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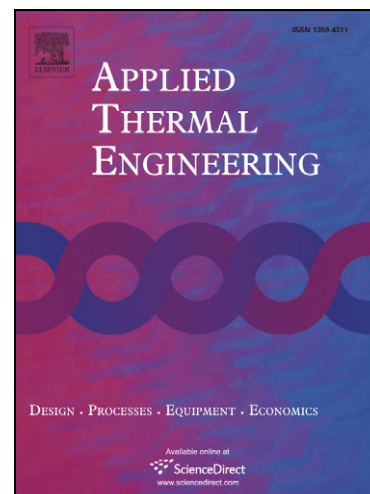
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DEVELOPMENT OF A HYBRID REFRIGERATOR COMBINING THERMOELECTRIC AND VAPOR COMPRESSION TECHNOLOGIES.

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Abstract.

A domestic refrigerator with three compartments has been developed: Refrigerator compartment, at 4°C (vapor compression cooling system); freezer compartment, at -22°C (vapor compression cooling system); and a new super-conservation compartment, at 0°C (thermoelectric cooling system). The thermoelectric system designed for the super-conservation compartment eliminates the oscillation of its temperature due to the start and stop compressor cycles, obtaining a constant temperature and thus, a better preservation of the food.

For the design and optimization of this application, a computational model, based in the numerical method of finite differences, has been developed. This model allows to simulate the complete hybrid refrigerator (vapor compression - thermoelectricity). The accuracy of the model has been experimentally checked, with a maximum error of 1.2°C for temperature values, and 8% for electric power consumption.

By simulations with the computational model, the design of the refrigerator has been optimized, obtaining a final prototype highly competitive, by the features on food preservation and power consumption: 1.15kWh per day (48.1W) for an ambient temperature of 25°C. According to European rules, this power consumption value means that this new refrigerator could be included on energy efficiency class B.

Keywords: thermoelectricity, computational model, refrigeration, Peltier, vapor compression.

1. INTRODUCTION

The cold production is based in a refrigerating machine, with a well known principle of operation. A heat flux is absorbed from a room, and evacuated to the exterior. To make this possible, an energy contribution is needed. There are four main cooling systems: vapor compression, absorption, gas and thermoelectricity. In the absorption systems the energy supply is by a heat flux, in vapor compression and gas is a mechanical power and in the thermoelectric systems is by an electric power.

In domestic refrigerators, the most used cooling system is vapor compression, as it has a good value of C.O.P. However, the control of the temperature inside the cooled compartment is inaccurate, as the compressor makes start and stop cycles, what makes a oscillation in the temperature higher than 8°C, as shown in [1]. This fact has a very damaging effect in the preservation of the food, especially in fishes, meats and fruits.

There are some domestic refrigerators with a new compartment, where the temperature is close to 0°C to improve the preservation of the food. However, as the cooling system is vapor compression, the temperature oscillates significantly (due to the start and stop cycles) not reaching the objective of a proper preservation.

On the other hand, there are thermoelectric refrigerators presented in [2], [3], and [4] with a good control in the temperature of the compartment and, thus, a better preservation of the food. This is due to the fact that it is possible to modify the supplied voltage to the Peltier modules to adjust the cooling power as needed. In addition, these devices are more compact and quiet because they have no moving parts. However, the cooling system has a lower value of C.O.P and thus, high power consumption.

In this work we have developed a domestic refrigerator that combines both technologies (thermoelectricity and vapor compression) in order to join the good C.O.P. values of the vapor compression system with the excellent control of the inside temperature of thermoelectric technology. The prototype is based on a domestic Combi refrigerator (bottom freezer), which includes a new super-conservation compartment, cooled by thermoelectricity.

2. OBJECTIVES.

The main objective of this work is to develop a hybrid domestic refrigerator that combines the cooling technologies of vapor compression and thermoelectricity. This refrigerator will have the following compartments:

- a. Freezer compartment at -20°C , with vapor compression cooling system.
- b. Refrigerator compartment at 5°C , with vapor compression cooling system.
- c. Super-conservation compartment at 0°C , with thermoelectric cooling system.

The maximum oscillation of the temperature is $\pm 0.5^{\circ}\text{C}$.

In order to meet this objective the following specific objectives have been planned:

- Development of a computational model that simulates the complete hybrid refrigerator.
- Adjustment and validation of the computational model.
- Design and optimization of the hybrid refrigerator.

3. DESCRIPTION AND OPERATION OF THE HYBRID REFRIGERATOR.

The prototype is based on a commercial domestic refrigerator from Bosch-Siemens, *BOSCH KGF-39*, with two compartments: refrigerator compartment, with its temperature oscillating around 5°C ; and freezer compartment, with its temperature oscillating around -20°C . Each compartment has an independent cooling vapor compression system. A new compartment of super-conservation, with a constant temperature of 0°C and a maximum temperature oscillation of $\pm 0.5^{\circ}\text{C}$, is added to this refrigerator. This new compartment is placed in the middle of the refrigerator, as shown in Figure 1, and has a thermoelectric technology based cooling system (TEC), [2], [5]. Dimensions and volumes of every compartment are presented in Table 1, along with the thickness values of all the walls.

Table 1. Dimensions of the hybrid refrigerator

COMPARTMENTS			
	<i>Refrigerator compartment</i>	<i>Freezer Compartment</i>	<i>Thermoelectric Compartment</i>
Height (m)	0.750	0.618	0.317
Width (m)	0.458	0.470	0.405
Length (m)	0.460	0.400	0.405
Inner Volume (m ³)	0,1580	0,1162	0,0520
WALL THICKNESSES			
	<i>Refrigerator compartment</i>	<i>Freezer Compartment</i>	<i>Thermoelectric Compartment</i>
Lateral walls (m)	0.060	0.070	0.070
Rear wall (m)	0.065	0.070	0.075
Ceiling wall (m)	0.060	0.062	0.053
Bottom wall (m)	0.053	0.106	0.062
Front door (m)	0.060	0.080	0.080

In the development of the hybrid refrigerator, we considered two different configurations for the thermoelectric modules that control the temperature inside the super-conservation compartment.

3.1. Configuration I

In this configuration, the Peltier modules are placed in the rear wall of the super-conservation compartment, as shown in Figure 1. Thus, when an electric power is supplied to the Peltier modules, these absorb the heat flux from the interior of the compartment and throw it to the exterior. To make this happen, the thermoelectric system has: Peltier modules, a cold extender (that separates the hot side from the cold side), a cold plate (that connects the cold side of the Peltier module and the air inside), and a dissipater (that helps to evacuate the heat absorbed from the inside plus the electric power supplied).

