Evaluation of the energy driving performance of a cooling system assembled with a Peltier module operated in hot climates at different electrical currents

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Abstract. Peltier devices have two sides with two different temperatures when an electrical current is applied through it. In the hot side, heat is dissipated and in the cool side, heat is absorbed, requiring additional electrical current to decrease heat absorption, primarily in hot climates. In this work, a block model was design with a Simulink tool of Matlab software to analyze thermal performance of a Peltier module in hot-imitate climate at different electric current levels. Through this model, it would be possible to evaluate the operating conditions of different control systems for Peltier applications, such as energy optimization in human thermal comfort devises, for sports, mobility, and medical care applications.

1. Introduction

Thermoelectricity was discovered in the early 1800s by a Thomas Seebeck, how applied a voltage through a junction of two different materials generating different temperatures. A Peltier module consists of the union of several pairs of semiconductors either p-type thermocouples (free holes) or n-type (free electrons). Semiconductors are thermally connected in parallel to reduce the thermal resistance, and electrically connected in series [1] to increase the operating voltage; these semiconductors are assemble between two ceramic plates [2, 3], as showed in Figure 1. A Peltier device works as a cooler-heater when it operates as a power generator or in Seebeck thermoelectric effect.
Peltier devices are solid-state energy converters, which operate without any mechanical or movement elements. These devices have some advantages compared to other equipment of similar applications such as low noise, compactness, reliability, long service life and stability [4,5]. Moreover, the Peltier modules are light, they do not use any refrigerant fluid and the cycle can easily switch between cooling and heating [6]. The main disadvantage of Peltier modules is their low-level efficiency or coefficient of performance (COP). Therefore, applications have been limited to scientific, spatial and medical equipment, where efficiency is not the most important factor [6]; however, this technology is now being used in cooling or warming on human comfort applications, such as, portable refrigerators [7], electronic circuit coolers, vehicle seat coolers and heaters [8].

In order to simulate the behavior and analyze the energy efficiency of the Peltier modules, some mathematical models for cooling-heating and power generation have been developed. The modeling and simulations allow the analysis, design and optimization of the Peltier modules with aim to obtain the energy performance of one or several modules for a specific application. Huan Liang Tsai [5] use the Matlab-Simulink software to construct a model of a Peltier module using block design, where the interaction of the input data is carried out through an interface, which allows to run a simulation with few data as well as exiting data, such as voltage and current requirements at certain difference of temperatures between the hot and cold sides of the Peltier.

In this work, a block diagram through Matlab-Simulink platform and mathematical equations of Peltier thermo electrical effect serve to analyze the thermal behavior of Peltier heat movement in base one experimental data and identification of heat sinks. The simulation considers environmental variables such as climate temperature and power supply. In the simulation process temperature data from both, the cold face (heat absorption), and hot face (heat dissipation), heat dissipated, heat absorbed, electrical power and the coefficient of performance (COP) can be obtained. The critical parameters for the operation of thermoelectric modules were identified and the influence of ambient temperature on the operation of the Peltier module obtained with the block model with a friendly-user interface for input data which allow the evaluation of the thermal and electrical behavior of Peltier module systems.

2. Operation Principles of thermoelectric modules

In cooling operations, the heat supplied to the hot side should be dissipate by a sink with the lowest possible thermal resistance, (Figure 2). That is, if the temperature of the hot side increase and the heat absorbed is lower, the temperature of the cold side increase, consequently, the COP decrease, and the electrical power required for module operation increase. When the temperature difference is constant at a fixed electric power; that is, if the temperature of hot side is increased, the temperature of the cold side increase as well [9].

![Figure 1. Peltier module components.](image-url)
Peltier modules can be considered as thermal systems because they involve energy transfer in two forms, one of heat dissipation on the hot side and the other of heat absorption on the cold side of the module. If the thermal system is analyzed in terms of thermal resistance and capacitance [10], Thermal resistance $R_T$ ($^\circ C / W$ or $^\circ K / W$) is defined as the ratio of the temperature gradient and the heat flux per unit of time, transported through a thermal conductor [10].

$$R_T = \frac{\Delta T(t)}{Q(t)}$$  \hspace{1cm} (1)

The following expression represents the differential equation of thermal capacity [10].

$$C \cdot \frac{dT}{dt} = Q(t) \Rightarrow T(t) = T(0) + \frac{1}{C} \int_0^t Q(t) dt.$$  \hspace{1cm} (2)

