Development of a thermoelectric ice maker of fingers incorporated into a static domestic refrigerator.

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Abstract

A domestic refrigerator wich incorporates in its interior a device to make ice cubes using thermoelectric technology has been developed. For its design a computational model has been implemented. This model solves both thermoelectric and heat transfer equations including the phase change equations. The inputs are the thermoelectric parameters as a function of the temperature and the boundary conditions: (room temperature and voltage supplied to the Peltier module). The outputs are the values of the temperature for all the elements of the thermoelectric ice-maker and the ice production.

We have studied the ice cube production in function of the thermal resistance of the hot side heat dissipater and the voltage supplied to the Peltier module, using a computational model and experimental data.

In an experimental phase a prototype has been built in order to adjust and validate the computational model, and to optimize the application. This ice-maker has two Peltier modules, some aluminum cylinders (fingers) where the ice is made and a thermal bridge that communicates the freezing space with the ice-maker fingers (placed in the refrigerated space). The ice formation on the fingers is obtained by the cold production of the Peltier modules. When the ice cubes are formed, the voltage of the thermoelectric modules is switched so the fingers warmed up until the ice around the fingers is melt and the ice cubes are dropped by gravity action.

Nomenclature

A	Area	(m^2)
C	Thermal capacity	($J\ K^{-1}$)
c_p	Specific heat under constant pressure	($J\ kg^{-1}\ K^{-1}$)
e	Thickness	(m)
h	Convection coefficient	(W/m^2K)
I	Electric current	(A)
k	Thermal conductivity	($W\ m^{-1}\ K^{-1}$)
L	Length	(m)
N	Peltier module thermocouples number	
$\dot{Q}$	Heat flux	(W)
$\dot{Q}_{evap}$	Heat flux from the evaporator of the freezer	(W)
$\dot{Q}_{disip}$	Heat flux from the hot side dissipater	(W)
$\dot{Q}_{leaks}$	Heat flux leaks through the walls	(W)
$\overset{*}{q}$	Rate of internal generation of heat	($W\ m^{-3}$)
r	Radius	(m)
R	Thermal resistance	($K\ W^{-1}$)
R_{cont}	Electric contact resistance	(Ohm)
R_O	Electric Peltier module resistance	(Ohm)
T	Temperature	(K)
T'	Temperature in next step	(K)
V	Voltage	(V)
$\dot{W}_p$	Electric power of the Peltier device	(W)

Greek letters

α	Seebeck Coefficient	(V/K)
ρ	Density	($kg\ m^{-3}$)
τ	Time	(s)

Superscripts, subscripts

c	Cold side of the Peltier module
dissip	Dissipater
exp	Experimental
fr	Freezer
h	Hot side of the Peltier module
i	Node i
ins	Insulation
J	Joule effect
j	Node j
mod	Model
pc	Phase change
ref	Refrigerator
room	Room

Introduction

The Peltier technology has undergone through a great advance in the last years, basically due to the development on semiconductors technology and the incorporation of thermoelectric devices in the civil environment. The Peltier modules have been used in several cooling applications for small power, such as stabilizing the temperatures in a laser, improving the integrated circuits cooling systems and it has been used in portable refrigerators for medical and leisure time applications.

This technology has to rival with the traditional systems of vapor compression. When developing applications based on the thermoelectricity, it appears the problem of handling the equations for the calculations and the design. There are several theoretical expressions to solve the COP of the thermoelectric refrigerators [1] assuming some hypothesis, for this expressions the experimental face temperature of the Peltier module is needed as a condition. Although these temperatures were known, the results obtained from the use of this expression are far from the reality due to the error of using the hypothesis in the analytical solution.

In this work it has been developed a computational calculation model that allows us to simulate the operation of a thermoelectric ice-maker, analyzing the most important parameters for its optimization, such as:

Formation time as a function of the hot side thermal resistance.

Supplied power needed in the Peltier module to obtain the minimum formation time for each case.

This model is based on a computational model developed for the simulation of thermoelectric refrigerators [2], [3].

Objectives

Our objectives are:

- Development of a computational model to simulates the ice formation in a thermoelectric ice-maker, including all the heat fluxes and the phase change process.
- Experimental validation of the computational model through experimental data obtained from a prototype of the thermoelectric ice-maker.
- Theoretical and experimental study of the ice cube production in function of the thermal resistance of the hot side dissipater and the Peltier module voltage.