This configuration has the inconvenience that, as the heat from the hot side of the Peltier module is thrown directly to the exterior, the temperature gap between the faces of the Peltier module is higher than 30°C. A consequence of this is that the C.O.P. of the thermoelectric device is very low, as demonstrated in [2] and [5].

One way to improve the C.O.P. value is to make lower the value of the thermal resistance of the heat exchanger on the hot side of the Peltier module. This was achieved by developing a phase-change thermosiphon, [3]. If configuration 1 was chosen, this

phase-change thermosiphon would be used.

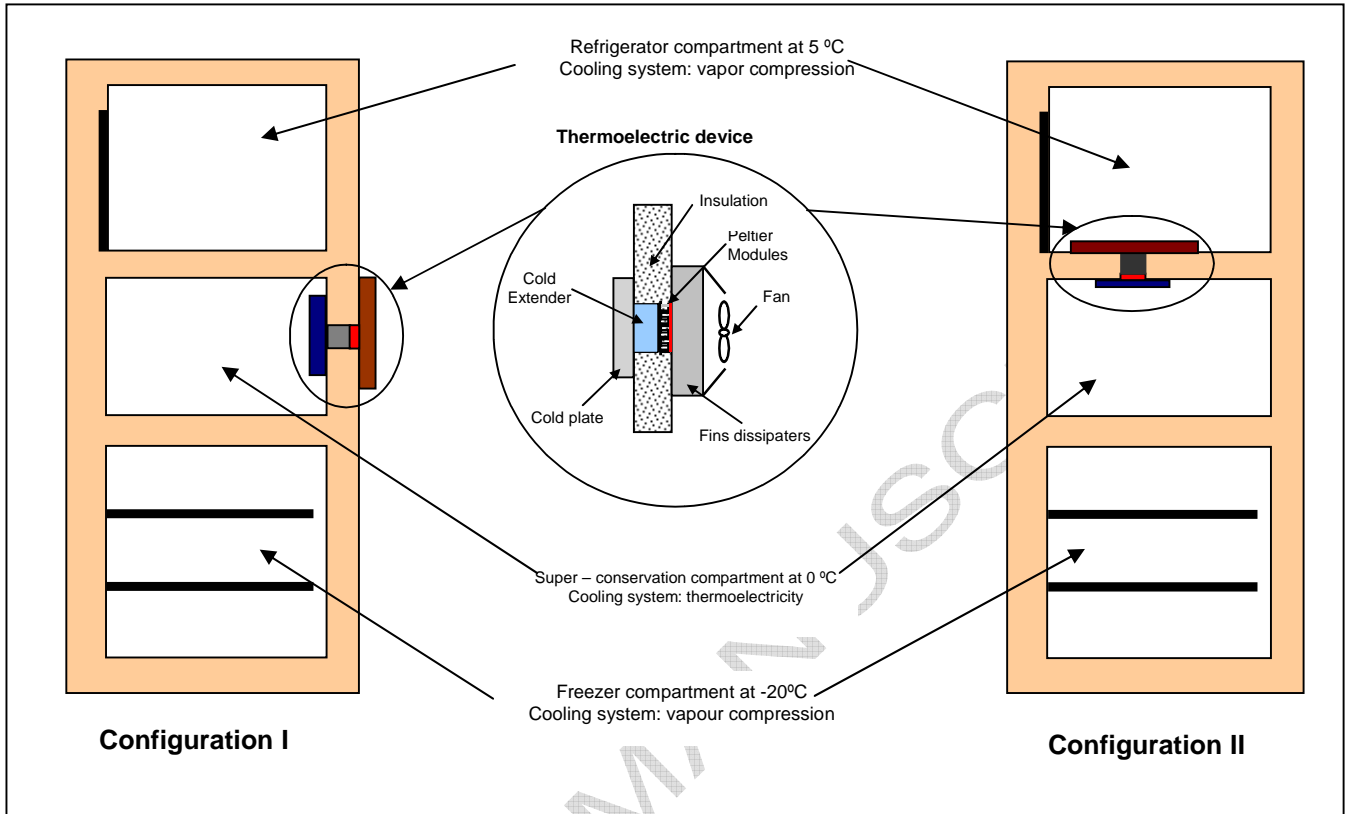


Figure 1. Sketches of the hybrid domestic refrigerator. Configurations I and II.

3.2. Configuration II

In order to decrease the temperature gap between the faces of the Peltier module, this new configuration was designed. The thermoelectric device is placed in the wall between the refrigerator and super-conservation compartments, as shown in Figure 1, configuration II. The heat flux from the hot side of the Peltier modules is introduced in the refrigerator compartment, where is absorbed by the evaporator and thrown to the exterior thanks to the vapor compression cooling system, which has a good COP value (approximately 1). It is a cascade refrigeration system that combines thermoelectricity and vapor compression.

The advantage of this configuration is that the temperature gap between the sides of the Peltier modules is decreased, as the heat exchanger of the hot side is in contact with air at

5°C. This means a significant improvement of the COP, as is shown in advanced.

4. COMPUTATIONAL MODEL

In order to make a study of this new application, a computational model has been developed. This model simulates the behavior of the complete hybrid refrigerator with the three compartments and their cooling systems. The inputs of the model are: materials and geometry of the refrigerator, type of Peltier modules (dimensions and materials), electric power supplied to the Peltier modules, thermal resistance of both the hot side dissipater and the cold side dissipater, and the average cooling power of the evaporator in both the refrigerator compartment and the freezer compartment. After the simulations, the model provides the following outputs: temperatures of all the elements and compartments as a function of time, heat fluxes, power consumptions and COP of both the thermoelectric device and the hybrid refrigerator.

This model is based on a previous model that was developed for thermoelectric refrigerators. Some results are shown in [5]. This previous model has been properly modified to this new application of hybrid refrigeration.

The model solves the following equations of the thermoelectric effects (Seebeck, Peltier and Joule) [6], as well as the heat conduction in transitory state:

$$\alpha_{AB} = \frac{dE_{AB}}{dT} = \alpha_A - \alpha_B \quad (1)$$

$$\dot{Q}_P = \pm \pi_{AB} I = \pm IT(\alpha_B - \alpha_A) \quad (2)$$

$$\dot{q}_J = \frac{J^2}{\rho} \quad (3)$$

$$\delta \cdot c_p \cdot \frac{\partial t}{\partial \tau} = \nabla(k \nabla t) + q^* \quad (4)$$

To simplify the model some hypothesis were taken to account:

- Materials are isotropic.

