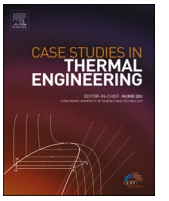
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Thermal investigation of a thermoelectric cooler based on Arduino and PID control approach

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ABSTRACT

In this study, an experimental and numerical approach is used in order to evaluate the thermoelectric cooler (TEC) control performance and efficiency. For this purpose, the refrigeration system is designed by using the semi-conductor material operating under Peltier effect, and Arduino device. The efficiency of the system is investigated through the performance coefficient and temperature span for carrier fluid between the hot and cold exchanger by using the prototype developed recently at Medea University. In addition, the proportional-integral-derivative (PID) is used in order to maintain temperature control and heat transfer of the system TEC in a closed-loop through the driving circuit, which is specially designed for the TEC can conveniently adjust the input current, which passes through the refrigerator so as to fully make use of quick cooling power advantages. The main obtained results including, the maximum coefficient of performance registered is 0.73 to 0.1 with a temperature span about of 51 °C, by inputting current of 5 A within a control temperature range 0–30 °C, while targeting a temperature of 5 °C at room temperature for the proposed control system had a control time of 21 s, with only a discrepancy of ±0.1 °C. The experimental results confirm that during the time interval 0–20 min, the inside temperature of thermoelectric refrigerator has been decreased rate of 1.5 °C/min.

It was shown through the different simulation results with PID controller by taking $k_p = 0.9$, $k_i = 0.15$, and $k_d = 0$, that the cooling temperature decreases over time to 5 °C, which means that these systems work in time-dependent conditions. The proposed controller is able to reach an error of 0.1 °C with minimal overshoot under than 20 s.

1. Introduction

The thermoelectric phenomenon has been known since the 19th century when it was first described. Since then, the phenomenon has not found a wider application, except for the measurement of temperature. It was only in the second half of the 20th century that advances in semiconductor materials achieved a sufficient efficiency for practical use. Thanks to these materials, Peltier cells designed for cooling and heating could be built using what is known as the Peltier effect [1,2]. Today, Peltier cells will achieve ever better parameters higher cooling capacities, more compact dimensions, and falling prices [3–5]. This article thus becomes more accessible and the possibility of their use increases.

Because of its several advantages, a thermoelectric refrigeration system can be a good alternative for conventional vapor

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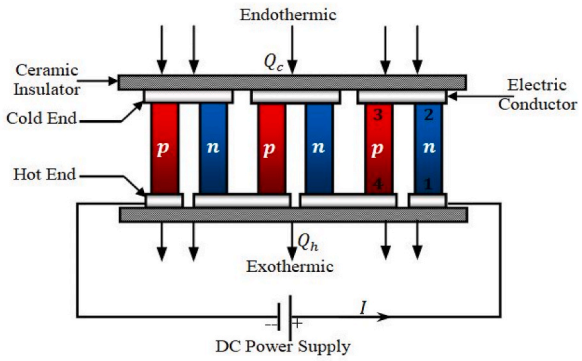


Fig. 1. Typical diagram of the Peltier module of the TEC.

compression refrigerator [6–8]. However, their lightweight and compact structure, long lifetime, rapid thermal response, silent operation, high reliability, low energy efficiency, and the fact that having no fluid with environmental impact, make them attractive to use as a portable refrigerator for preserving drugs and foods in small places such as a mini-refrigerator. In addition, the thermoelectric refrigerators system can be a good solution in several applications. In particular, we can see its efficiency in the transportation of medicinal materials to people in remote and developing communities [9–11], in addition to air-conditioning and cooling electronic components [12–14]. Peltier effect is also utilized in the design and manufacturing of isothermal microcalorimeters and PC processors [15,16], heat flow compensation and thermal analysis [17].

The flow of heat absorbed from TEC cold-side and transported to the hot-side depends on the TEC coefficients. In practice, there are two effects which are Joule heat and conducted heat, preventing ideal conditions in real applications [18–21].

One of the possibilities, which is not widely used today, is flow cooling and heating of liquids. In this work, we design and build a cooling device, in which more Peltier cells will be used to achieve sufficient performance.

Thermoelectric cooler (TEC) or Peltier module consists of N and P-type semiconductors cells by using metal plates in which. When a number of these devices are connected thermally in parallel, a single stage TEC module is formed as shown in Fig. 1. If the Peltier module is supplied by direct current (DC), it will produce heat on one side and cool on the other one [21–24].

Nowadays, thermoelectric cooling technology has been used in many industrial applications such as the TE refrigerator, production of fresh water and active building envelope system, electronic and automobile cooling, aerospace equipment, etc. However, the thermoelectric coefficient of performance (COP) and cooling rate are the important indicators for any design of thermoelectric cooling systems [25–28].

There exist several approaches for the enhancements of thermoelectric cooling control system performance including Proportional-Integral-Differential (PID) Control [29–32], fuzzy control [33], neural network control, and adaptive control. Some methods that combine PID control with fuzzy logic control have been applied in the field of temperature control [34].