Computational model

In the study of thermoelectric systems, both cooling and generation applications, the temperatures of the faces of the modules and in the nodes between cannot be determined analytically without knowing the heat fluxes due to the thermoelectric effects. The system of equations to solve in order to obtain the temperatures is non linear.

A computational model that simulates the operation of an ice maker device based on thermoelectric technology has been implemented. This model solves using the finite difference method the non linear systems of equations including the thermoelectric equations, the heat transfer equations, and the phase change equations, as well the model calculates the temperature in separated points in the space for discrete intervals, in the transient state the temperatures of these points are calculated in discrete time intervals.

While solving the model using the implicit finite difference method, using the temperatures in the step before allows us to determine the heat fluxes.

The inputs of the model are:

- Geometry and material of the ice-maker
- Peltier module specifications (material and dimensions)
- Electric voltage
- Thermal resistance of the hot dissipater.

After the simulation the model supplies as outputs:

- Temperatures of the nodes
- Heat fluxes
- Electric power consumption of the Peltier module
- COP of the ice-maker
- Formation time of the ice cubes

Our model can be used as a design tool to build a thermoelectric ice-maker, becase all the temperatures and heat fluxes of the system can be determined knowing the specifications of the system and the voltage supplied to the Peltier modules.

Model hypothesis

- The materials are considered isotropic.
- The Thomson effect is negligible, compared to the Peltier and Joule effects.
- The model does not take care of magnetic fields, so Hall, Nerst, Ettingshausen and Righi-Ludec effects are not taken into account.

Model equations

The model solves the heat transfer conduction equation in transient state for the one-dimensional case. The solidification of substances can be considered an one-dimensional case if the cooling ambient has constant temperature or if the length of the tubes is not very big (L/D≤100), London et al [4]:

$$\rho c_p \frac{\delta T}{\delta \tau} = k\left(\frac{\delta^2 T}{\delta x^2}\right) + q^* \quad (1)$$

The heat conduction equation (1) multiplied by the volume, applied to the node i as a function of the thermal resistances and capacities is:

$$\frac{T_{i-1}' - T_i'}{R_{i-1,i}} + \frac{T_j' - T_i'}{R_{i,j}} + \dot{Q}_i = \frac{C_i}{\delta\tau}\left(T_i' - T_i\right) \quad (2)$$

The expression of the thermal resistance between the nodes i and j and the capacity of each node are parameters that our model needs. The values of these two values are necessary to be calculated with the maximum possible accuracy in order to ensure reliable results.

The thermal resistance and capacity of the Peltier module and the refrigerator are studied in the same way as done in reference [3]. The Peltier module is divided in nine nodes. The thermal resistance between nodes and the thermal capacity associated to each node is a function of the temperature.

The thermal contact resistances between the cold face of the Peltier module and the device used to make the cubes (fingers), and the hot face of the Peltier module and its dissipater has been calculated using the works of Ritzer and Lau [5].

The thermal resistance of the "Thermal Bridge – hot dissipater" with the interior of the freezer was calculated using a computational model of fluid mechanics on 3D, (FLUENT). The objective was to obtain the influence of the thermal bridge in the thermal resistance. Then we could design this component of the prototype.

With this computational model we have studied the influence of the aluminum slab and the fans used in the thermal resistance of a hot dissipater. Fig. 1 is an example of the temperature distribution in one of the simulated cases.

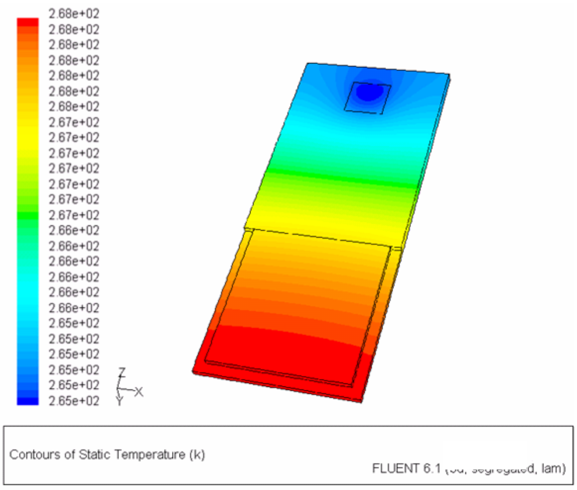

Fig. 1: Hot dissipater temperature distribution.

The thermal resistance between the hot dissipater and the freezer was obtained using FLUENT for each of the different configurations of the dissipater studied as is shown in Table 1.