- The Thompson effect has been neglected by the Peltier and Joule effects as shown in [7].

For the numeric solution of equation (4) the implicit finite difference method has been used. For the one-dimension case, the next step temperature at node i , t_i' , can be calculated as a function of the present temperature at node i and the next step temperatures on the close nodes.

In order to simulate the two configurations, a discretization and modelization of both of them were made.

In Figure 2 and 3 the discretization of both configurations are shown. The electro-thermal analogy has been used.

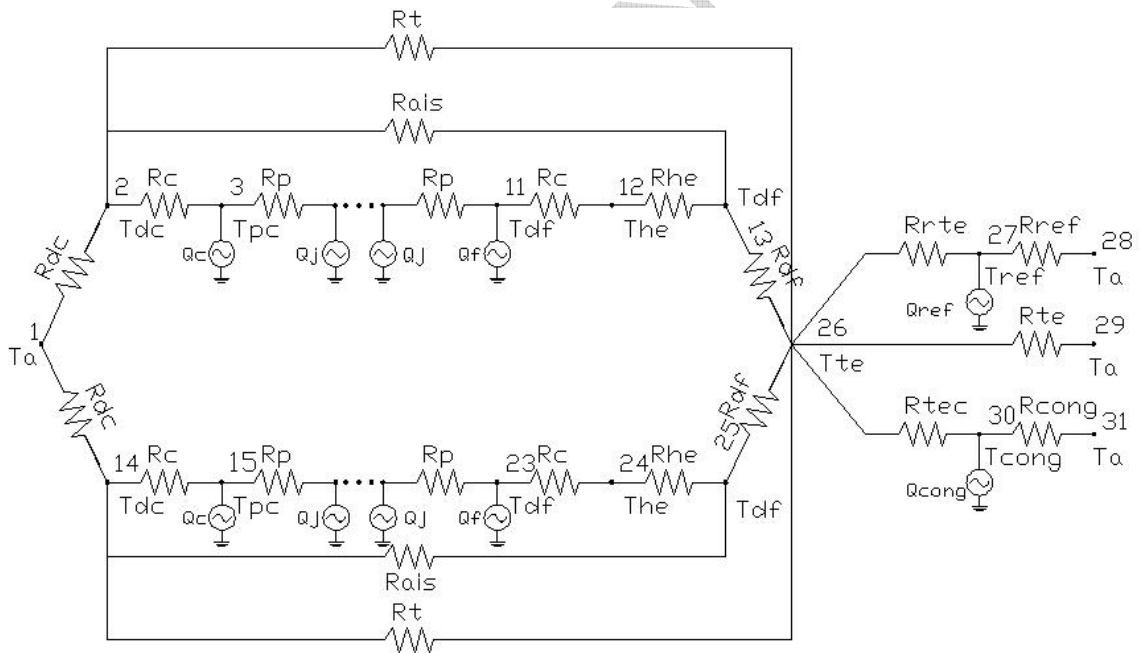


Figure 2. Sketch of the discretization of the hybrid refrigerator for configuration I.

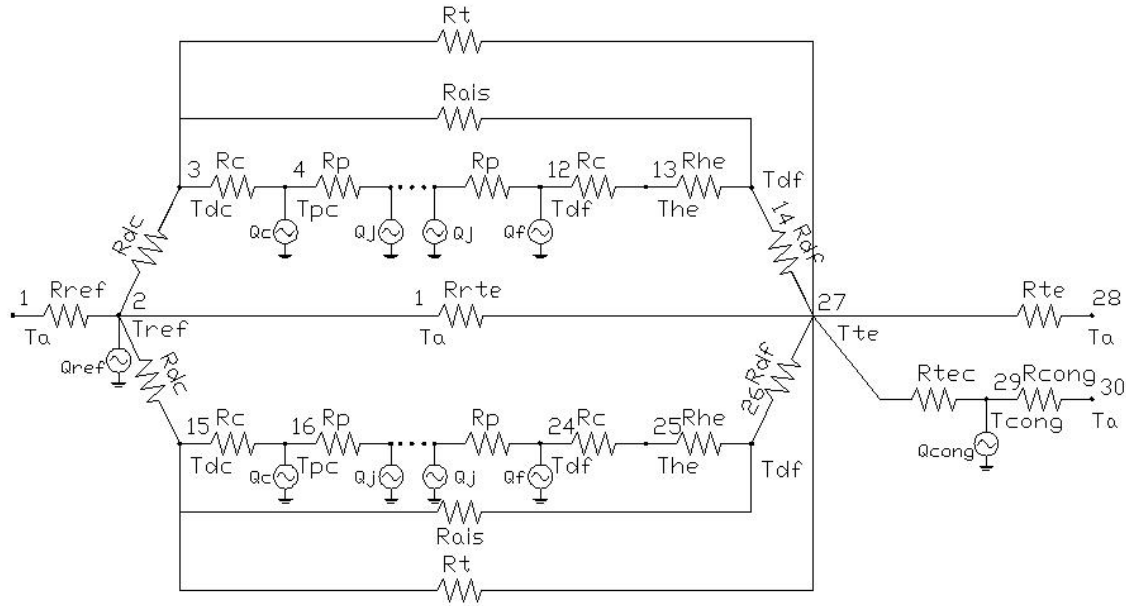


Figure 3. Sketch of the discretization of the hybrid refrigerator for configuration II.

The temperatures of the nodes of Figure 2 and 3 are described in the nomenclature. In the discretization, each node represents a volume with a thermal resistance and a thermal capacity. These values are obtained by using the following general expressions:

$$R = \frac{L}{k.A} \quad (5)$$

$$C = V.\delta.c_p \quad (6)$$

Some thermal resistances, as the insulator walls (R_{cong} , R_{te} , $R_{r\ te}$, R_{tec} , and R_{ref}), where the convection appears in addition to the conduction effect, are calculated by using the following equation:

$$R_{ais} = \frac{1}{U.S} \quad (7)$$

Where S is the surface and U is the global heat transfer coefficient between the interior and the exterior of each compartment, obtained from the equation:

$$U = \frac{1}{\frac{1}{h_{int}} + \frac{e}{k} + \frac{1}{h_{ext}}} \quad (8)$$

To calculate the internal and external convection coefficients, the equation experimentally checked by G.V. Parmelee in [8] for a plate was used. Viscous dissipation was neglected and laminar flow was assumed, since the air velocity is low:

$$Nu_L = 0.664.Pr^{1/3}.Re_L^{1/2} \quad (9)$$

$$\left[\begin{array}{l} 0.6 \leq Pr \leq 50 \\ Re < Re_{x,c} \approx 5 \times 10^5 \end{array} \right]$$

The contact resistance between the Peltier module and the heat extender has been obtained from the Ritzer and Lau work (1994) [9], which provides a value of 0.03K/W.

