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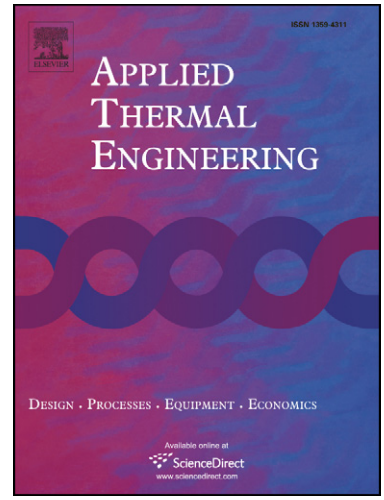

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DEVELOPMENT OF A THERMOELECTRIC REFRIGERATOR WITH TWO-PHASE THERMOSYPHONS AND CAPILLARY LIFT.

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Abstract

A thermoelectric domestic refrigerator has been developed, with a single compartment of 0.225m^3, for food preservation at 5ºC. The cooling system is made up of two equal thermoelectric devices, each composed of a Peltier module (50W) with its hot side in contact with a two-phase and natural convection thermosyphon (TSV) and a two-phase and capillary lift thermosyphon (TPM), in contact with the cold side.

The entire refrigerator has been simulated and designed using a computational model, based on the finite difference method. Subsequently an experimental optimization phase of the thermosyphons was carried out, untilthermal resistance values of R_{TSV}=0.256K/W and R_{TPM}=0.323K/W were obtained. These values were lower than those obtained with finned heat sinks.

Finally, a functional prototype of a thermoelectric refrigerator was built, and the results which were obtained demonstrate that it is able to maintain a thermal drop (Ambient Temperature – Inside Temperature) of 19ºC. The electric power consumption at nominal conditions was 45W, reaching a COP value of 0.45. The study demonstrated that by incorporating these two-phase devices into thermoelectric refrigeration increases the COP by 66%, compared with those which use finned heat sinks.

Keywords: Thermoelectricity, simulation, refrigeration, Peltier, two-phase, capillarity

1. INTRODUCTION

In all refrigeration systems, heat exchange plays a fundamental role in the COP value of the devices. In vapour compression and absorption systems phase changing fluids are used, taking advantage of the good heat transfer coefficients produced, not only during the condensation but also during the evaporation.

Thermoelectric refrigerators are composed of the so-called Peltier modules, whose most notable physical phenomena are: Seebeck, Peltier, Joule, Thompson and Fourier effects [1]. Aluminium heat sinks, with or without fins and with one or several fans for moving the air, are used for heat transfer, both in the cold and hot sides of the Peltier module. This is shown in applications such as those presented in references [2] and [3]. There are also heat exchanges with a fluid inside (water or water with ethylene glycol). In both cases there is no two-phase, and the efficiency in the heat transfer is poor, achieving very high thermal resistances, even when specific optimizations have been carried out, such as those presented in references [4] and [5]. This is mainly due to the problem caused by the high heat flow produced in the hot and cold sides of the Peltier module (up to 40600 W/m^2). Consequently, the thermal resistances produced in thermoelectric refrigeration are very high, and this causes much lower COP values than the ones obtained in vapour compression refrigeration.

The influence of heat dissipation on the COP of Peltier modules was shown in reference [6]. In this regard, a two-phase thermosyphon system (TSF), with incorporated fan, for the hot side of the Peltier module was developed, as shown in reference [7]. It improved the thermal resistance by 36% in comparison with a finned heat sink. Also another thermosyphon with two-phase and capillary lift (TPM) for the cold side of the Peltier module has been developed, improving its thermal resistance by 37% in comparison with a finned heat sink, as shown in reference [8].

Hongxia has conducted a review [9] of thermoelectric refrigeration devices, where Riffat et al's work is worth noting [10], in which a heat pipe is used in the hot side and a PCM thermosyphon in the cold side of the Peltier module.

The improvement of these devices in order to transfer heat from the Peltier module, and its application to a domestic refrigerator, is the principal aim of this work. A two-phase thermosyphon, without moving parts, has been designed to improve the heat transfer from the hot side of the Peltier module, as well as an original assembly system, which allows for easier assemblies and avoids the appearance of thermal bridges which are produced in the screw joint of finned heat sinks.