Configuration	**Technical characteristics**	**Thermal resistance**
1	Dissip. with central fan & without fins	0.82 **K/W**
2	Dissip. with central fan & with fins	0.30 **K/W**
3	Dissip. with 2 fans & with fins	0.24 **K/W**

Table 1: Dissipater thermal resistances.

The thermal resistance of the fingers with the ice was calculated with (FLUENT), $R_{fingers\text{-}ice} = 0.1$ [K/W]. The temperature distribution, Fig. 2, allows studying the zones where a greater portion of insulator is needed.

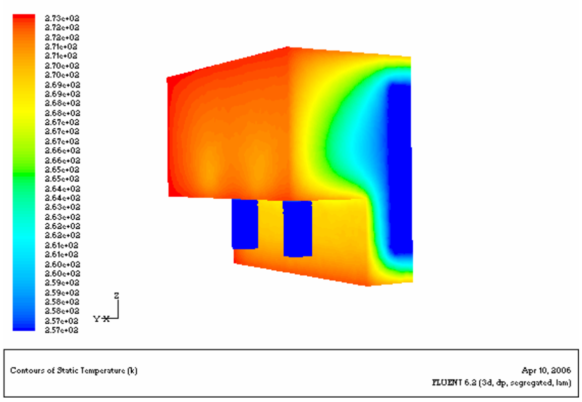

Fig. 2: Finger temperature distribution.

The thermal resistance between the ice cube and the water has two different terms. The first one is due to the heat conduction through the ice and the second one is due to the convection between the water and the ice. These terms are variable with the thickness of the ice cube, we can see in the equations (3) and (4).

$$R_{ice-water(1)} = \frac{1}{4*2*\pi*L_{fingers}} * \left(\frac{\log\left(\left(r_{fingers}+e_{ice}\right)/r_{fingers}\right)}{k_{ice}} \right) \quad (3)$$

$$R_{ice-water(2)} = \frac{1}{4*2*\pi*L_{fingers}} * \left(\frac{1}{\left(r_{fingers}+e_{ice}\right)*h_{ice-water}} \right) \quad (4)$$

The thermal resistance associated with the phase change is one of the most difficult terms to calculate becouse it depends on the geometry of the cold body in contact with the fluid and the fluid used. There are a very few investigations that analyze the problem of fusion-solidification in cylindrical coordinates. These kinds of problems are known as boundary value problems [6].

In our case using the experimental data we have determined an average value for the convection coefficient between ice and water; the surface where the heat transfer is made is the ice-cube surface in contact with the liquid phase. This surface increases as the ice mass increases, so the thermal resistance between the node which represents the solid phase and the node which represents the liquid phase is a function of time.

The fingers has a part in contact with the air of the refrigerator and another part in contact with the insulator. The expression of its thermal resistances are:

$$R_{fingers-ref} = \left[\frac{1}{4*2*\pi*L_{fingers}} * \left(\frac{1}{r_{fingers}*h_{fingers-ref}} \right) \right] \quad (5)$$

$$R_{fingers-ins} = \frac{e_{ins}}{k_{inis}*A_{fingers-ins}} \quad (6)$$

The thermal resistance between the vessel and the water is due to the natural convection between the water and the interior of the vessel, eq. (7).

$$R_{vessel-water} = \frac{1}{h_{vessel-water}*A_{vessel-water}} \quad (7)$$

The thermal resistance between the vessel of the ice-maker and the refrigerator has two terms: the conduction due to the vase thickness and the natural convection between the air of the refrigerator and the exterior of the vessel, eq. (8).

$$R_{ref-vessel} = \frac{e_{vessel}}{k_{vessel}*A_{ref-vessel}} + \frac{1}{h_{ref-vessel}*A_{ref-vessel}} \quad (8)$$

The discretization of the thermoelectric ice-maker uses the symbols of an electrical analogy, as is shown in Fig. 3. The model assigns different nodes for the ice and the water.