From the above concepts, the thermoelectric cooling system performance has been guaranteed by controlling the variation of input current. TEC module of 12,706 types which is composed of Bi_2Te_3 semiconductor material [35], has been used. Here, the purpose of cooling system control is expected to keep the internal temperature of an object below the ambient temperature of around ± 30 °C.

In literature, Temperature control systems in the thermoelectric cooler have been investigated by several researchers with regard to working environmental conditions and energy efficiency.

Shaojing et al. [36] have developed an adaptive PID neural network approach to control the temperature in thermoelectric systems.

Vian and Astrain [37], have carried an experimental analysis of hybrid refrigerator including vapor compression and thermo-electric cooling.

Çağlar et al. [38] have designed a mini-thermoelectric refrigerator using a Peltier heat pump. Both sides of refrigerator were equipped with fans-Peltier element. The results showed that the environment temperature obtained was 293 K. Moreover, the COP has been decreased from 0.351 to 0.011 when the cooled space temperature has been reduces from 293 to 254.8 K.

The experimental results obtained in Ref. [39], have demonstrated that the portable solar thermoelectric refrigerator designed, could reach the desired temperature of about 10 °C. The higher COP founded is about 0.61 with a temperature difference of 50 °C.

Erdem Cuce et al. [40], have investigated through a comprehensive experimental methodology of the impacts of nanofluid use in thermoelectric coolers (TECs) on cooling power and main performance parameters. They found that the achieved results for the COP ranges between 0.62 and 0.42.

The authors Min and Rowe have studied a domestic TEC to assess the performance of the prototype in terms of cooling rate and the COP [41]. They have registered an increase in COP through improvement contact resistances, thermal interfaces and the effectiveness of heat exchangers. As for the COP value, it has varied in the range of 0.3 and 1.1.

Ning Wang et al. [29], have based on an improved PID algorithm to design an efficient TEC temperature control system.The aim of their research was to determine which energy feedback approach is used to enhance TEC cooling. To improve the energy utilization efficiency of the system, The COP value was increased from 4.2 to 5.08 for changing the duty cycle.

Faraz Afshari [42] has presented a theoretical and experimental approach to evaluate the TEC efficiency in two different modes. Air-to-water mode is more efficient than air-to-air mode. However, the obtained COP value of air-to-water mode is approximately

Table 1
Temperature span and COP ranges and of refrigerators presented in literature.

TEC description/Numbers	Heat transfer description	Temperature span ΔT (°C)	Performance Coefficient COP	References	Year
TEC1-24116T200/4	Forced air/Forced air	85	–	[30]	2018
-/48	Open cathode/Air (integrated cooling fan)	65	–	[7]	2019
TEC1 -12706/1	Forced air/forced air	49.3	0.011–0.351	[44]	2018
TEC1 -12706/1	Forced air/Forced air	32.7	0.74	[20]	2021
TEC1 -09605FX/1	Aluminum plate/Forced air	30	0,28-0,31	[2]	2021
TEC1-12706 (15 mm × 15 mm x 5 mm)/1	Forced air/Natural convection	30	0.61	[23]	2020
TEC1-12715/1	Forced water/forced air	26	0.41–0.46	[40]	2020
MCPF-161-12-10-E and MCPF-127-14-16-E/ Series and Parallel	Forced air/Forced air	22 –	0.74 0.70	[71]	2019
–	Forced air/forced air	25	0.16–0.64	[73]	2018
–	Aluminum plate/forced air	15.1	0.07	[4]	2017
TE-127-1.4-1.5	Forced air/Forced air	10	0.0735	[26]	2018
CP2-127/1	liquid cooling/forced air	13.6	1.16	[38]	2006
Bi_2Te_3 TEC type/1	Aluminum plate/Forced air	58.75	4.2036–5.0866	[29]	2022
TEC1-127,061	liquid cooling/liquid cooling	20	6	[49]	2020
TEC1-12,715/1	liquid cooling/Forced air Forced air/Forced air	– –	0.016 0.0085	[42]	2020
Single TEC/TEC1-12709	Minichannel, forced water/ Forced air	–	0.18	[43]	2017
TEC 12706/2 seriesconnected	Forced air/forced air	–	0.21	[31]	2017
TEC1 -12715/2 stage parallel	Natural convection/Natural convection	–	0.327–0.401	[21]	2021
TEC1-12706/3	Air conditioning/liquid cooling	–	0.6091	[22]	2020
TEC-12715/1	Forced air/forced air	–	0.6694	[39]	2020
TEC1 -12706/1	Evaporator plate/Stainless steel block	–	0.56–1.05	[3]	2019
Modified pulse operation of 24 TECs in series	Natural convection/Natural convection	–	1.01	[25]	2017

0.3–0.5 higher than that of air-to-air refrigerator.

Murat Gökçek et al. [43], have presented the experimental performance assessment of water-cooled Mini-block based thermoelectric cooler. The COP value of the refrigeration system has been evaluated at 0.41 in different supplied voltages and water flow.