2. OBJECTIVES

The overall aim of this work is to design a domestic refrigerator, without moving parts, whose cooling system is based on thermoelectric technology and two-phase thermosyphons.

In order to achieve this overall aim the following specific objectives have been put forward: :

- Numerical simulation of the entire thermoelectric domestic refrigerator.
- Application of the thermosyphon with two-phase and capillary lift (TPM) design, on the cold side of a thermoelectric module.
- Design and optimization of a thermosyphon, with two-phase and without fan (TSV) for the hot side of a Peltier module.
- Design of an assembly system which will break thermal bridges and make assembly easier.
- Design and construction of a thermoelectric domestic refrigerator prototype, which incorporates TPM systems, Peltier modules, TSV devices and assembly system. Experimental analysis of the improvement obtained in its COP.

3. THERMOELECTIC REFRIGERATOR DESCRIPTION

This is a domestic refrigerator with a single refrigerator compartment of 0.225 m^3 whose cold production system uses thermoelectric modules coupled to thermosyphons (TPM and TSV) without moving parts. The refrigerator is specifically composed of two identical thermoelectric devices, as shown in Figure 1, which consists of:

- A 40*40mm and 50W maximum power Peltier module, Marlow 6L model.
- A thermosyphon, with two-phase and capillary lift (TPM), with the cold extender incorporated, for the cold side of the Peltier module. This device was

presented in [8].

- A thermosyphon, with two-phase without moving parts (TSV), to dissipate the heat from the hot side of the Peltier module.

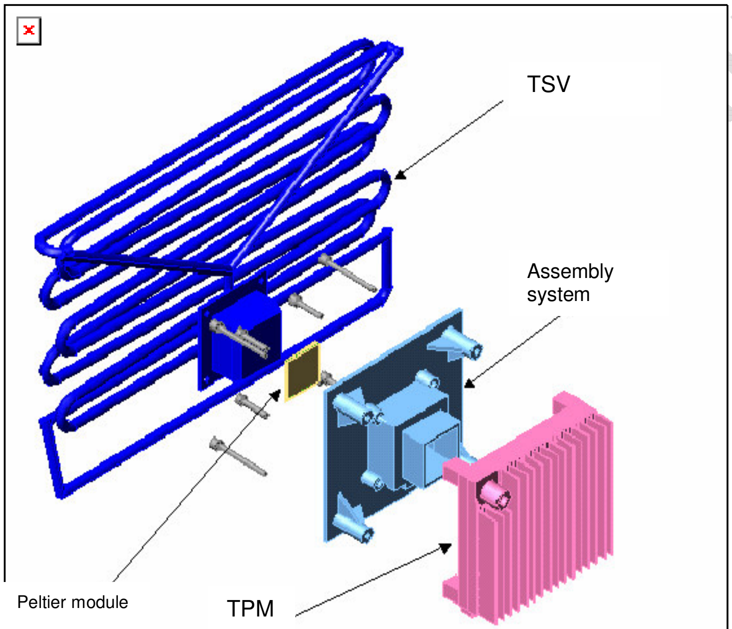

Figure 1. Thermoelectric device composed of: Peltier module, TPM, assembly system and TSV.

