis of the influence of flow rate on power generation for a hot side mean temperature of 55°C.

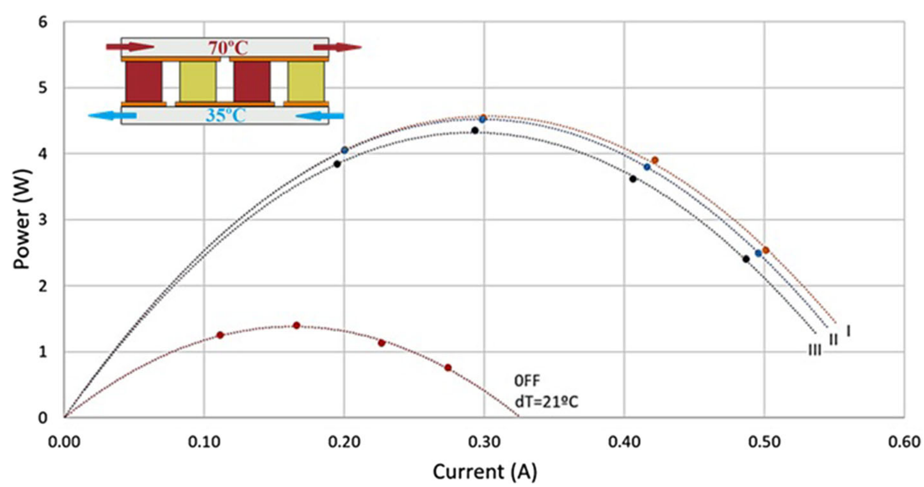

Fig. 9. Analysis of the influence of fan speed on power generation for a hot side mean temperature of 70°C.

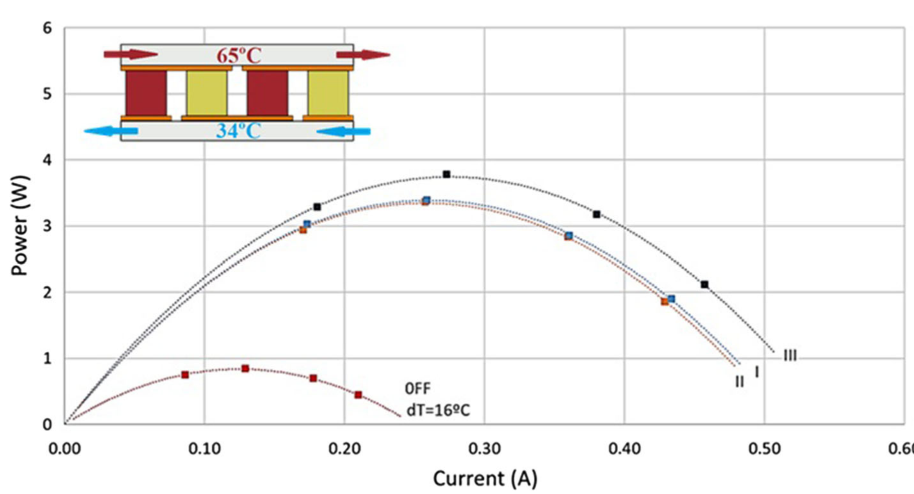

Fig. 10. Analysis of the influence of fan speed on power generation for a hot side mean temperature of 65°C.

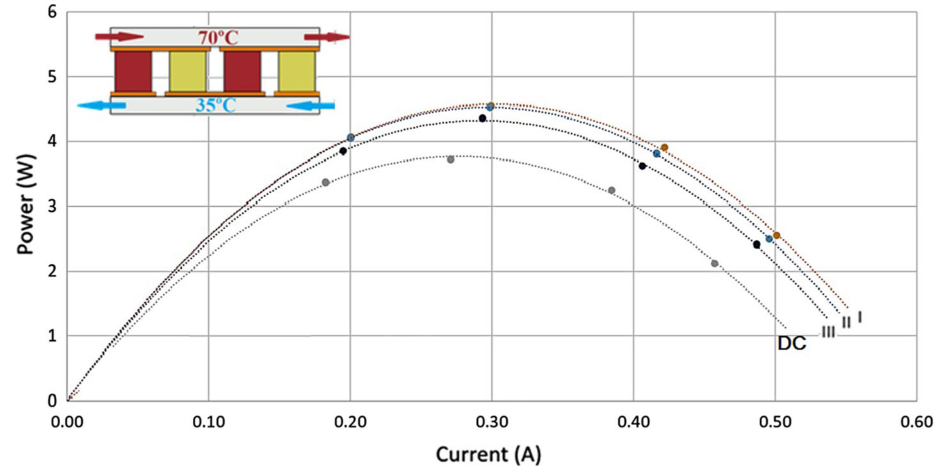

Fig. 11. Comparison of power-current diagrams for I, II, III levels of speed for AC fan and DC fan for a hot side mean temperature of 70°C.