Paulo Rafael V. Meris et al. [44], have designed a portable thermoelectric cooler with Arduino-based temperature controller for Prevnar 13 vaccine. The lowest temperature attained in the prototype was 8 °C in a conditioned environment and 11 °C in an unconditioned environment which are within the required temperature range. The computed COP value for the system was 0.67 and the actual value of the whole was 0.09.

Feng Chi et al. [45], have introduced the principles of TEC temperature control circuit based INA330, power amplifier circuit, and PID compensation utilized to keep the ambient temperature of the photodiode stable. A literature review has been performed to establish a comparison with our present study. All the published papers are summarized in Table 1.

In this work, an experimental and numerical approach is used in order to evaluate the TEC performance through its operational parameters. The refrigerator system was modeled and controlled using the PID based Matlab/Simulink and S-function block to set the error between input current profile and cold-side desired temperature of TEC efficiency.

2. Numerical model of TEC

2.1. TEC description and governing equations

A thermoelectric refrigeration system is essentially based on the Peltier effect. The Peltier thermoelectric effect is that when a direct current flow passes through a circuit consisting of different metal conductors, a slight effect of cooling (Q_c) will occur in the lower side of the thermocouple (where heat is absorbed), and a heating effect (Q_h) will occur in the upper side (where heat is expelled).

The efficiency of a TEC module depends on the amount of heat transferred, the temperature difference between its sides, and the applied current. Note that this effect can be reversed [46]. The main elements of the TEC are presented in Fig. 1.

The heat produced or absorbed per the Peltier element, is determined by:

$$Q_p = \alpha.I \tag{1}$$

where α is the Peltier effect represents the amount of heat transported by a single charge at the TEC cold side and $\alpha = (\alpha_1 - \alpha_2).T$. Here, α_1 and α_2 are respectively the thermoelectric voltage coefficient of semiconductor type p and n junctions. T is the temperature on the relevant side of TEC device.

The TEC can not only produce the Peltier effect, but it can also introduce other effects such as the Seebeck effect, the Thomson effect, and the Joule effect [47]. It is important to keep in mind that the Peltier effect and the Joule effect are not excluded. They have different physical bases and coexisting, in addition to the thermal conduction impact, in this case. The Thomson effect is relatively

Table 2
Technical characteristics of Thermoelectric Module (TEC1-12706).

Hot side temperature[°C]	30
Maximum Temperature difference ΔT_{max} [°C]	$\geq$ 65
Maximum Absorbed heat Power Q_{max} [W]	$\geq$ 51
Number of the thermocouples, n	127
Material	Aluminum Oxide
Thickness [mm]	3.8
Length [mm]	40
Width [mm]	40
Geometric factor, Ge [mm]	1.2
Length of element, Le [mm]	2
Maximum Electric current I_{max} [A]	6
Maximum Voltage U_{max} [V]	15.4
Measured Resistance $R(\Omega)$	2.5

negligible [48,49].

The TEC cooling efficiency should be the result of the mixture of these phenomena. The rate of thermal energy generation by Joule effect is [50]:

$$Q_j = \frac{1}{2} I^2 R \tag{2}$$

where R is the thermoelectric cooler resistance. The amount of heat transfer from the hot side to the cold side is given by following equation:

$$Q_e = \kappa_{th}.(T_h - T_c) \tag{3}$$

where K_{th} the thermal conductivity coefficient of the thermoelectric refrigerator. T_h and T_c are respectively the hot side temperature and cold side. Therefore, the heat transfer rate between the two sides of TEC can be calculated by the following relations:

$$Q_c = \alpha.I - \frac{1}{2} I^2 R - \kappa_{th}(T_h - T_c) \tag{4}$$

$$Q_h = \alpha.I + \frac{1}{2} I^2 R - \kappa_{th}(T_h - T_c) \tag{5}$$

The temperature of the thermoelectric module hot side is assumed that is higher than that of the ambient temperature, which allowed to neglect the effect of thermal conduction from the outside to the inside of the Thermoelectric device [24]. The other parameters are calculated by the following equations [41].

Electric Voltage (V):

$$U = \alpha.(T_h - T_c) + I.R \tag{6}$$

Input electric power (W):

$$P = \alpha.I.(T_h - T_c) + I^2.R \tag{7}$$

Cooling production:

$$Q_c = \alpha.I.T_c - \frac{1}{2} I^2 R - \kappa_{th}(T_h - T_c) \tag{8}$$

where Q_c represents the cooling production by the Peltier junction. When the two terminals of the TEC are under tension, the Peltier effect, the thermal conduction power $\alpha.I.T$ through the thermocouple according to Fourier's law, and losses due to the Joule effect will be generated at the contact surfaces of the two sides of Thermoelectric device. As a result, the TEC cooling capacity can be calculated by Eq. (8).

2.2. Temperature control approach of TEC

When designing TEC control, the input electric current must be regulated. The direction of current flow can achieve the conversion between heating and cooling in TEC [51–53].

The ambient temperature can be influenced the cooling efficiency of the refrigerator. However, the cooling temperature that the TEC device can reach is not the same under different values of ambient temperature.