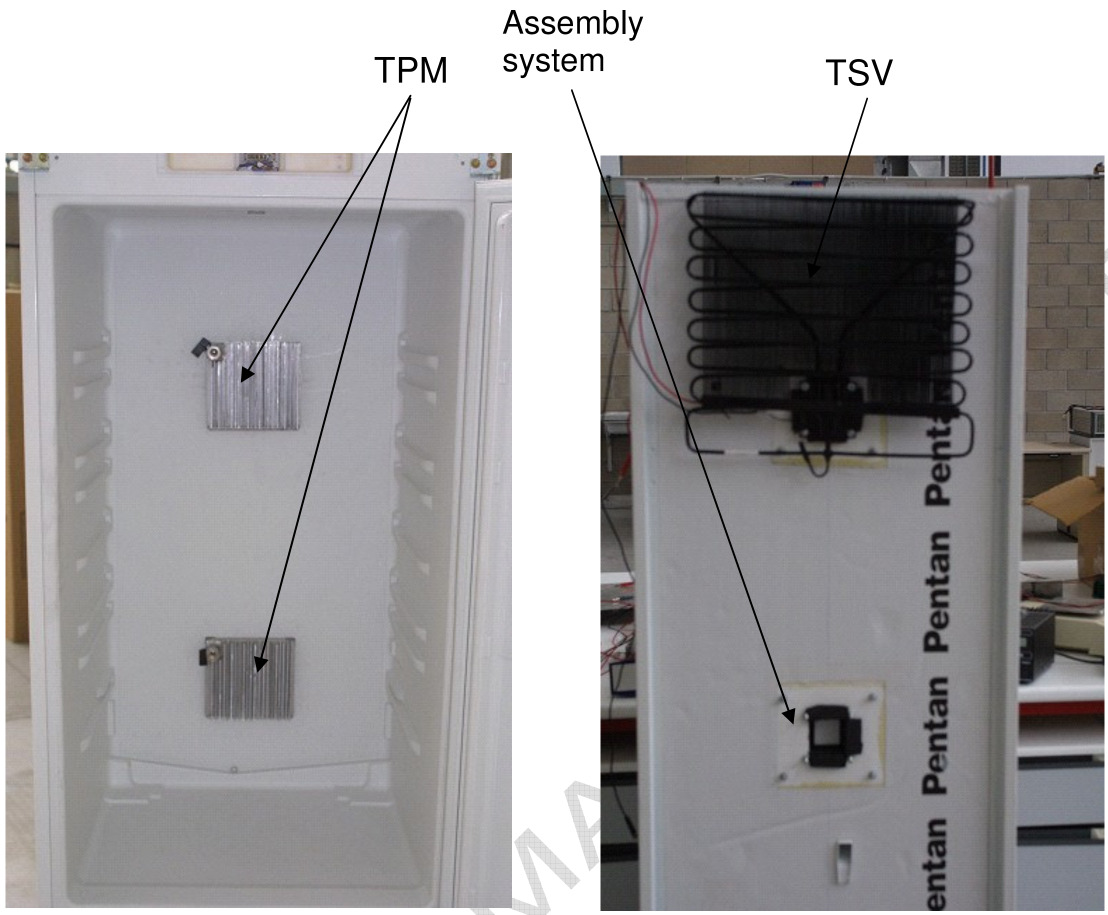

Figure 2. Photographs of the thermoelectric domestic refrigerator prototype with its thermosyphons.

For the construction of this thermoelectric refrigerator, we started with a vapour compression commercial domestic refrigerator from Bosch-Siemens, *BOSCH KGP39*. The entire cooling system (evaporator, compressor, condenser and valves) was removed, leaving only the appliance casing.

Two photographs, of the thermoelectric domestic refrigerator prototype, are shown in Figure 2, where the TPM, the TSV and the assembly part incorporated in the refrigerator furniture can be seen.

3.1. Two-phase thermosyphon without fan (TSV)

The operating principle of the TSV is based on a steel tank, whose volume is a right angle prism, with a fluid inside (see Fig. 1). The Peltier module is placed on the outside part of this tank's back wall. The hot side of the Peltier module, which is in contact with this wall, transfers the thermal power produced by the module, to the tank. The heat dissipated is thus transmitted to the inner fluid, which leads to its boiling. The vapour which is generated by the boiling rises by natural convection towards the top of the thermosyphon where it comes into contact with a coil composed of steel tubes, through which the vapour flows. When the vapour makes contact with this coil (which is located on the outside of the refrigerator), it condenses and returns by way of gravity in a liquid state to the bottom, returning once again to the tank and forming, in this way, a closed and self-powered cycle.

The TSV uses the specific latent heat of two-phase, in the boiling process as well as during condensation, in order to dissipate the heat efficiently, enabling it to spread from a small hot surface (40*40mm of the Peltier module) to a large one (the entire coil of the thermosyphon). This effect is shown in the thermographs of Figure 3, taken from both the TSV and a finned heat sink without thermosyphon. These thermographs demonstrate how the TSV device spreads the heat flow over the entire area, while in the finned heat sink the heat flow is concentrated in the area near the Peltier module.