In the Peltier module, in addition to the thermal capacities and resistances, there are heat sources due to the thermoelectric effects, equations (2) and (3). As an example, the equations for the discretization of node 6 in Figure 3 are the following ones. This node is an internal node of the Peltier module.

$$\frac{t'_5 - t'_6}{R_{56}} + \frac{t'_7 - t'_6}{R_{67}} + q_6 = \frac{c_6}{\delta\tau} (t'_6 - t_6) \quad (10)$$

$$-\frac{t'_5}{R_{56}} - \frac{t'_7}{R_{67}} + \left(\frac{1}{R_{56}} + \frac{1}{R_{67}} + \frac{c_6}{\delta\tau} \right) t'_6 = \frac{c_6}{\delta\tau} t_6 + q_6 \quad (11)$$

$$-\frac{\delta\tau}{c_6} \frac{1}{R_{56}} t'_5 - \frac{\delta\tau}{c_6} \frac{1}{R_{67}} t'_7 + \frac{\delta\tau}{c_6} \left(\frac{1}{R_{56}} + \frac{1}{R_{67}} + \frac{c_6}{\delta\tau} \right) t'_6 = t_6 + \frac{\delta\tau}{c_6} q_6 \quad (12)$$

$$-\frac{\delta\tau}{c_6} \frac{1}{R_{56}} t'_5 + \left[\frac{\delta\tau}{c_6} \left(\frac{1}{R_{56}} + \frac{1}{R_{67}} \right) + 1 \right] t'_6 - \frac{\delta\tau}{c_6} \frac{1}{R_{67}} t'_7 = t_6 + \frac{\delta\tau}{c_6} q_6 \quad (13)$$

Where q_6 represents the heat generation due to the Joule effect, described in equation (3); c_6 is the thermal capacitance obtained by using equation (6); R_{56} and R_{67} are the thermal resistances between the nodes 5-6 and 6-7, from equation (5); t_6 and t_7 represent the temperature of the nodes 6 and 7 in the time step τ ; t'_5 , t'_6 and t'_7 represent the temperature of nodes 5, 6 and 7 in the time step $\tau + \delta\tau$.

Proceeding in the same way with the rest of the nodes of the discretization presented above in Figure 2 and 3, two matrix systems (one for each configuration) like the following one are obtained:

$$[M] \cdot [T_i'] = [T_i] + \frac{\delta\tau}{C_i} \cdot [\dot{Q}_i] \quad (14)$$

The system is non linear as the heat fluxes from the thermoelectric effects (equations 2 and 3) depend on the temperature. Thus, it has been solved using an iterative method, which uses the temperatures and heat fluxes from the n time step to calculate the temperatures of the $n+1$ time step. Also, $[M]$ matrix and $[\dot{Q}_i]$ vector must be recalculated in every step.

5. RESULTS AND DISCUSSION

5.1. Validation of the computational model

Once the computational model was developed and the first prototype was built (configuration II), we proceeded to validate experimentally the computational model and to calculate its accuracy.

Several thermocouples were placed in the prototype: hot and cold side of the Peltier module; freezer, super-conservation and refrigerator compartments; and ambient.

In Figure 4, we compare the temperatures of the first prototype with the simulated temperatures given by the computational model, when the ambient temperature is 30°C and the Peltier module supplied voltage is 4V.

It can be seen that, when steady state is reached, the experimental temperatures of the three compartments are close to the temperatures predicted by the model. However, the temperatures of the different elements of the hybrid refrigerator drop quicker than the model predicts. This is because the cooling power is introduced in the model as a mean value obtained from the following equation:

$$\text{Mean Cooling Power} = \text{Real Compressor Cooling Power} * \text{Operational relation} \quad (15)$$

Where:

Mean Cooling Power: is the cooling power (Watts) and would represent the equivalent cooling power of the vapor compression system, if it worked the whole day without stopping. It is an input of the model.

Real Compressor Cooling Power: is the real cooling power (Watts) of the vapor compression system when it works normally.

Operational relation: number of hours per day that the compressor works, divided by 24 hours.

However, the compressor works with start and stop cycles. When the hybrid refrigerator is working, the compressor of the refrigerator compartment works at full power until the thermostat turns it off. The mathematical model does not represent this behavior but it simulates the compressor as working at mean cooling power all the time. This fact also explains why in the simulations there are no cycles on the temperatures, as shown in Figure 4.