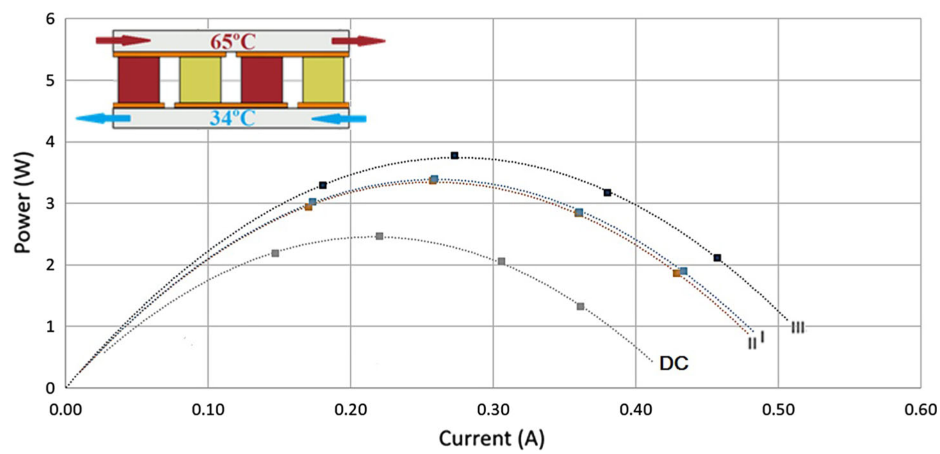

Fig. 12. Comparison of Power-Current diagrams for I, II, III levels of speed for AC fan and DC fan for a hot side mean temperature of 65°C.

steady-state period and a cooling down process until detecting that the generated power is not enough for moving the fan.

Room temperature, hot and cold side inlet and outlet temperatures, and voltage and current supplied to the fan have been measured during tests. Results are shown below:

Figure 13 shows that the voltage supplied to the fan increases fast during the first seconds of the test. This happens because the temperature difference between the hot and cold sides of the thermoelectric modules increases fast as well during this period. When the output voltage reaches the value of 6 V, the fan starts to move. Then the voltage drops down to around 4 V because of the impedance of the fan. After 25 min, the maximum output voltage and maximum power is reached, and it tends to stabilize to 8.8 V and 2.7 W, respectively, from there as it is shown in Fig. 14.

It can be appreciated that the voltage signal has an important noise while the fan is running. It is due to the electromagnetic noise introduced by the coils of the fan motor.

As it is shown in Fig. 14, the water mean temperature of the cold side of thermoelectric generator, is around 40°C during the steady-state period. This water is the one who passes through the fancoil heat exchanger and that carries the heat that will be transferred finally to the room. The temperature of the driven air will depend on that water temperature and on the air flow rate, among others, and at the same time, all these operating conditions will result in a determined comfort level for the user. This comfort level is the key factor which will make the system suitable or unsuitable for domestic applications. This point will be analyzed in future works.

Figure 15 shows that the voltage supplied to the fan starts to decrease as the temperature difference between the hot and cold sides of the thermoelectric modules goes down. When the voltage supplied to the fan drops below 4 V, the