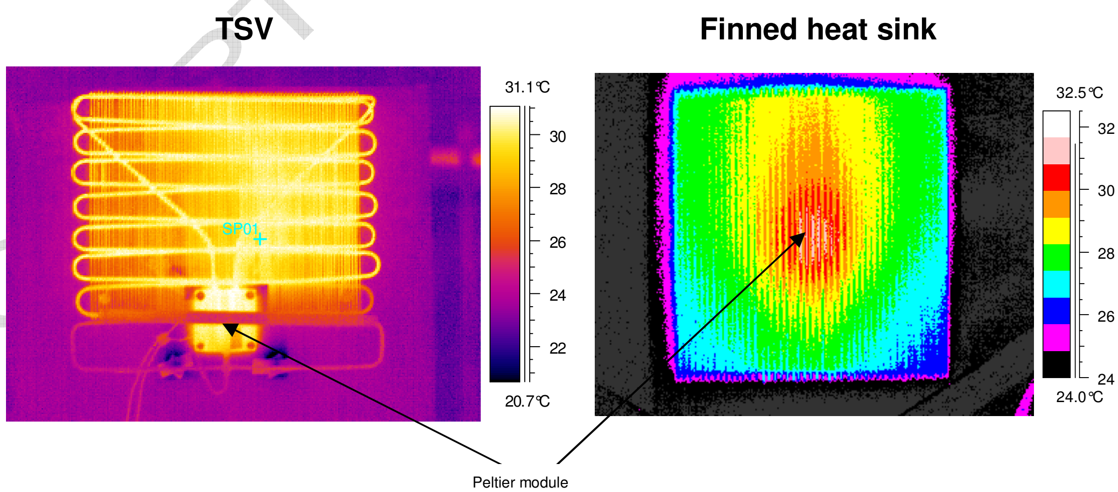

Figure 3. Comparison of TSV and finned heat sink thermographs, with a 50W Peltier module

The main contribution of this TSV device, as regards its predecessor TSF, which has been presented in [7], is the fact that the change of plane geometry for tubular geometry has allowed us: on one hand, to use ammonia as refrigerant, given that this geometry withstands higher pressures, and, on the other hand and more importantly, the fluid condensation area has been greatly increased. This enables it to be operated without an exterior fan. This makes the system cheaper and quieter, by removing all the moving parts in a domestic refrigerator.

3.2. Assembly system.

The assembly system, which allows us to join the heat exchanger of the cold side (TPM) with the Peltier module and the heat exchanger of the hot side (TSV) in the thermoelectric domestic refrigerator prototype, is based on an injected plastic part, which lodges the Peltier module. This plastic part, which contains the three elements mentioned above, is incorporated in the foam of the prototype furniture. This way, the thermosyphons and the Peltier module can be put in and removed easily, as shown in Figure 1. The designed plastic part not only fulfils the assembly function, but it also breaks the thermal bridge produced in the current assembly systems, because in these systems, the hot side of the heat sink is joined to the cold side of the dissipater by screws.

4. METHODOLOGY

A numerical simulation was made with a computational model, which was developed in [11], for the purpose of determining the number of Peltier modules required for this application. This model simulates the entire refrigerator, that is, the appliance casing, Peltier modules and its heat sinks, as well as the thermal bridges produced by conventional assembly systems with screws. The model provides us with information about the total electric power consumption of the thermoelectric refrigerator and, thus, of the expected COP also by incorporating the above-noted thermosyphons instead of the conventional finned heat sinks.