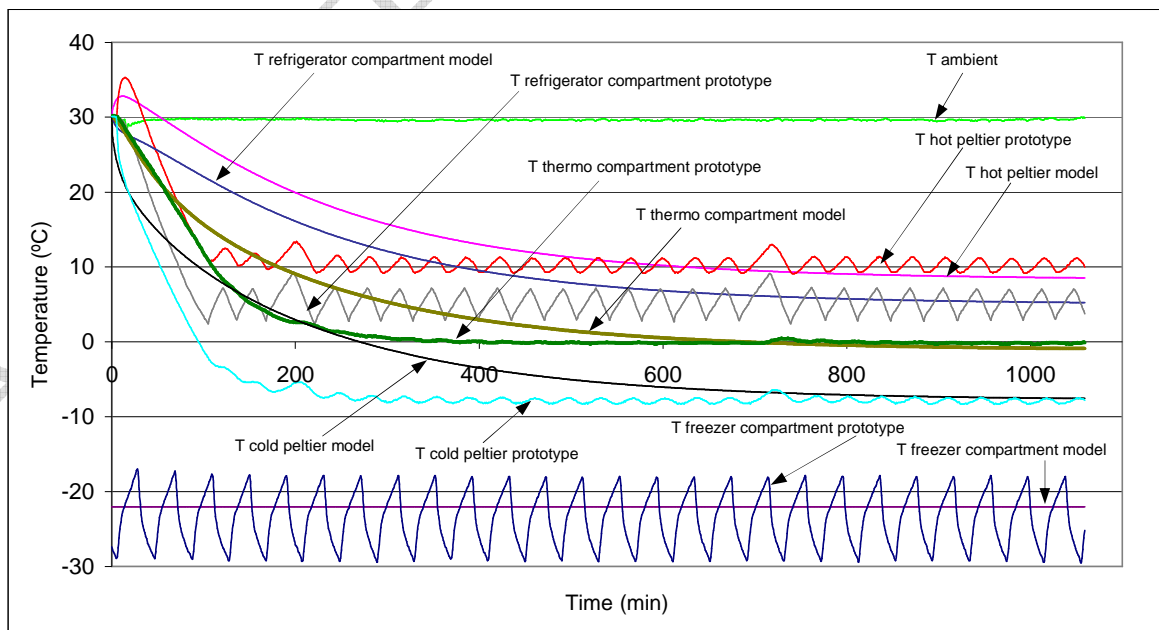


Figure 4. Comparison of the results from the prototype and the computational model.

A resume of these results is shown in Table 2 for steady state, comparing the experimental and simulated results for the first prototype and the computational model. The good accuracy of the model can be seen. It predicts temperature values with a maximum error of 1.2°C and the electric power consumption of the cooling system with a maximum error of 8.3%.

Table 2. Resume of the results for the first prototype and the computational model for steady state.

INPUTS		OUTPUTS							
Ta (°C)	Vte (V)		TEMPERATURES			ELECTRIC POWER CONSUMPTION			
			Tref (°C)	Tte (°C)	Tcong (°C)	Pref (W)	Pcong (W)	Pte (W)	Ptotal (W)
25	3.6	Experimental data	6,1	0,6	-23,1	27,3	24,1	8,9	60,3
25	3.6	Computational data	6,09	-0,52	-23,11	28,9	26,1	8,7	63,8
25	3.6	Deviation	0 °C	1,2 °C	0,0°C	6,1%	8,3%	1,9%	5,8%
30	4	Experimental data	6,0	1,1	-23,5	35,0	28,9	11,2	75,2
30	4	Computational data	6,01	-0,08	-23,38	35,8	30,2	10,7	76,7
30	4	Deviation	0°C	1,2°C	-0,1°C	2,1%	4,5%	4,6%	2,1%

5.2. Results of the simulations using the model for different configurations of hybrid refrigerators.

After the accuracy of the computational model was checked, the model was used as a design and optimization tool of the hybrid domestic refrigerator (vapor compression – thermoelectricity).

In the first study, we analyzed which configuration (see Figure 1) was better from a thermal point of view. In order to complete this study, both configurations were simulated under the same conditions. The results of these simulations are shown in Table 3, where can be seen the electric power consumption of the freezer compressor, of the refrigerator compressor and of the thermoelectric modules, for two different ambient temperatures (25°C and 30°C). The total hybrid refrigerator power consumption and all the temperatures for both configurations are presented as a function of the thermal resistances of the dissipaters in the hot and the cold side of the Peltier modules.

Table 3. Results of the simulations for the studied configurations.

CONFIGURATION I								
Ta (°C)	25				30			
Rdc (K/W)	0,35	0,22	0,15	0,22	0,35	0,22	0,15	0,22
Rdf (K/W)	1,75	1,75	1,75	0,97	1,75	1,75	1,75	0,97
Vte (V)	12,0	12,0	12,0	12,0	12,0	12,0	12,0	12,0
Tref (°C)	4,0	4,1	4,0	4,0	4,1	4,1	4,1	4,0
Tte (°C)	0,2	-2,4	-3,9	-4,9	4,3	1,7	0,3	-0,7
COPte	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
Pref (W)	13,8	13,6	13,6	13,6	17,3	17,2	17,1	17,1
Pte (W)	99,6	99,6	99,6	99,6	97,5	97,5	97,5	97,5
Pref+Pte (W)	113,4	113,2	113,2	113,2	114,8	114,7	114,6	114,6
CONFIGURATION II								
Ta (°C)	25				30			
Rdc (K/W)	0,35	0,22	0,15	0,22	0,35	0,22	0,15	0,22
Rdf (K/W)	1,75	1,75	1,75	0,97	1,75	1,75	1,75	0,97
Vte (V)	3,2	3,1	3,0	2,5	3,9	3,7	3,6	3,0
Tref (°C)	4,0	4,0	4,1	4,0	4,0	4,1	4,0	4,0
Tte (°C)	0,0	0,0	0,0	0,0	0,0	0,1	0,0	0,0
COPte	1,2	1,3	1,4	2,0	1,0	1,1	1,1	1,7
Pref (W)	24,7	24,3	24,0	22,5	32,7	31,7	31,3	28,8
Pte (W)	7,0	6,5	6,2	4,2	10,6	9,5	9,0	6,0
Pref+Pte (W)	31,7	30,8	30,2	26,8	43,3	41,2	40,4	34,9

These results show that configuration II is more efficient from an energetic point of view, since it needs 80% less electric power consumption than configuration I. This is due to the fact that, as the thermoelectric system is operating in cascade with the vapor compression system, the temperature of the hot side of the Peltier module is closer to the cold side, what makes the COP value greater (near 1 for configuration II against 0.1 for configuration I). It means that, for configuration II, the Peltier modules should be supplied with a lower voltage (3V against 12V for configuration I) what makes a lower power consumption (6.5W against 99.6W, for 25°C ambient temperature). This advantage of configuration II makes the total electric power consumption of the appliance lower, although the power consumption of refrigerator compressor is greater (24.3W against 13.6W for configuration I), since the heat flux from the hot side of the Peltier module is absorbed by the evaporator of the refrigerator compartment.

Besides, configuration I is not capable of reaching 0°C in the thermoelectric

compartment, even if the Peltier modules are supplied at full power, as can be seen in Table 3. Thus, configuration II was elected.

Another conclusion from the analysis of the results from Table 3 is the significant influence of the thermal resistance of the dissipaters of the thermoelectric system on the global behavior. For example, for configuration I, when reducing the thermal resistance of the hot side from 0.35K/W to 0.15K/W, the temperature of the thermoelectric compartment decreases 4.1°C. For configuration II, the same improvement in this thermal resistance makes a decrease of 65% in power consumption.