Joule effect and thermal conductivity reduce the cooling performance of the TEC. The use of a fan is necessary for heat dissipation under the cooling condition of TEC, which allowed to reduce the influence of the refrigeration effect due to thermal conductivity and Joule effect.

The semiconductor device used in this study is the TEC1-12706 Module. Practically, when powering TEC with DC source and controllable input current, the temperature values of the cold and hot sides can be obtained with two DHT22 sensors (accuracy of up to

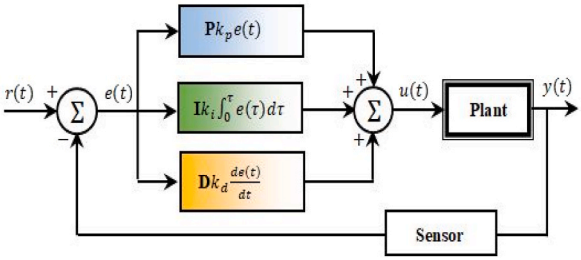


Fig. 2. Functional block diagram of PID controller.

0.1 °C).

The TEC input current varied from 0 A to 6 A with a step of 1A was adjusted and simulated the variation of the temperature after waiting 10 s to reach the steady-state in the TEC system. The characteristics data on the TEC device are given in Table 2.

Table 2. Technical characteristics of TEC1-12706 Module.

The temperature difference named temperature span ΔT between the cold side and hot side of the TEC module can be expressed as [12,54–56]:

$$\Delta T = \left(S.I.T_h - 0.5I^2R\right)/(S.I + \kappa_{th}) \tag{9}$$

where S the Seebeck coefficient. Because the Peltier coefficient α is much more difficult to measure than the Seebeck coefficient used the conversion equation to reach them from known values of Seebeck coefficient $\alpha = S.T$.

The expression of the maximum temperature difference gradient can be defined by putting the derivative of ΔT (°C) with respect to I and setting out the result to zero. The maximal current and temperature forms can be given as follows [12,54,57,58]:

$$I_{\max} = \kappa_{th}\left(\left(1 + 2.S^2.T_h/R.\kappa_{th}\right)^{0.5} - 1\right) \Big/ S \tag{10}$$

$$\Delta T_{\max} = T_h + \left(1 - \left(1 + 2.S^2.T_h/R.\kappa_{th}\right)^{0.5}\right) \Big/ S^2.T_h \,/\, R.\kappa_{th} \tag{11}$$

However, the maximum voltage between the TEC terminals can be rewritten as [41,59]:

$$U_{\max} = S.T_h \tag{12}$$

The expression of electric current at the TEC input can be given as indicated in Eq. (13) which takes into account the voltage drop and the Seebeck effect:

$$I = \frac{U - \alpha.\Delta T}{R} \tag{13}$$

By using Eqs. (4), (5) and (7), the heat dissipated at the hot side of the TEC is the sum of the one consumed at the TEC cold side and the one absorbed by the Peltier Module:

$$Q_h = Q_c + P \tag{14}$$

Then, the hot side cooler power is given as:

$$Q_h = \alpha.I.T_h + \frac{1}{2}I^2R - \kappa_{th}(T_h - T_c) \tag{15}$$

Substituting Eq. (9) into Eqs. (8) and (15), the update of the absorbed and released heat powers can be obtained respectively:

$$Q_c = \frac{\alpha.U.T_c}{R} - \frac{\alpha^2.T_c.\Delta T}{R} - \kappa.\Delta T - \frac{U^2}{2.R} + \frac{(\alpha.\Delta T)^2}{2.R} \tag{16}$$

$$Q_h = \frac{\alpha.U.T_h}{R} - \frac{\alpha^2.T_h.\Delta T}{R} - \kappa.\Delta T + \frac{U^2}{2.R} - \frac{\alpha.\Delta T}{2.R} + \frac{(\alpha.\Delta T)^2}{2.R} \tag{17}$$

3. PID control algorithm design

Among the types of control used in residential and industrial installations, the PID methods are the most accurated and recommended [60–68]. Due to their simplicity and ability to provide an excellent control performance, they constitute a good solution to the control of large number of current industrial processes, because the implementation of the PID is based on a digital design. Thus, these digital PID include many algorithms to improve their performances, such as autotuning, anti-windup mechanisms, fuzzy fine-tuning, and adaptive. However, the basic actions remain the same [69]. PID control is based on the mathematical modeling of a problem, represented by a process loop to control.

This type of control works with the difference between the expected value of a process variable and its real value, measured using a sensor. It allows the control with low offset error and good stability, which is the reason why it is widely used in academic projects and industry [70,71].

The proportional action (P mode) adjusts controller output according to the size of the error. It is based on current behavior of the system. The integral action (I mode) is the accumulated effort using the experience information of bygone state to eliminate the steady-state offset and the future trend is anticipated via the derivative action (D mode), which makes use of the predicted future values of the control error and accelerate thus the response time. In order to enjoy the advantages of each of these control modes, these three actions are combined, in such a way that a stable feedback controller is produced, and the control output at desired setpoint is delivered (see Fig. 2).