4.1. Methodology for the experimental analysis of the hot side thermosyphons

A series of tests were carried out for the experimental study of the TSV, whose primary objective was to learn about its thermal resistance, based on the following expression:

$$R = \frac{(T_h^p - T_{amb})}{\dot{Q}_h^p} \tag{1}$$

To obtain these thermal resistance values, it is necessary to know both the temperature of the hot side of the Peltier module (T_h^p) and the ambient temperature (T_{amb}), as well as the thermal power dissipated by the hot side of the Peltier module ($\dot{Q}_h^p$). Thermocouples were placed to measure these temperatures. However, the precise measurement of the heat flow presents greater technical difficulties. Its calculation is based on the first law of thermodynamics regarding energy and steady state , applied to the Peltier module:

$$\dot{Q}_h^p = \dot{Q}_c^p + \dot{W}_e^p \tag{2}$$

Insulating the cold side of the thermoelectric module, $\dot{Q}_c^p = 0$ is achieved, and so the expression (2) becomes:

$$\dot{Q}_h^p = \dot{W}_e^p \tag{3}$$

Where:

$$\dot{W}_e^p = V^p . I^p \tag{4}$$

whose magnitudes are easily measured.

4.2. Methodology for the experimental analysis of the thermoelectric refrigerator prototype

The main objective of the thermoelectric refrigerator study was to determine the maximum thermal drop the refrigerator was able to achieve, the electric power consumption and the COP, in different operating conditions. To this end, the prototype was put into a standard climatic chamber, in order to control the ambient conditions. Both the thermal drop and the electric power consumption can be measured directly, however several calculations are necessary to know the COP. The COP calculation for this refrigerating device was based on the following expression:

$$COP = \frac{\dot{Q}_c^p}{\dot{W}_e^p} \tag{5}$$

To determine the refrigeration power of the thermoelectric module, the heat flow entering the enclosure is calculated, since in a steady state it is equal to the refrigeration power. That is:

$$\dot{Q}_c^p = S.U.(T_{amb} - T_{\text{int}}) \tag{6}$$

Where:

$$U = \frac{1}{\frac{1}{h_{\text{int}}} + \frac{e}{k} + \frac{1}{h_{ext}}} \tag{7}$$

Convection coefficients are calculated by using the expression suggested by Parmelee et al. in [12] for a flat plate, disregarding the viscous heating and considering laminar flow, given that the air speeds are small:

$$Nu_L = 0.664.\text{Pr}^{1/3}.\text{Re}_L^{1/2} \quad \begin{bmatrix} 0.6 \le \text{Pr} \le 50 \\ \text{Re} < \text{Re}_{x,c} \approx 5\times10^5 \end{bmatrix} \tag{8}$$

In the event that a fan is not used inside, i.e. natural convection, the expression suggested by Churchill et al. in [13] is used to calculate the convection coefficient:

$$Nu_L = 0.68 + 0.67 Ra_L^{1/4}\left[1+\left(\frac{0.492}{\Pr}\right)^{9/16}\right]^{-4/9} \quad (9)$$
$$\left[0 < Ra_L < 10^9\right]$$

5. RESULTS AND DISCUSSION

An experimental study has been carried out with the TSV which was built, comparing it with its predecessor TFS, whose geometry was flat instead of tubular. The study was carried based on tests performed with both thermosyphons, in natural convection as well as in forced convection, using a fan and a wind tunnel. The results are shown in Figure 4, where it can be observed that both thermosyphons give similar results in forced convection, while in natural convection the thermal resistance of the TSV is much lower than that of the TSF. In addition, the thermal resistance value of the TSV in natural convection is good enough for it to be used in the thermoelectric refrigerator, since this avoids the use of two fans.