To optimize the system, simulations studying the possibility of using thermal bridges between the freezer and the super-conservation compartments were made. These thermal bridges are aluminum slabs that connect both compartments. The objective of these devices is making the freezer absorb the maximum heat flux from the thermoelectric compartment as possible, in order to keep the temperature of this compartment at 0°C (design temperature). By doing this, the power consumption of the Peltier modules could be reduced.

The results of the simulations are shown in Figure 5, and the effect of the thermal bridges can be appreciated there. These thermal bridges make the power consumption of the freezer compartment greater, since some of this cooling power has to cool the thermoelectric compartment (super-conservation compartment). On the other hand, a lower electric power consumption of the Peltier modules is needed. As a consequence of this, the power consumption of the refrigerator decreases, since less heat flux from the hot side of the Peltier modules is introduced into the refrigerator. The most important value is the total power consumption of the hybrid refrigerator (the addition of the electric power consumption of the freezer, thermoelectric and refrigerator compartments) and this value decreases if thermal bridges are used. This effect is greater as the size of the thermal bridges is bigger.

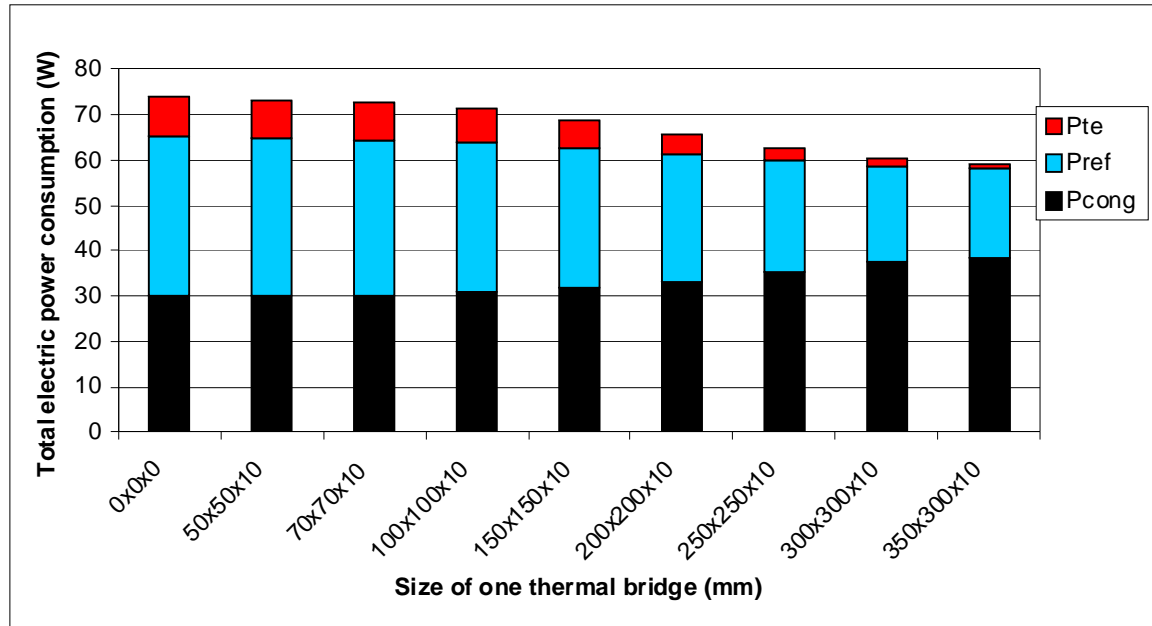


Figure 5. Results of the simulations for the refrigerator with thermal bridges.

After these results, we decided to build a new hybrid prototype with two thermal bridges, each of them 200*200*10mm.

5.3. Results of the different prototypes of hybrid refrigerators.

During the development of this work and based on the data from the simulations, three different hybrid refrigerators have been built.

The temperatures of the first prototype are shown in Figure 4 and in Table 2, where they are compared with the temperature values predicted by the computational model. These results certify that the first prototype works properly, keeping the thermoelectric compartment at 0°C, even if the room temperature rises to 30°C. The power consumption for an ambient temperature of 25°C is: 0.67kWh per day (28W) for the refrigerator, 0.58kWh per day (24.1W) for the freezer and 0.2kWh per day (9W) for the thermoelectric cooling system, what means a total power consumption of 1.5kWh per day (61W).

In Figure 6, there are two pictures of the construction process of the third prototype of hybrid refrigerator. Two thermal bridges of 200*200*10mm were incorporated, based on the results provided by the computational model (see Figure 5).