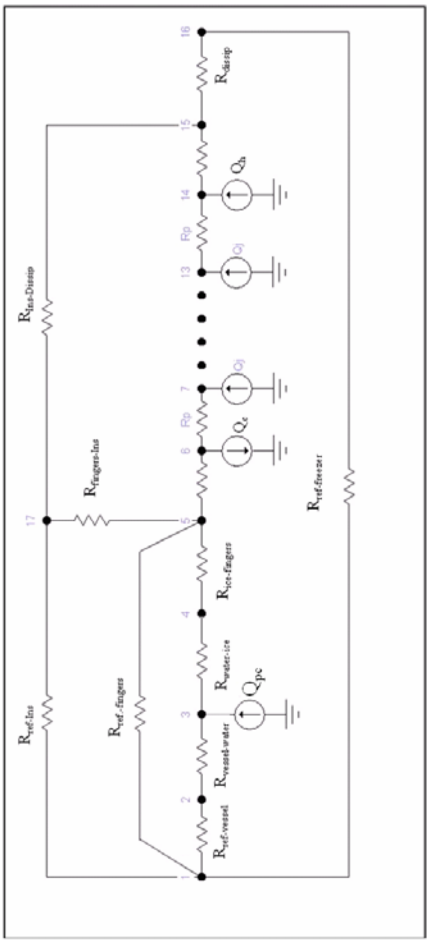

Fig. 3. scheme of the electric and thermal analogy of the computational model.

The term $\dot{Q}$ cf represents in the water node the energy needed to the phase change. When both solid and liquid phases coexist and until the phase change is over:

$$\dot{Q}_{pc} = \dot{Q}_3 = \frac{T_3 - T_2}{R_{3-2}} + \frac{T_4 - T_3}{R_{3-4}} \qquad (9)$$

The model incorporates the equations of the thermoelectric phenomena, which are the heat fluxes due to the Peltier effect eq. (10) and (11), and Joule eq (12), with no magnetic field.

$$\dot{Q}_h = -N2\alpha_h I T_h + I^2 R_{cont} \qquad (10)$$

$$\dot{Q}_c = N2\alpha_c I T_c + I^2 R_{cont} \qquad (11)$$

$$\dot{Q}_J = I^2 R_0 = N I^2 2\rho L / A \qquad (12)$$

The temperature gap used to calculate the heat fluxes due to the Peltier effect are the temperatures of the extremes of the semiconductors. The contribution of the contact thermal effects is developed in [1].

With the scheme shown in Fig. 3 and equation (2) the next system of equations in matrix format can be written:

$$[M][T_i^{'}] = [T_i] + \frac{\partial \tau}{C_i}\left[\dot{Q}_i\right] \qquad (13)$$

Experimental assembly

The assembly of the thermoelectric ice-maker in a domestic refrigerator is shown in Fig. 4 has been designed for this work and it has:

- A vessel with water.
- An ice maker device formed by 4 aluminium cylinders, called “fingers” attached to the aluminium base.
- A heat extender with known thermal resistance, used as a hot dissipater of the Peltier module. This heat extender communicates the Peltier module with the freezing space.
- Two Peltier module.

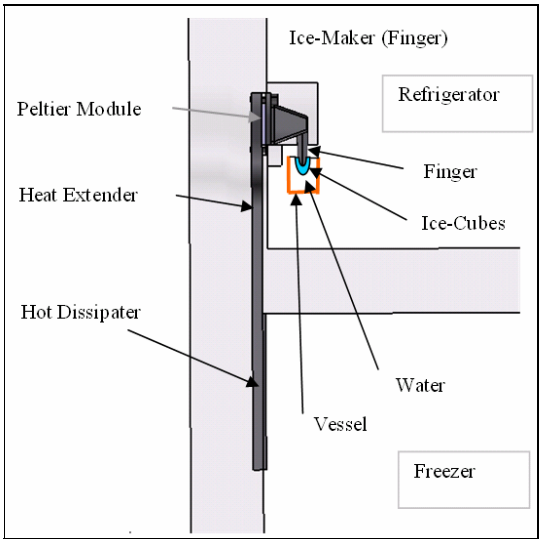

Fig. 4: Scheme of the system to model.

The Peltier module is supplied with electrical power $\dot{W}_p$. The contact face with the ice maker absorbs a heat flux $\dot{Q}_5$ and in the other face yields $\dot{Q}_{14}$.

Results and discussion

We have developed a run of test for the prototype in order to adjust the computational model. These tests were made in a climatic room to keep constant the room temperature and the humidity. The parameters that have been modified to make the study in the model and in the prototype are:

- Peltier module voltage.
- Inner temperature for the freezer and refrigerator.
- Thermal resistance of the Peltier module,
  - Varying the dissipater
  - Varying the air flux modifying the configuration of the dissipater fans.

Computational model validation

In order to make the computational model validation we have used the more favorable conditions of the refrigerator to make ice cubes. The position of the thermostat of the fridge were in the lower temperature values T_{ref} = 275 K, T_{fr}= 247 K. Configuration 2 has been used for this validation process.