3. Model building

A Peltier module has two sides, heat sinks for both sides of the module; this is a key factor to consider for the development of a model, cold side (heat absorption) and hot side (heat dissipation). The heat dissipation in this model is carried out by an electric fan. To fix properly, the use of thermal paste between the heat sink and the Peltier device is required. Heat sink and fan devices were assembled to generate the following data: Thermal resistances on the cold and hot sides ($R_c$ and $R_h$), thermal capacities of the cold and hot sides ($C_c$ and $C_h$) and thermal resistance of the paste used between the heat sink and the Peltier device ($R_s$). The thermal resistances and capacities of the hot and cold faces of the module during the absorption and dissipation of heat towards the environment are represented in Figure 3.
Considering that the energy capacity of the heat-sinks and if each heat-sink is isothermal, these can be considered as capacitive elements. By solving the previous equation for both sides of the module and rebuilt to Laplace transform, the following transfer functions were obtained:

\[
\frac{T_h - T_a}{Q_h} = \frac{R_h + R_s}{1 + C_h s (R_h + R_s)}.
\]

\[
\frac{T_a - T_c}{Q_c} = \frac{R_c + R_s}{1 + C_c s (R_c + R_s)}.
\]

\(T_a\) (K) is the ambient temperature, \(R_h\) (K/W) and \(R_c\) (K/W) are the thermal resistance of the hot and cold side of the Peltier module and the air, \(C_h\) and \(C_c\) is the thermal capacity of both sides and \(s\) is the Laplace variable used to express the equations as a function of transfer.

It should be noted that the thermal capacity depends of the size of the heat-sink and the thermal resistance depends on the following factors:

- The thermal contact between the Peltier module and the heat-sink.
- The heat-sink model
- The voltage with which the fans are fed, that is the speed at which the air through the fan moves.

Once defined the principles than run the thermal system and considering the effects and mathematical expressions that lead the behavior of the Peltier module, a block diagram model was constructed to represent the dynamics of the Peltier module in the Simulink Matlab software. The Figure 4 shows the block model obtained from the Peltier module while operating in cooling mode, where the red color represents the hot side and the blue color represents the cold side of the Peltier module. The Table 1 shows the input data required by the model to evaluate the different variables involved in the operation of the Peltier module.

![Figure 4. Diagram of the Peltier module.](image-url)
Table 1. Input parameters.

| Parameters                      | Unit |
|---------------------------------|------|
| Seebeck Coefficient            | V/K  |
| Electric Resistance            | Ω    |
| Thermal Resistance Module       | k/W  |
| Thermal Resistance Cold Side    | k/W  |
| Thermal Resistance Hot Side     | k/W  |
| Thermal Resistance Grease       | k/W  |
| Thermal Capacity Hot Side       | J/K  |
| Thermal Capacity Cold Side      | J/K  |
| Ambient Temperature             | °C   |

4. Model validation

Some graphs were generated in order to compare the behavior of the technical data of the Peltier module and the behavior obtained according to the simulations of the developed model.

Figure 5 shows that the temperature differences obtained from the simulations (left) were smaller than the ones of the technical data of the module (right), same behavior can be observed for voltage values with equal electric current values in both graphs. The temperature difference can be explained as the result of the thermal resistance variables considered for the construction of the model (hot, cold side, thermal paste and thermal capacity of heat sinks); according to X. Hao et al. [11] the higher the thermal resistance value (K/W) on the hot side of the Peltier module, the smaller the temperature difference between the hot and cold side.

5. Conclusions

The developed model allows better knowing of the Peltier module’s behavior under different conditions of ambient temperature and electric power supply; moreover, the simulations result in graphs with similar results to those provided in the technical data of the module used as reference.

Therefore, the model represents an accurate and immediate way to simulate the electrical and thermal behavior of a Peltier module under certain operating conditions and it could be used to test if the module meets the necessary conditions for a specific application. One of the advantages of the model is the possibility to perform simulations of Peltier systems without physically building the system, inferring a time and resources reduction option.

The model has no limitations and can be adapted to any type of module or manufacturer. It is only necessary to know the characteristic data of the module such as the Seebeck coefficient, the electrical resistance, the thermal resistance, and the resistance of the thermal grease used between the heat sink.
and the module. It is also necessary to know data such as thermal resistance and thermal capacity of the heat sinks that will be coupled to the hot and cold side of the module and the temperature of the environment where the Peltier system will operate.

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