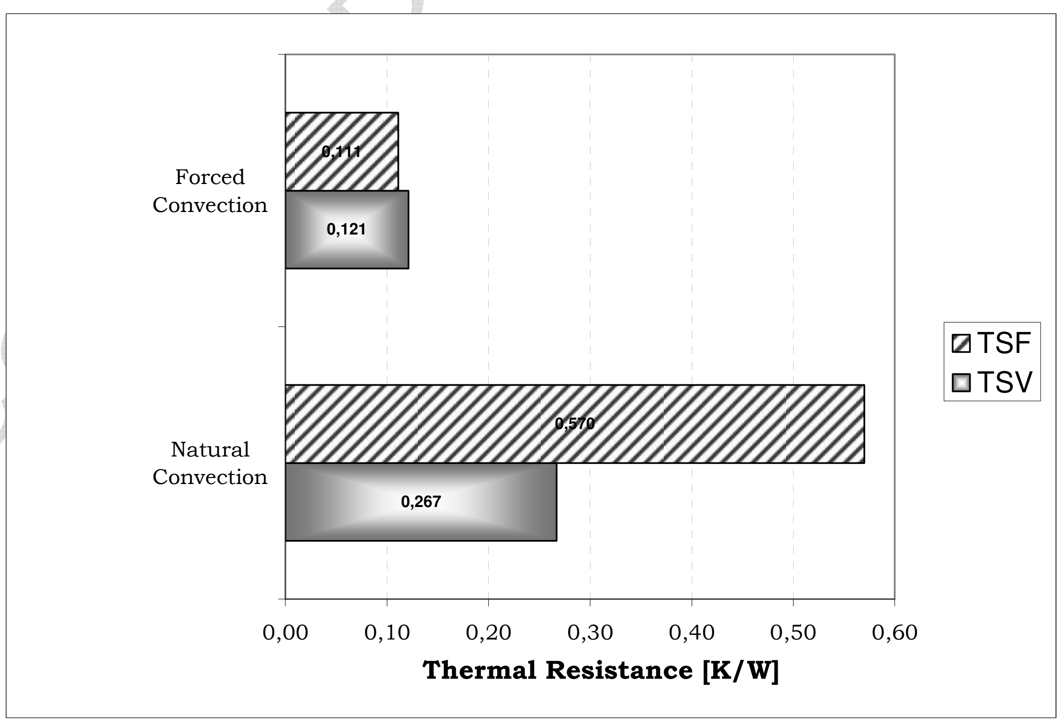

Figure 4. Comparative experimental study of both thermosyphons, in natural and forced convection

The graph, in Figure 4, shows a timeline of the temperatures obtained in a test with the final prototype thermoelectric refrigerator. These tests were carried out at different supply voltages of thermoelectric modules. As expected, the higher the voltage, the greater the thermal drop obtained. It is worth noting that the temperature inside the refrigerator remains constant over time, at a given voltage. This helps considerably in preserving food, unlike vapour compression cooling systems, which follow start-stop compressor cycles that reach temperature variations of up to 8ºC. This is one of the important advantages of the thermoelectric refrigerator, since it is possible to keep the temperature constant just by varying the voltage. The difference between the two interior temperatures, represented in the graph, is due to the stratification caused by the absence of a fan inside, since one of the sensors is placed at the top and the other at the bottom.