The ice cube formation is a transient process, because the time needed to reach the steady state temperatures is greater than the time needed to have the ice cubes done. We calculate average temperatures. The comparison between the average temperatures in the model and the experimental temperatures from the prototype are shown in Fig. 5.

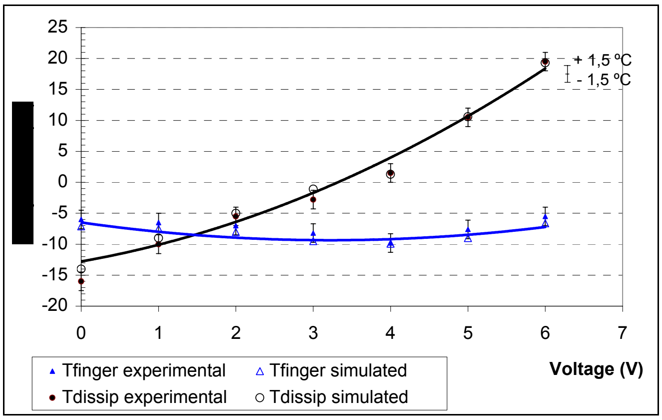

Fig. 5: Comparison of the simulated and the experimental temperatures of the ice maker.

The model results are very close to the experimental results with deviations lower than 1.5 K.

The model represents the transient state of the ice cube formation process, with great accuracy as we can see in the charts of Fig. 6 in the test made for $V_{Peltier}$= 3V.

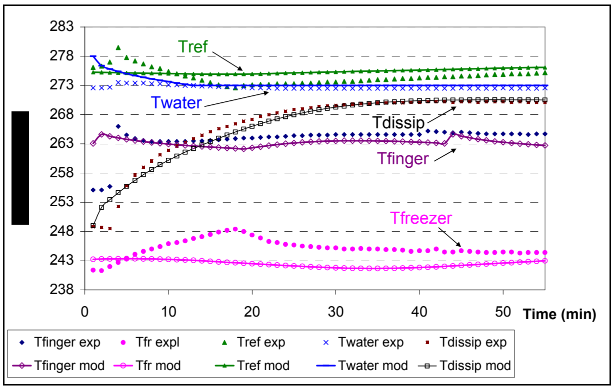

Fig. 6: Comparison of the computational model and experimental temperatures.

Influence of the refrigerator and finger temperatures in the ice production.

In order to determine the influence of the refrigerator temperatures we have tested experimentally and simulated with the model both extreme conditions. The conditions of the tests are:

The most favorable conditions to make ice cubes corresponds with the lower temperatures of the refrigerator and the freezer T_{ref}=275 K, and T_{fr}=247 K.

The less favorable conditions to make ice cubes corresponds with the higher temperatures of the refrigerator and the freezer T_{ref}=279 K, and T_{fr}=255 K.

The results have been obtained varying the voltage supplied to the Peltier modules from 0 to 5 V. The tests for both cases have a maximum of ice production lower than 5V. For voltages in the Peltier module over the ice production maximum, as the voltage is increased the temperature of the finger and the average freezer temperature are risen so the production is lower.

The two parameters that influence in the ice production are:

- The refrigerator's temperature, influences in the ice production with a decrease of the 18% in the most favorable to the less favorable working in the same conditions as shown in Table 2.
- The finger´s temperature, is directly related with the ice cube production. We have observed that the production of ice cubes increases in a 55% between higher finger temperature (T_{finger} = 267,0 K, $V_{Peltier}$= 0V) and the lower (T_{finger}=263,1 K, $V_{Peltier}$= 4V) for the case (T_{ref} = 275 K, T_{fr} = 247 K), and increases a 84% between higher finger temperature (T_{finger} = 268,0 K, $V_{Peltier}$= 0V) and the lower (T_{finger}=266,0 K, $V_{Peltier}$= 2V) for the other case (T_{ref} = 279 K, T_{fr} = 255 K), as is shown in the Table 2.