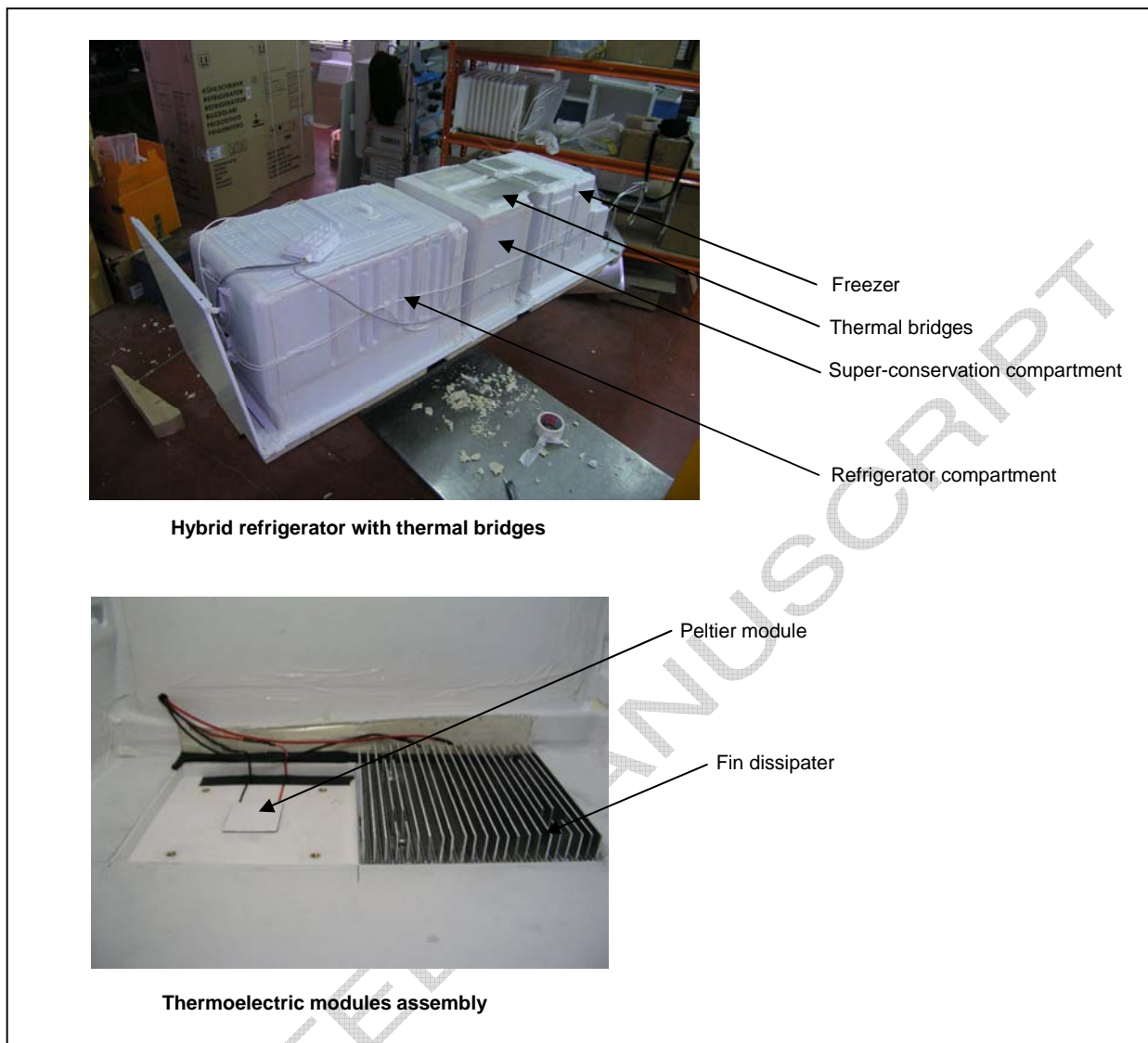


Figure 6. Photographs of the third prototype hybrid refrigerator.

The results of one of the several tests that were taken on the third prototype are shown in Figure 7. In spite of the temperature cycles in the freezer and refrigerator compartments, the temperature of the thermoelectric compartment (super-conservation) is kept constant at 0°C.

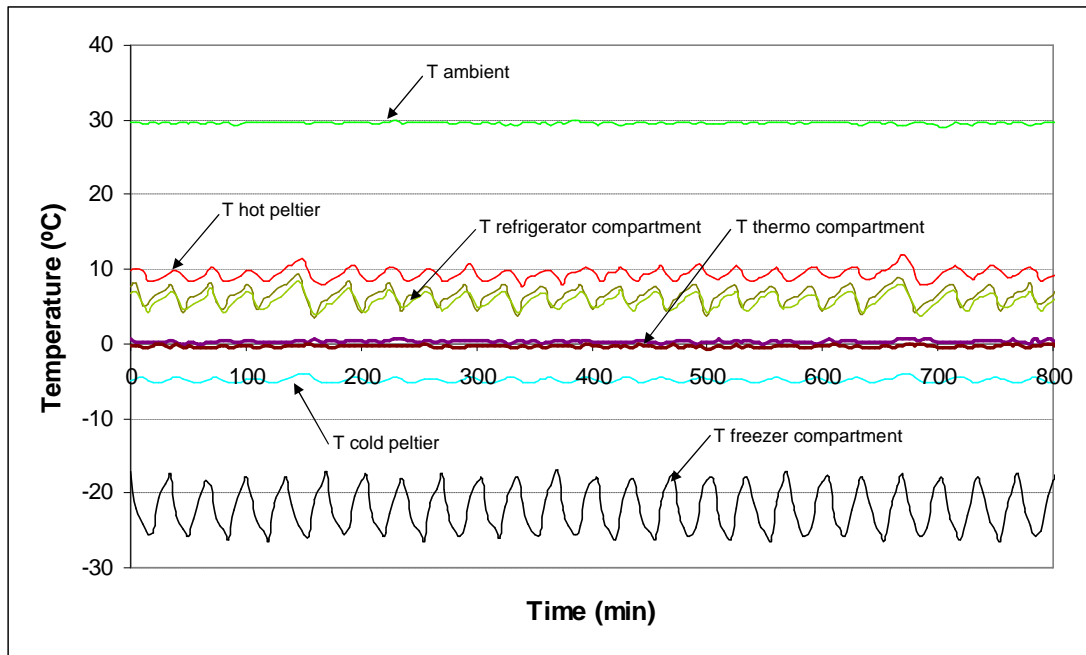


Figure 7. Results of the prototype 3 with a supplied voltage for the Peltier modules of 2.9V

Table 4 shows a resume of the results obtained from the tests run on prototype 3 for steady state. It can be seen that these results match with the computational results (see Figure 5), which foresee a decrease in the power consumption of the Peltier modules and in the total electric power consumption. If these results are compared with prototype 1 results (see Table 2), it can be checked that the total electric power consumption of the hybrid refrigerator, for a ambient temperature of 25°C, has decreased from 60.3W to 49.9W, what means an improvement of 20%, due to the thermal bridges.

Table 4. Prototype 3 results for steady state.

DATA			RESULTS						
Ta (°C)	Thermostat position	Vte (V)	TEMPERATURES			POWER CONSUMPTION			
			Tref (°C)	Tte (°C)	Tcong (°C)	Pref (W)	Pcong (W)	Pte (W)	Ptotal (W)
25	6 °C	2,2	5,5	-0,3	-22,1	19,7	25,2	4,9	49,9
30	6 °C	2,9	6,1	0,0	-22,1	26,9	30,9	7,4	65,2
30	4 °C	2,3	4,6	0,1	-22,8	26,1	30,4	5,3	61,9

Another important conclusion obtained from the data in Table 4 is that, when the thermostat of the refrigerator compartment is in a lower position, the total power consumption decreases. This is due to the fact that when the thermostat is in lower temperature positions, the temperature in the refrigerator is lower, what makes the Peltier modules work with a greater value of COP and, thus, lower power consumption. This fact makes, in addition, that the Peltier modules introduce less heat flux into the refrigerator. This effect is greater than the effect of lowering the temperature by a lower position of the thermostat, so that the total power consumption is lower.