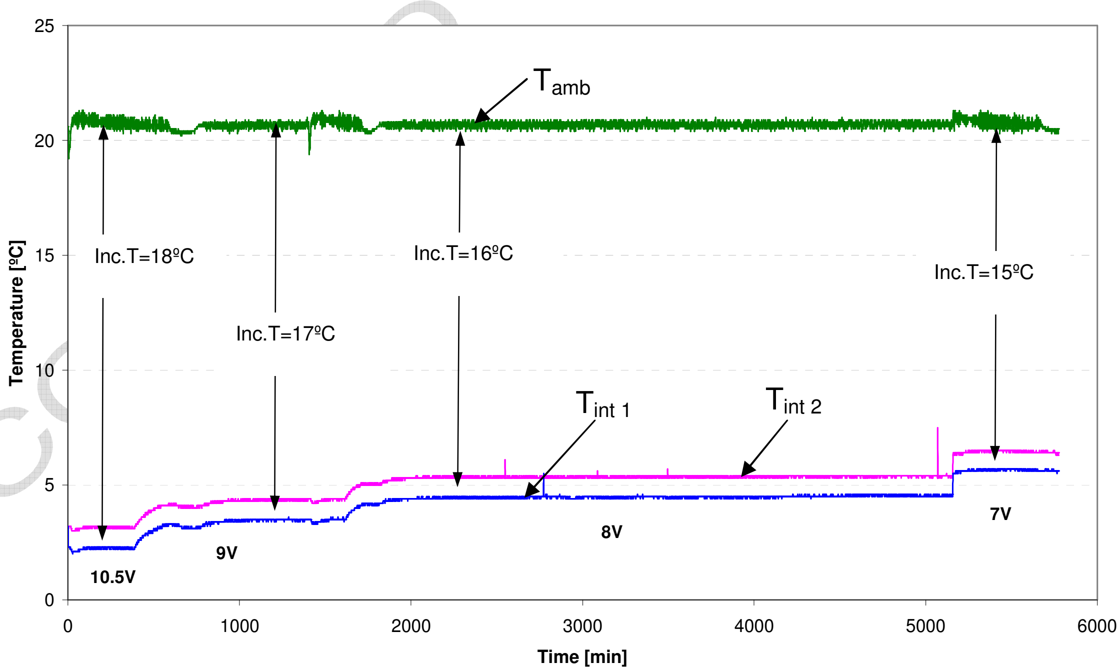

Figure 5. Temperature timeline in the thermoelectric refrigerator prototype, for different voltage ranges applied on the Peltier modules

In Figure 6 can be seen the starting up of the refrigerator without load, for a room temperature of 22ºC after the prototype door was kept open so the inner temperature was the same as the room temperature. It can be noted that after 300 minutes the refrigerator reaches an inner temperature of 6ºC.

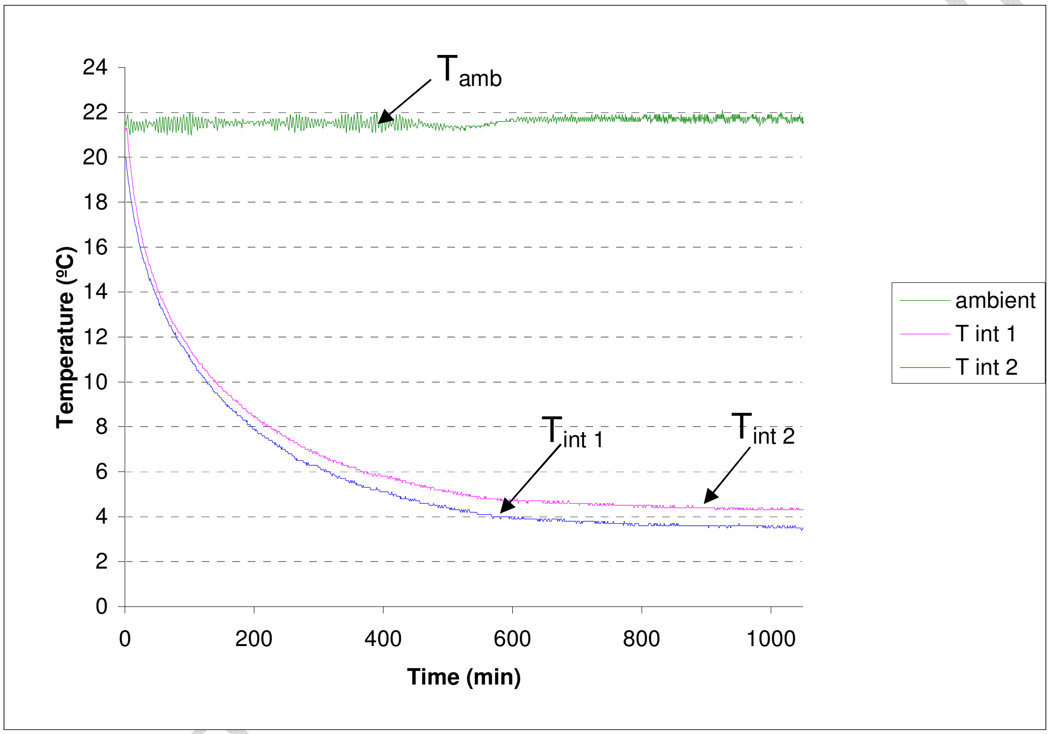

Figure 6. Experimental results of the starting up process of the thermoelectric refrigerator

Table 1 shows the calculated values for steady state. It can be seen that the higher the thermal drop between the inside and the ambient temperature, the higher, understandably, the electric power consumption of the refrigerator. The maximum thermal drop reached is 19ºC, so, if the room temperature is higher than 25ºC, the inner temperature will not reach the desired values for good preservation (as an example, if the room temperature is 30ºC, the inner temperature would be around 11ºC) More interesting is the fact that the COP significantly increases when the Peltier modules supplied voltage decreases. From these values it can be deduced that for nominal working conditions at an ambient temperature of

22°C and 6ºC inside the refrigerator, the total electric power consumption of the refrigerator is 1.08kWh/day (44.9W), and the COP 0.45. This COP value achieved in the thermoelectric refrigerator with the incorporation of the thermosyphons (TSV and TPM), means an increase of 66%, when compared to the value achieved in a thermoelectric refrigerator with finned heat sinks and fan, for the same ambient conditions, which value, COP=0.27, was obtained experimentally in reference [7]. Another advantage is that with the TSV the fans have been completely removed, so it results in a completely noise-free domestic refrigerator.