$V_{Peltier}$ [V]	T [K] Prod [kg/día]	T_{ref} = 275 K T_{fr}= 247 K Mod.	Exp.	T_{ref} = 279 K T_{fr}= 255 K Mod	Exp.
0	T_{finger}	265,9	267,0	268,6	268,0
	Production	1,96	1,77	0,90	1,00
1	T_{finger}	265,5	266,6	267,1	267,5
	Production	2,20	2,01	1,27	1,68
2	T_{finger}	265,2	266,0	266,2	266,0
	Production	2,40	2,28	1,52	1,87
3	T_{finger}	263,5	264,8	266,0	266,6
	Production	2,63	2,42	1,66	1,84
4	T_{finger}	263,1	263,2	266,5	267,3
	Production	2,77	2,75	1,44	1,64
5	T_{finger}	264,0	265,4	267,5	268,0
	Production	2,45	2,59	1,17	1,26

Tabla2. Resume of the ice production of the thermoelectric ice-maker of 4 fingers.

Influence of the thermal resistance of the hot side dissipater in the ice production.

The influence of the thermal resistance of the hot side dissipater have been tested for three different configurations. The thermal resistance for each configuration dissipater (Table 1) has been studied using a computational fluid mechanics program (FLUENT). The comparison between the model results and the experimental results is shown in Table 3. These essays were tested in the same conditions of temperature of T_{fr}=247 K and T_{ref}=275 K.

The accuracy of the model is high; the maximum error in the thermal jump is 1 K. The temperature of the fingers decreases in a 35% in case of using the 3rd configuration instead of the 1st configuration.

The experimental results of ice cubes production are represented in Fig. 7, where the mass of the ice cubes formed in a day is shown as a function of the voltage supplied to the Peltier module for the same conditions of T_{fr} =247 K and T_{ref} =275 K and for the three configurations of the hot side dissipater. This study shows the influence of the hot side dissipater in the thermoelectric devices as is shown in references [3] and [7].

	Configuration	Temperature [K]	Mod.	Exp.
1	Dissip. with central fan & without fins	T_{finger}	265,2	266,0
		T_{dissip}	268,0	267,5
		$(T_{dissip}-T_{fr})$	27,4	25,7
2	Dissip. with central fan & with fins	T_{finger}	262,3	263,0
		T_{dissip}	264,5	264,8
		$(T_{dissip}-T_{fr})$	17,5	17,9
3	Dissip. with 2 fans & with fins	T_{finger}	261,9	262,5
		T_{dissip}	263,8	264,5
		$(T_{dissip}-T_{fr})$	16,8	17,4

Table 3: Comparison between the model and prototype temperatures temperatures ($V_{Peltier}$ = 2V and T_{room} = 298 K).

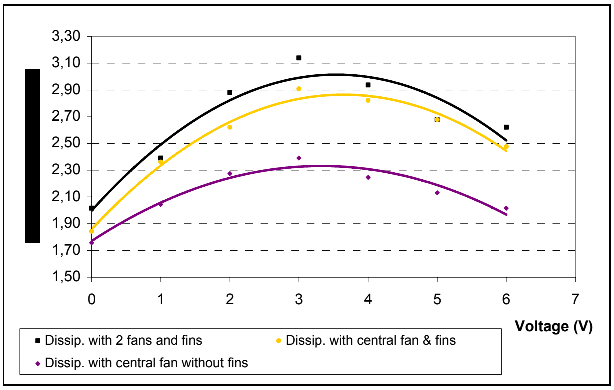

Fig. 7. Production of ice per day as a function of the voltage of the Peltier module.

The maximum ice production, reached with this prototype with the 3rd configuration is 3.2 kg/day, with a power consumption of 30W. The maximum ice production increases in a 75% in case of using the 3rd configuration instead of the 1st configuration.

The time to detach the ice cubes was very satisfactory, lower than a minute. To eject the ice cubes the voltage supplied to the Peltier module is switched so the fingers are warmed up and a thin film of liquid around the fingers is created, what allows its ejection by gravity.

Conclusions

- We have developed a computational model that simulates the behavior of the thermoelectric ice maker. This model is capable to supply the power consumption, ice formation time data so the optimal supplied voltage of the Peltier module can be calculated.
- We have studied the influence of the freezer and refrigerator temperature in the ice cubes production, for the most favorable conditions (T_{ref} = 275 K, T_{fr} = 247 K) and for the less favorable (T_{ref} =279 K, T_{fr} =255 K). The ice production decreases in an 18% from the most favorable to the less favorable case for a finger temperature of 266 K and a voltage of $V_{Peltier}$ = 2V.
- The influence of the thermal resistance of the hot side dissipater in the development of thermoelectric ice makers has been demonstrated with simulations and experimental data. The maximum ice production increases in a 75% in case of using the 3rd configuration in stead the 1st one.
- The tests show very satisfactory results with a maximum ice production of 3.2 kg/day and a power consumption of 30W approximately.

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