Fig. 2 shows a closed loop of our thermoelectric cooler control system [72], in which a PID controller operates. A set-point is defined, i.e. a desired value for the controlled variable. The exit of the loop is a sensor that monitors the value of the same variable. The system calculates the difference between the set-point and the measured value and transmits it to the PID controller, which acts to reduce this difference to zero. In the actual system, the Plant is the TEC.

Continuously, a PID controller algorithm calculates an error value $e(t) = r(t) - y(t)$ as the difference between a desired setpoint $r(t)$ and a measured process variable $y(t)$ as the feedback signal from the process plant and produces a combined response or controlled output signal $u(t)$ which is applied to plant control devices.

The gains or adjustment parameters of the PID can be obtained by different methods. In this work, trial and error method has been adopted; this method makes the adjustment relatively easy. The first step is to set I and D terms to 0. Then, we increase the proportional gain P until we notice an oscillation in the response, which should revolve around the set point. Care should be taken with the stability of the system. From there you can change the full term of the controller. Increasing this term reduces the error between the actual temperature and the desired.

Finally, also modifying the value of the derivative term generates a decrease in overshoot, an increase in gain a maintain of stability, thus providing a system that is very sensitive to noise. The latter parameter is generally used only in systems that require greater precision and control to dealing with sudden and rapid changes in external parameters.

The temporal representation of the actions described above is given below:

$$u(t) = k_p e(t) + k_i \int e(\tau) d\tau + k_d \frac{de(t)}{dt} \tag{18}$$

where k_p, k_i, and k_d denote respectively, the proportional, integral, and derivative action gain.

The temperature of the thermoelectric cooler system has been set to shorten the stabilization time upon reaching a steady-state signal, while trying to minimize the overshoot of the desired temperature [5,73]. PID regulator is based only on the variation of the temperature measured inside the thermoelectric cooler and not on the knowledge of the underlying system. The response of the controller can be described in terms of the difference made between the desired temperature and the measured temperature [74,75].

The feedback control loop designed to regulate the cold flow of the TEC module which decreases the refrigerator actual temperature is based on the minimization of the quantity [71]:

$$e(t) = T_{C_Actual}(t) - T_{C_ref}(t) \tag{19}$$

where $T_{C_ref}(t)$ is the user-defined reference cold side temperature of the TEC.

In the closed-loop of the TEC system simulation model, the cold side reference temperature of the TEC model is chosen to be equal to the DC power supply current form as below:

$$T_{C_ref}(t) = I(t) \tag{20}$$

The TEC model presented in MATLAB/Simulink is developed as a function of time to approximate the evolution of the parameters depending on the temperature over the length of TEC. In this article, S-Function developed allowing to process a set of programs and interface it with the Simulink model to allow dynamic changes of TEC parameters. The measured values of T_h, T_c, and I are respectively used at the input of the thermoelectric refrigeration simulation model.

To start the simulation, the initial values shown in Table 2 have been used. The output of this S-function is again used as feedback for the next simulation step.

Some applications require using only one or two terms and setting the other parameters to zero in order to achieve the performance of the appropriate system control. The PID controller is quite more efficient, since the measurement noise of the sensors affects the sensitivity of the derivative action, whereas the absence of an integral action may prevent the closed-loop system from reaching its desired performances [74].

The developed PID controller has been implemented on Matlab/Simulink model in order to impose for simulation the different temperature gradient from the temperature values taken on the cold side of the TEC model.

Generation of a certain waveforms of the input DC current is expected to produce specific of TEC cold side temperature response. However, it is tricky designing a controller adapts to these input and output waveforms of the system. The refrigerator thermal behavior is dynamic and inherently nonlinear. As for the parameters of the PID controller, they will often vary in optimal values under different operating states. Fortunately, in thermoelectric refrigeration systems, the temperature response is slowly occurring over several moments. This allowed us to adjust the PID controller in real-time and by simple modifications of its parameters.

The Zeigler-Nichols closed-loop method is used to manually adjust the PID controller parameters with keeping constant two

