DOMESTIC REFRIGERATOR WITH COLD PRODUCTION BY VAPOUR COMPRESSION AND THERMOELECTRICITY

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Abstract.

In this study we have developed a domestic refrigerator which combines both technologies, thermoelectricity and vapor compression, in order to make the most of the machine compression good COP, with the excellent control and inside temperature regulation of the thermoelectric technology. It is composed of three compartments: conservation (4ºC), freezer (-22ºC) and a new super-conservation space at 0ºC (thermoelectric cooling system).

For the design and optimization of this application, we have developed a computational model based on the numeric method of the finite differences, what allows us to simulate the whole hybrid fridge. The accuracy of this method has been experimentally checked, obtaining a maximum error 8%

1. INTRODUCTION

There are four main cooling systems: vapor compression, absorption, gas and thermoelectricity. In the domestic refrigerator the most used cooling system is the vapor compression, as it has a good value of C.O.P. However, the temperature control inside the cooled room is inaccurate, as the compressor makes start and stop cycles, what makes a variation higher than 8ºC in the temperature, as shown in [1]. This fact has a very damaging effect in the preservation of the food, especially in fishes, meats and fruits.

On the other hand there are thermoelectric refrigerators presented in [2], [3], and [4] with a good control in the temperature of the space and thus, a better preservation of the food. 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 use the C.O.P. good value of the vapor compression system and the excellent inside temperature control using thermoelectric technology. The prototype is based on a domestic Combi refrigerator (bottom freezer) where it has been placed a new super-preservation room with a cooling system based on 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 spaces:

a. Freezer compartment at -22ºC, with vapor compression cooling system.
b. Refrigerator compartment at 5ºC, with vapor compression cooling system.
c. Super-preservation compartment at 0ºC and with a maximum oscillation of the temperature of ±0.5ºC, with thermoelectric cooling system.

3. DESCRIPTION AND OPERATION OF THE HYBRID.

The prototype is based on a commercial domestic refrigerator from Bosch-Siemens, *BOSCH KGF-39*, with two compartments (refrigerator with a temperature oscillating around 5ºC and freezer around -20ºC), each compartment with an independent cooling vapor compression system. To this refrigerator is added a new compartment of super-preservation with a constant temperature of 0ºC and a maximum temperature variation of ±0.5ºC. This compartment is placed in the middle of the appliance as shown in Figure 1 with a thermoelectric technology based cooling system (TEC), [2], [5]

In the development of the hybrid refrigerator two configurations were considered for the thermoelectric modules that control the temperature inside the compartment of super-preservation.

3.1. Configuration I

In this configuration the Peltier modules are placed in the back wall of the super-preservation room, 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.

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 produced between the faces of the Peltier module is higher than 30ºC and as a consequence of this, the C.O.P. of the thermoelectric device is low as demonstrated in [2] and [5].

One way to improve the C.O.P. value in making lower the value of the thermal resistance of the heat exchanger on the hot side of the Peltier module.

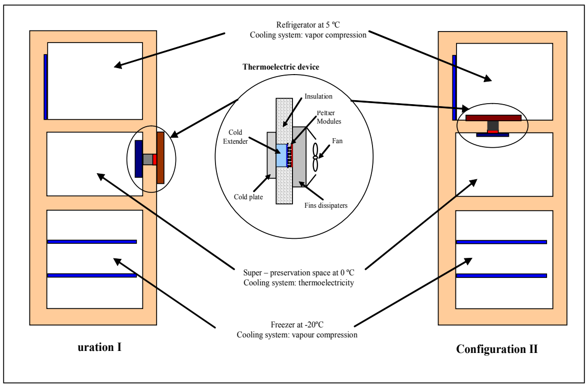

Figure 1. Sketches of the hybrid domestic refrigerator. Configurations I and II.

3.2. Configuration II

In order to decrease the temperature gap between the faces of the Peltier module, this new configuration has been designed. The thermoelectric device is placed in the wall between the refrigerator and the super-preservation as shown in Figure 1, configuration II. The heat flux from the hot side of the Peltier modules is introduced in the refrigerator room where the evaporator is in charge to absorb and throw it to the exterior thanks to the vapor compression cooling system, with a good C.O.P. value (approximately 1).

4. COMPUTATIONAL MODEL

In order to make a study of this new application a computational model has been developed. This application simulates the behavior of the complete hybrid refrigerator with the three compartments and their cooling systems. The inputs of the model are: material, geometry of the appliance, model of the Peltier modules (dimensions and materials), electric power supplied to the Peltier, thermal resistances of the hot side and cold side dissipaters and the average cooling powers of the evaporators of the refrigerator and freezer rooms. After the simulations, the model supplies the following outputs: temperatures of all the elements and compartments as a function of time, heat fluxes, power consumptions, C.O.P. of the thermoelectric device and the hybrid refrigerator.

This model is based in a previous model developed for thermoelectric refrigerators which results are shown in [5].

The model solves the equations of the thermoelectric effects, and the heat conduction in transitory state with the following equations:

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

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

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

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

For the numeric solution of equation (4) the implicit finite difference method has been used. In order to simulate the two configurations a discretization and modelization of both of them were made.

The calculation of the thermal resistances and capacities has been carried out as is indicated in reference [5].

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).