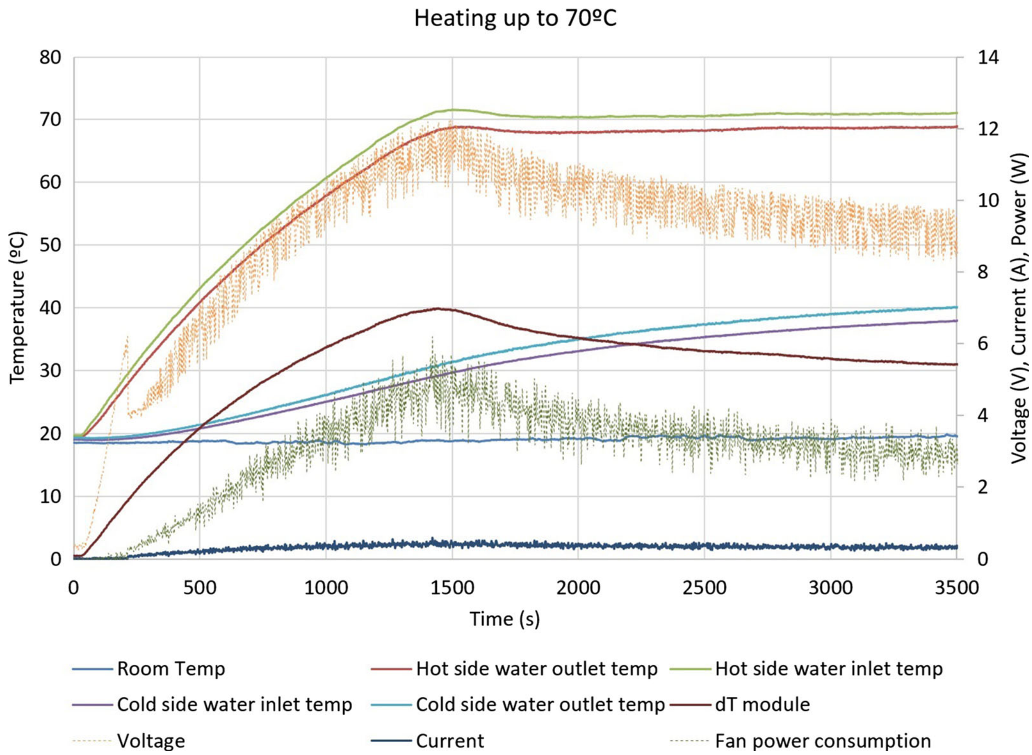

Fig. 13. Heating up process up to a hot side mean temperature of 70°C.

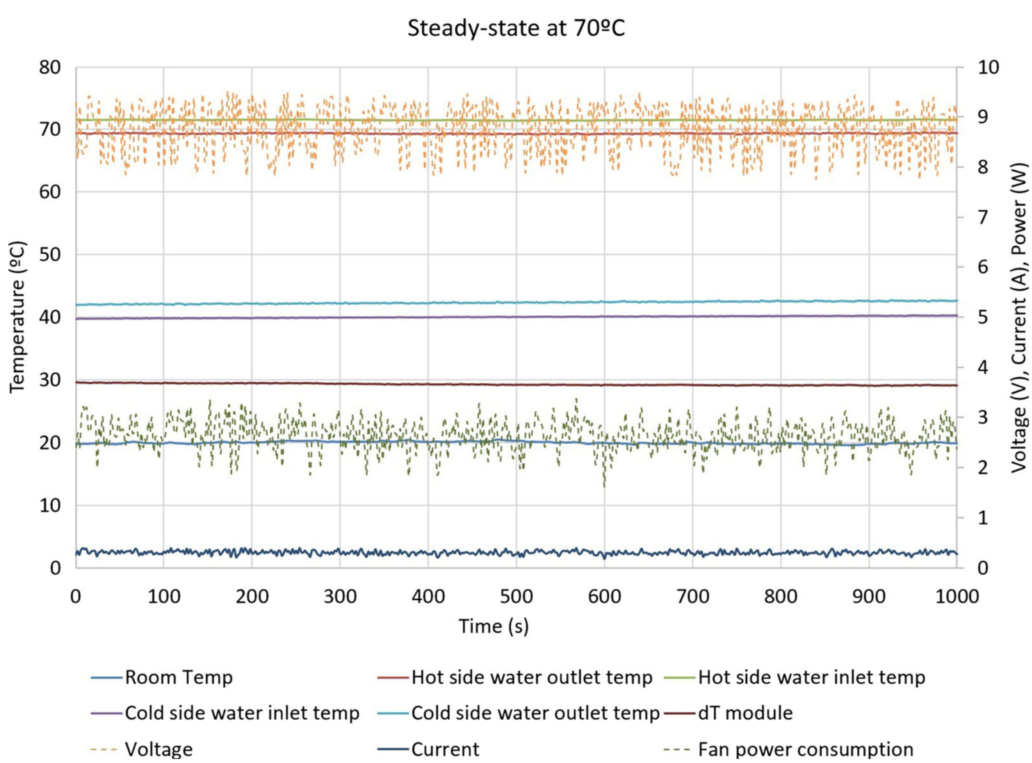

Fig. 14. Steady state at a hot side mean temperature of 70°C.