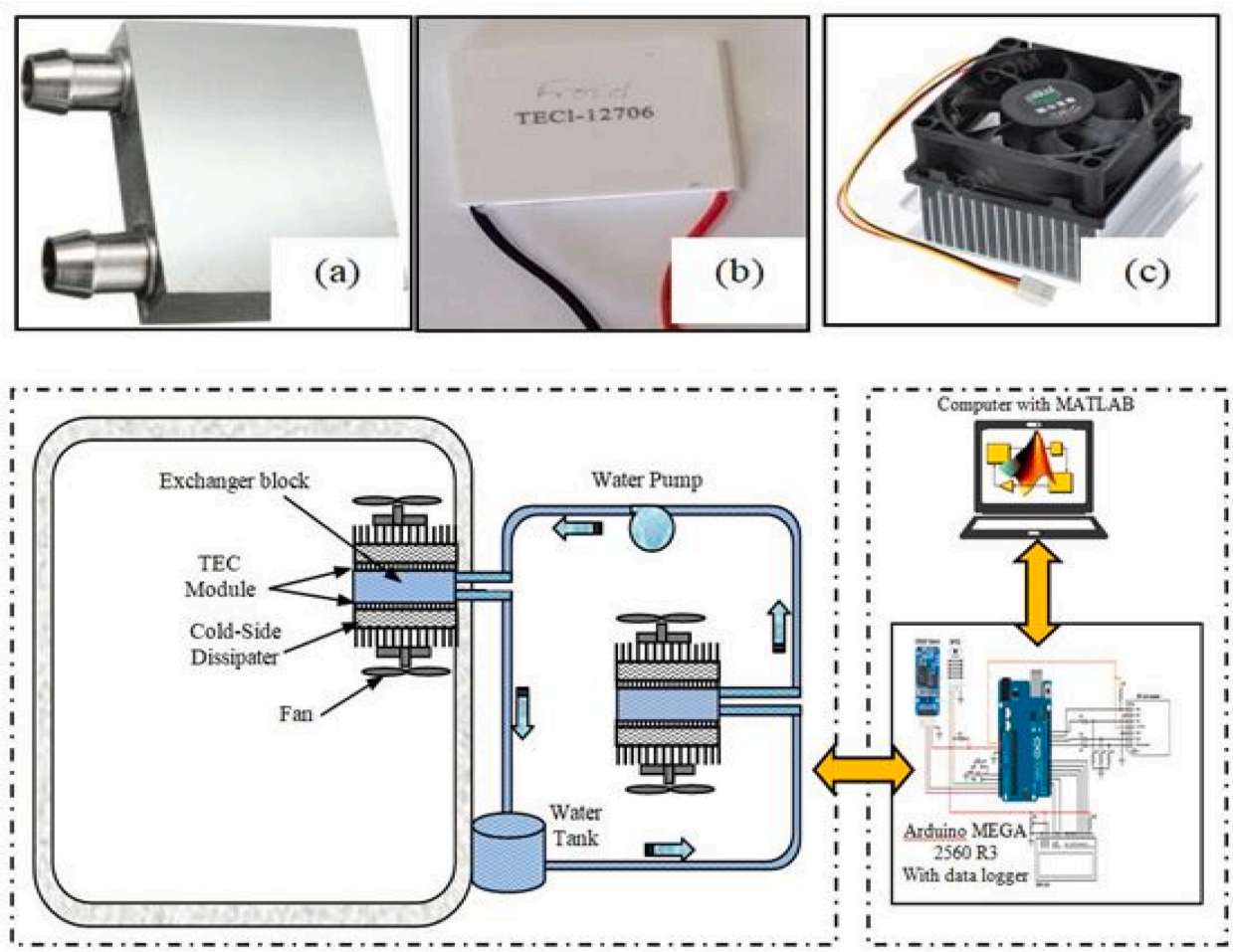


Fig. 3. Schematic diagram of the experiment setup (a) cooler-water block; (b) TEC module; (c) Heat sink and cooling fan.

Table 3
Specifications of the water-cooler block.

Specifications	Value
Dimensions (LxWxH) [mm]	40 × 40 × 12
Internal fin thickness [mm]	0.5
Spacing [mm]	1

parameters and varying the remaining ones until the overshoot and settling phase specifications were reached on all ranges of interest [75].

4. Experimental apparatus

This section involves an experimental construction of a thermoelectric refrigerator. A schematic diagram of the experimental setup used in our study is shown in Fig. 3. The device consists of internal and external heat exchangers. The first one is designed according to the possibility of use in the food industry. As for the second one, it will be used for possible heat dissipation. The heat transfer between these exchangers will be provided by Peltier cells, Heat sink, fans, water tank, DC power supply, and pump.

A refrigerator is designed for the experimental study with an inner volume of 0.05 m^3. As the device contains a number of these cells in which the consistent selection is the key to the proper functioning of the device, a comparative cell measuring device is designed and constructed. Therefor, it will be possible to determine how a particular cell will behave in the device.

For the proper functioning and use of the properties of Peltier cells, a source using pulse width modulation with processor control is designed and constructed. The processor will allow a great variety of the system. It will therefore be possible to find the optimal parameters.