To conclude, a domestic refrigerator has been developed with a new super-conservation compartment, based on thermoelectricity, where the temperature is kept constant at 0°C. The total power consumption of the appliance is highly competitive. For example, for an ambient temperature of 25°C, the power consumption of the refrigerator compartment is 19.7W, the freezer compartment consumes 25.2W and the thermoelectric device 3.1W, what makes a total power consumption of 48.1W. According to European rules on energy efficiency of refrigerators, this new model could be included on class B.

For an ambient temperature of 30 °C, the temperature of the thermoelectric compartment can be kept constant at 0 °C, as can be seen in figures 4 and 7. Obviously, if the ambient temperature rose, the electric power consumption would increase. In particular, if the ambient temperature rises from 25°C to 30°C, the electric power consumption is increased by 30%, as can be seen in table 4.

6. CONCLUSIONS

A new computational model that uses the numerical method of finite differences has been developed. This model is capable of simulating the whole hybrid refrigerator behavior (refrigerator compartment, freezer compartment and thermoelectric compartment). The model has been experimentally validated. It predicts the temperature in

the thermoelectric compartment with a maximum error of 1.2°C, and the electric power consumption with a relative error of 8%.

A thermoelectric system has been designed for the super-conservation compartment. It has been placed in a domestic refrigerator, which uses vapor compression as cooling system. The temperature of the super-conservation compartment is kept constant at 0°C, even if the ambient temperature rises to 30°C. This design has been optimized with a thermal bridges system, which implies an additional heat flux from the thermoelectric compartment to the freezer, reducing the total power consumption by 20%.

To conclude, we have developed a three-compartments-hybrid refrigerator, whose total power consumption is very competitive. For an ambient temperature of 25°C, the electric power consumptions were:

- Refrigerator compartment compressor ($T_{\text{average}} = 4^{\circ}\text{C}$): 0.47 kWh/day (19.7W)
- Thermoelectric modules ($T_{\text{average}} = 0^{\circ}\text{C}$): 0.07 kWh/day (3.1W)
- Freezer compartment compressor ($T_{\text{average}} = -21^{\circ}\text{C}$): 0.6 kWh/day (25.2W)
- Total power consumption of the hybrid refrigerator: 1.15kWh/day (48.1W)

According to European rules on energy efficiency of refrigerators, this developed model could be included on class B.

Since this application has a big commercial interest, it has been patented under [10]. The company that is using this patent is Bosch-Siemens.

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NOMENCLATURE

A	Section	m^2
C	Calorific capacity	$W/s.K$
COP	Coefficient of operation	
COP_{te}	Coefficient of operation of the thermoelectric system	
c_p	Specific heat at constant pressure	J/kgK
e	Insulator thickness	m
E_{AB}	Seebeck thermoelectric force	V
h_{int}	Internal convection heat transfer coefficient	W/m^2K
h_{ext}	External convection heat transfer coefficient	W/m^2K
I	Electric current	A
J	Electric current density	A
k	Thermal conductivity	W/mK
L	Length	m

Nu	<i>Nusselt number</i>	
P_{ref}	<i>Electric power consumed by the refrigerator compressor</i>	W
P_{te}	<i>Electric power consumed by the Peltier modules</i>	W
P_{cong}	<i>Electric power consumed by the freezer compressor</i>	W
P_{total}	<i>Total electric power consumed by the hybrid appliance</i>	W
Pr	<i>Prandtl number</i>	
\dot{Q}	<i>Heat flux</i>	W
\dot{Q}_P	<i>Heating power due to Peltier effect.</i>	W
\dot{Q}_C	<i>Heating power of the hot side of the Peltier module</i>	W
\dot{Q}_f	<i>Absorbed by the Peltier pellet cold side heating power</i>	W
\dot{Q}_J	<i>Heating power generated in the Peltier module due to the Joule effect</i>	W
\dot{Q}_{cong}	<i>Cooling power of the freezer evaporator</i>	W
\dot{Q}_{ref}	<i>Cooling power of the refrigerator evaporator</i>	W
\dot{q}_J	<i>Heating power due to Joule effect per unit volume</i>	W/m ³
q^*	<i>Generated heat by unit time and volume</i>	W/m ³
R	<i>Electric resistance</i>	K/W
R_{he}	<i>Thermal resistance of the heat extender</i>	K/W
R_p	<i>Thermal resistance of the Peltier module</i>	K/W
R_{ais}	<i>Thermal resistance of the insulator which separates the hot side dissipater from the cold side dissipater</i>	K/W
R_t	<i>Thermal resistance of the assembly screws</i>	K/W
R_c	<i>Contact thermal resistance</i>	K/W
R_{dc}	<i>Hot side dissipater thermal resistance</i>	K/W
R_{df}	<i>Cold side dissipater thermal resistance</i>	K/W
R_{ref}	<i>Refrigerator insulator thermal resistance</i>	K/W
R_{cong}	<i>Freezer insulator thermal resistance</i>	K/W
R_{tec}	<i>Thermal resistance of the insulator between the freezer and the thermoelectric compartment</i>	K/W
R_{te}	<i>Thermal resistance between the thermoelectric compartment and the exterior</i>	K/W
$R_{r,te}$	<i>Thermal resistance between the thermoelectric compartment and the refrigerator</i>	K/W
Re	<i>Reynolds number</i>	
S	<i>Section</i>	m ²
T	<i>Absolute temperature</i>	K
t	<i>Temperature</i>	°C
T_a	<i>Ambient temperature</i>	K
T_{dc}	<i>Hot side dissipater temperature</i>	K
T_{pc}	<i>Hot side Peltier module temperature</i>	K
T_{te}	<i>Thermoelectric compartment temperature</i>	K
T_{pf}	<i>Cold side Peltier module temperature</i>	K
T_{he}	<i>Heat extender temperature</i>	K
T_{df}	<i>Cold side dissipater temperature</i>	K
T_{ref}	<i>Refrigerator temperature</i>	K
T_{cong}	<i>Freezer temperature</i>	K
U	<i>Global heat transfer coefficient</i>	W/m ² K
V_{te}	<i>Voltage supplied to the Peltier module</i>	V
V	<i>Volume</i>	m ³

∇	<i>Gradient</i>	
α	<i>Seebeck coefficient</i>	V/K
ρ	<i>Electric resistivity</i>	$Ohm. m$
σ	<i>Thomson coefficient</i>	V/K
τ	<i>Time</i>	s
δ	<i>Density</i>	kg/m^3
π_{AB}	<i>AB join Peltier coefficient</i>	V
γ	<i>Specific weight</i>	N/m^3

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