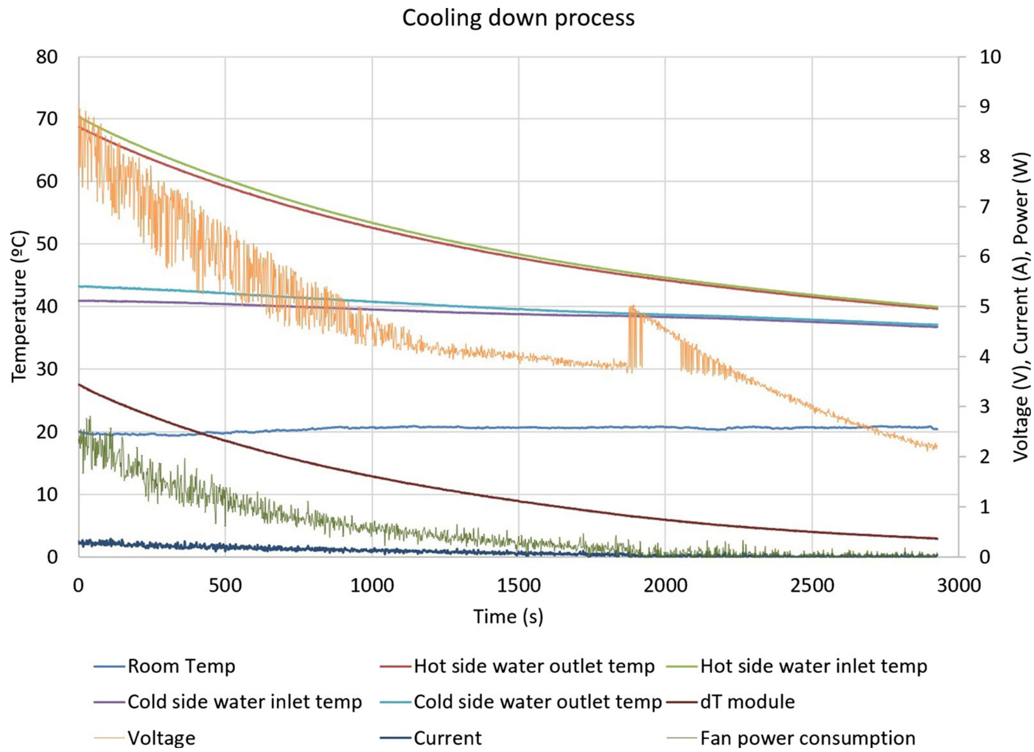

Fig. 15. Cooling down process.

fan stops and immediately the available voltage increases again to 5 V.

CONCLUSIONS AND FUTURE WORK

Cooling water flow rate and air flow rate through the heat exchanger condition the thermal balance in the system and, therefore, the output power of the thermoelectric device. In order to develop a competitive thermoelectric fancoil for domestic applications, a balance between cost and comfort should be achieved. Cost is mainly related to the size and number of thermoelectric modules. Comfort is dependent, among others, on the temperature and the velocity of the driven air towards the room, which are affected by the operating conditions of the pump and fan. As both, pump and fan, need to be powered directly by the thermoelectric generator, lowest power consumption devices working on DC, that assure the required comfort level, should be selected. Thus, the quantity of necessary thermoelectric modules, and; therefore, the overall cost are kept at minimum.

In this work, the characterization of a thermoelectric generator has been carried out and a proper DC fan has been selected to implement into the system. The performance of the system has been analyzed with this new fan and results show that the thermoelectric generator can directly run the selected DC fan. The comfort level that will provide this system will be analyzed and compared with conventional heating systems such as radiators in future works because that is the key factor which makes the solution suitable or unsuitable for domestic applications.

From the present study, a modular thermoelectric generator solution is going to be implemented in order to arrange the maximum amount for a thermoelectric heating device that is adequate for the most common domestic room sizes. This modular thermoelectric generator is going to be redesigned according to the results of the present work and cost and space requirements.

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REFERENCES

1. Panasonic, Nuevo Aquarea Air, el fancoil-radiante. (Panasonic Marketing Europe GmbH, 2018). http://www.aircon.panasonic.eu/ES_es/happening/nuevo-aquarea-air-el-fancoil-radiante/ Accessed 7 June 2018.
2. HTP Comfort Solutions. HTP Ultra-Thin Hydronic Fan Coil. (HTP Comfort Solutions LLC, 2018). http://www.htproducts.com/fan-coil.html Accessed 16 February 2018.

3. 123 Zero Energy. Ultra-Thin Fan Coil Unit. (123 Zero Energy, 2018). https://www.123zeroenergy.com/ductless-split-fan-coil.html Accessed 17 February 2018.
4. M.P. Codecasa, C. Fanciulli, R. Gaddi, F. Gomez-Paz, and F.J. Passareti, *Electron. Mater.* (2015). https://doi.org/10.1007/s11664-014-3297-9.
5. The Radfan—Proven Energy Savings (HeatwaveUK Ltd, 2018). https://www.radfan.com Accessed 28 May 2018.
6. Radiatorbooster (Radiatorbooster, 2018). https://radiatorbooster.com/ Accessed 6 June 2018.
7. A. Montecucco, J. Siviter, and A.R. Knox, *Appl. Energy* (2017). https://doi.org/10.1016/j.apenergy.2015.10.132.