The two hot-sides of peltier for which the characteristics are listed in Table 3, were attached to their inner water-cooler block to

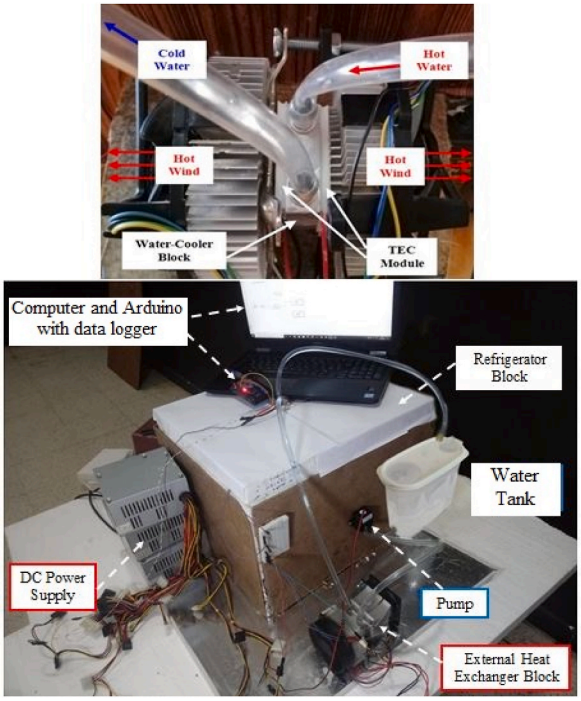


Fig. 4. A complete assembled to the thermoelectric refrigerator and external Installation of the Water Cooler Block.

reject the heat flow released in the inside of the TEC. The heat sink in the TEC cold side is made of aluminum alloy. The heat sink and cooling fan dimensions are 40mm × 40 mm, which is the same size as that of the TEC.

Fig. 3, shows the TEC1-12706 Peltier unit and a schematic diagram of the experiment Setup. The thickness is 3.8 mm. To eliminate the thermal contact resistance effect in each surface of the TEC, a paste with high thermal conductivity has been used. The module has been designed so that the heat sink is in the internal part of the refrigerator. However, the TEC is in the middle and vertical to the wall (refer to Fig. 3).

The Peltier thermoelectric module constituted of two symmetrical internal heat sinks, two TEC cells placed symmetrically with respect to the heat block of the internal exchanger, and two external heat sinks located in the upper part of the inner case. One of the heat sinks has been installed to increase the cooling of the box and the other to improve the heat rejection effect.

A cold-water circulation system was used to cool the surfaces of the modules inside the refrigerator. In order to keep the cold water at the same temperature (always between 13 °C and 15 °C) during the measurement, a PID-controlled water distributor with LM35 temperature sensor input, is used. Here, it is important to highlight that the reference temperature can be adjusted. The volume of water in the cooled-circuit has been chosen to be 0.3 L. To detect the thermal values of the hot (T_h) and cold (T_c) surfaces, two DHT22 types thermocouples have been used to find the temperature difference (ΔT) between surfaces.

A data acquisition system, At Mega Arduino 2560 and MATLAB/Simulink, allows the periodical acquisition on the related measures in real-time. The water flow has been regulated by the power supply voltage of the pump. The water leaving the system has been passed through another heat exchanger block which is located outside the refrigerator for water cooling by the TEC cold sides and the hot sides of outer TECs are provided by fans (12 V-3A) in order to evacuate the heat released in the heat sink and to reduce water temperature. DC power supply has been used to provide the power required in cooling fans.

The Arduino platform has been chosen to control the cooling flow. Arduino which is based on a simple board and an IDE environment, is one of the most popular open-source platforms today.

The main goal is to improve the performances of the designed refrigerator using a PID algorithm.The refrigerator COP and its Inner temperature have been adopted as two different performance indices. To enhance the refrigeration performance, the temperature of the circulating water must be maintained. The COP expression is the ratio between the cooling production and electrical power consumption of the refrigerator. It can be obtained as follows [12,76]:

$$COP = \frac{Q_c}{W} = \frac{T_c}{T_h - T_c} \tag{21}$$

Fig. 4 shows in details of the external configuration of the water-cooler block, with Peltier elements, fans and heat sinks. Thermal paste and screws have been used to merge each of them. The displays of the full assembly of the thermoelectric refrigerator installation have been powered with a DC source (voltage = 12.0 V, current = 5.0 A). To obtain a stable decrease of temperature in the internal of the refrigerator box, the experiment has been lasted 2 h and a half long. During this experience, the TEC Peltier surface temperatures (T_c and T_h), the temperature of internal space T_{int} have been measured then logged. The temperature of the ambient ($T_{ambient}$) has been

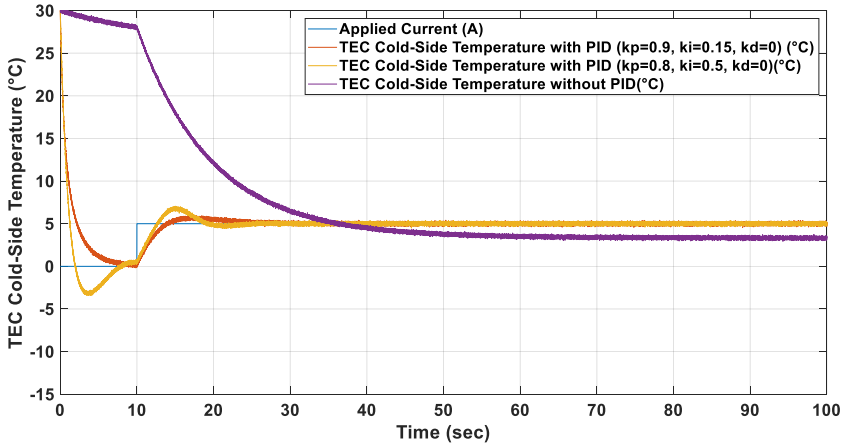


Fig. 5. Thermoelectric cold-side temperature with PID and Without PID controller.