When the studied system is discretizated, we can obtain the following eq. system:

$$[M].[T_i'] = [T_i] + \frac{\delta\tau}{C_i}.\left[\dot{Q}_i\right] \qquad (5)$$

5. RESULTS AND DISCUSSION

5.1. Validation of the computational model

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

In Figure 2 is shown a comparison of the results between the temperatures of the first prototype and the temperatures simulated using the computational model, for an ambient temperature of 30ºC and a Peltier module supplied voltage of 4V. In all tests developed, the maximum error in the computational model was lower than 8.3%. En todos los ensayos realizados, el máximo error del modelo computacional fue de 8.3%.

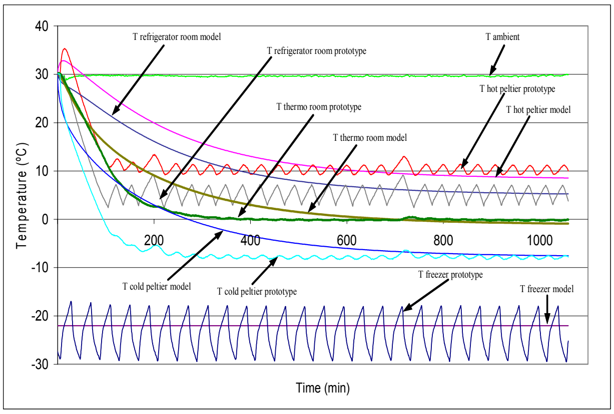

Figure 2. Comparison of the results from the prototype and the computational model.

5.2. Results of the simulations for different configurations.

The first study made was analyzing which configuration (see Figure 1) is 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 1.

These results show how configuration II is more efficient from an energetic point of view, as 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 much closer to the cold side, what makes the C.O.P. value greater. This fact is traduced as for configuration II the Peltier modules work with a lower, what makes a lower power consumption. This advantage of configuration II makes the total electric power consumption of the appliance much lower, although the refrigerator compressor is greater as the heat flux from the hot side of the Peltier module is absorbed by the refrigerator evaporator. Thus, configuration II was elected.

Another conclusion from the analysis of the results from Table 1 is the influence of the thermal resistance of the dissipaters placed on the thermoelectric system in the global behavior.

Table 1. Results of the simulations for the studied configurations.

CONFIGURATION I								
Ta (ºC)	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 (ºC)	4,0	4,1	4,0	4,0	4,1	4,1	4,1	4,0
Tte (ºC)	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 (ºC)	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 (ºC)	4,0	4,0	4,1	4,0	4,0	4,1	4,0	4,0
Tte (ºC)	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

5.3. Results for the different prototypes of hybrid refrigerators.

In the development of this work and based on the results of the simulations, three different hybrid refrigerators have been built.

Table 2 shows a resume of the results obtained from the tests run on prototype 3 for steady state.

Table 2. Prototype 3 results for steady state.

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

6. CONCLUSIONS

- A new computational model using the numerical method of finite differences has been developed. This model is capable to simulate the whole hybrid refrigerator behavior. The model has been validated experimentally, with very good predictive values and a maximum error for the temperatures in the thermoelectric compartment of 1.2ºC and 8% for the power consumption.
- A thermoelectric system has been designed for the super-preservation space, in the interior of a domestic appliance which uses vapor compression as cooling system. With this system the temperature of the super-preservation space remains constant at 0ºC even when the ambient temperature is greater than 30ºC.
- To conclude, we have developed a hybrid refrigerator with three compartments and total power consumption very competitive. For a ambient temperature of 25ºC the results were:
  - Refrigerator space compressor power consumption ($T_{average}$ = 4ºC): 0.47 kWh/day (19.7W)
  - Thermoelectric pellets power consumption ($T_{average}$ = 0ºC): 0.07 kWh/day (3.1W)
  - Freezer space compressor power consumption ($T_{average}$ = -21ºC): 0.6 kWh/day (25.2W)
  - Total power consumption for the hybrid appliance: 1.15kWh/day (48.1W)
- As this application has a big commercial interest, it has been patented under [10]. The company who is using this patent is Bosch-Siemens.

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NOMENCLATURE

COP	*Coefficient of operation*	
c_p	*Specific heat at constant pressure*	*J/kgK*
E_{AB}	*Seebeck thermoelectric force*	*V*
I	*Electric current*	*A*
J	*Electric current density*	*A*
k	*Thermal conductivity*	*W/mK*
P_{ref}	*Electric power consumed by the refrigerator compressor*	*W*
P_{te}	*Electric power consumed by the Peltier modules*	*W*
P_{cong}	*Electric power consumed by the freezer compressor*	*W*
P_{total}	*Total electric power consumed by the hybrid appliance*	*W*
$\dot{Q}$	*Heat flux*	*W*
q^*	*Generated heat by unit time and volume*	W/m^3
R_{dc}	*Hot side dissipater thermal resistance*	*K/W*
R_{df}	*Cold side dissipater thermal resistance*	*K/W*
T	*Absolute temperature*	*K*
T_a	*Ambient temperature*	*K*
V_{te}	*Voltage supplied to the Peltier module*	*V*
α	*Seebeck coefficient*	*V/K*
ρ	*Electric resistivity*	*Ohm. m*
τ	*Time*	*s*
δ	*Density*	kg/m^3