However, the electric power consumption of the thermoelectric refrigerator (1.08kWh/day) is still much greater than the vapour compression cooling systems consumptions. The same domestic refrigerator model with vapour compression cooling system and rated A needs 0.5kWh/day.

Table 1. Calculated values of the tests with the thermoelectric domestic refrigerator prototype, for steady state

V^p (V)	T_{amb} (ºC)	T_{int} (ºC)	$T_{amb} - T_{int}$ (ºC)	$\dot{Q}_c^p$ (W)	$\dot{W}_e^p$ (W)	COP
12	25,9	7	18,9	24,7	106,1	0,233
10,5	20,6	3	17,6	23,1	77,4	0,299
9	20,8	3,9	16,9	22,2	56,8	0,392
8	20,8	4,9	15,9	20,9	44,9	0,455
7	20,9	6	14,9	19,7	34,5	0,571

6. CONCLUSIONS

A thermosyphon with two-phase, to dissipate the heat from the hot side of the Peltier module, has been developed with a thermal resistance of 0.256K/W and without fan.

A thermoelectric domestic refrigerator with an inner volume of 225. 10^{-3} m^3 has been designed and built. It is composed of two Peltier modules (Marlow 6L), two TSV's and two TPM's, which we have developed. The two TPM's are presented in reference [8]. Its main experimental results can be summarized as follows:

- Maximum thermal drop: 19ºC
- Zero noise (due to the absence of external fans), completely silent
- Electric power consumption in nominal conditions (6ºC inside and 22ºC outside): 1.08kWh/day
- COP value in nominal conditions: 0.45

It has been experimentally demonstrated that, by including the developed thermosyphons (TSV and TPM), there is an increase of 66% in the COP of the thermoelectric refrigerators.

This refrigerator represents an important step in thermoelectric refrigerators due to the development of the two thermosyphons and their assembly. However, using thermoelectricity in domestic refrigeration is far from reaching the values of vapour compression cooling systems. The same domestic refrigerator with a vapour compression cooling system and rated A needs 0.5kWh/day, which represents half the consumption of the thermoelectric refrigerator in the same conditions.

As a result of this research carried out by the research group of the Public University of Navarre, and financed by the multinational Bosch-Siemens, two patents [14] and [15] have been obtained.

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NOMENCLATURE

COP	*Coefficient of performance*	
e	*Thickness*	*M*
h_{int}	*Interior convective heat transfer coefficient*	W/m^2K
h_{ext}	*Exterior convective heat transfer coefficient*	W/m^2K
I^p	*Peltier electric current*	*A*
k	*Thermal conductivity*	*W/mK*
Nu	*Nusselt number*	
Pr	*Prandtl number*	
$\dot{Q}_h^p$	*Peltier module hot side heating power*	*W*
$\dot{Q}_c^p$	*Absorbed by the Peltier module cold side heating power*	*W*
Ra	*Rayleigh number*	
R	*Thermal resistance*	*K/W*
Re	*Reynolds number*	
S	*Surface*	M^2
T	*Absolute temperature*	*K*
T_{amb}	*Ambient temperature*	*K*
T_h^p	*Peltier hot side temperature*	*K*
T_{int}	*Inner temperature*	*K*
TPM	*Thermosyophon with two-phase and capillary lift*	
TSF	*Thermosyophon with two-phase in forced convection (fan)*	
TSV	*Thermosyophon with two-phase in natural convection (without fan)*	
U	*Heat transfer global coefficient*	W/m^2K
V^p	*Peltier supplied voltage*	*V*
$\dot{W}_e^p$	*Electric power consumption of the Peltier module*	*W*