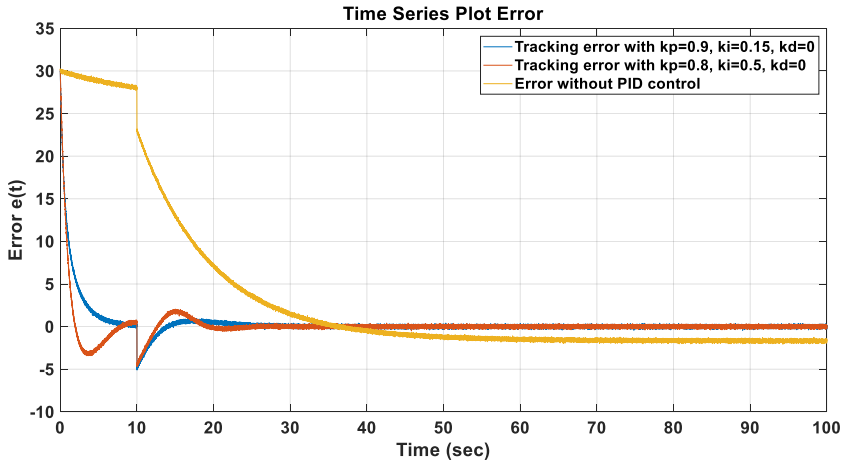


Fig. 6. Time series error with PID and Without PID controller.

measured and recorded every 60 s because the experiment has been conducted in an open environment.

5. Results and discussions

PID Control block receives the values of (k_p, k_i, k_d), and the desired temperature value after computing the difference between this value and the temperature of the cold side of the TEC Module. The initial value of TEC cold side temperature has been chosen to be equal to the ambient temperature for the different simulation cases, $T_{c_ambient} = 30\ ^{\circ}C$.

The simulation result of Fig. 5 shows that the TEC's cold-side can have the lowest temperature of −4 °C. However, this lowest temperature has lasted only for 3 s and after a period of 20 s the value of the temperature of the TEC's cold side reaches is 5 °C and stabilizes at this value when the PID control is applied in both cases. This stable temperature value is used as the reference set value of the PID algorithm. We obviously prove that applying PID into a thermoelectric refrigerator accelerates the cooling rate about three times faster.

Based on the Ziegler-Nichols tuning method, k_p, k_i, and k_d were predicted around 0.9, 0.15, and 0 respectively. Varying the k_p, k_i, and k_d these parameters around the previous values leads us to the conclusion that the best PID parameters fit well with the Ziegler-Nichols prediction.

A Comparison of the open-loop error response of the TEC system with respect to the closed-loop error response is illustrated in Fig. 6. It shows a significant improvement in terms of the desired temperature tracking performances.

The electric power used in each TEC is equal to 60 W. The water in the internal water-cooler block used to reject the released heat from the hot side of the TEC was absorbed by the pump to cool it by the external water-cooler block. During 150 min, the ambient temperature has been varied between 30 °C and 31 °C as a condition of experimental study.

Fig. 7 shows that the inner temperature values and time were measured for finding the temperature increases rate and the ambient temperature of refrigerator box. During the interval of time between 0 and 20 min, the inside temperature of refrigerator box has been

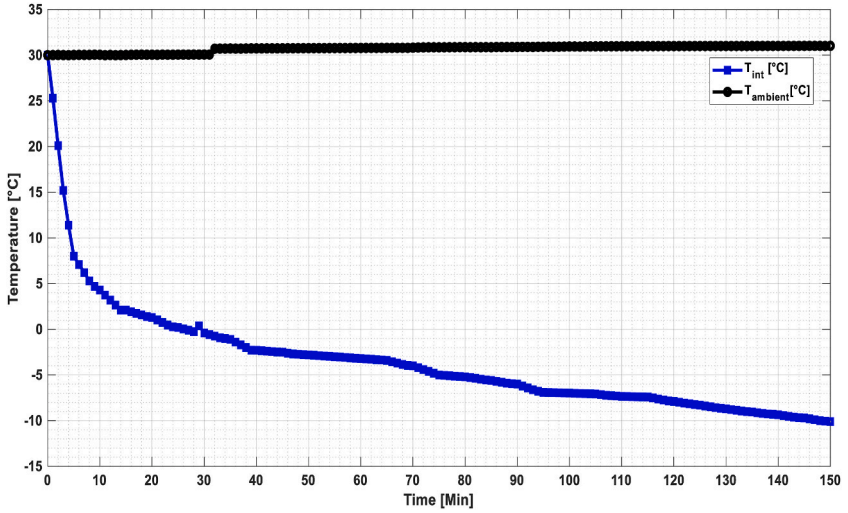


Fig. 7. Inner temperature, ambient temperature of TEC profiles versus time.

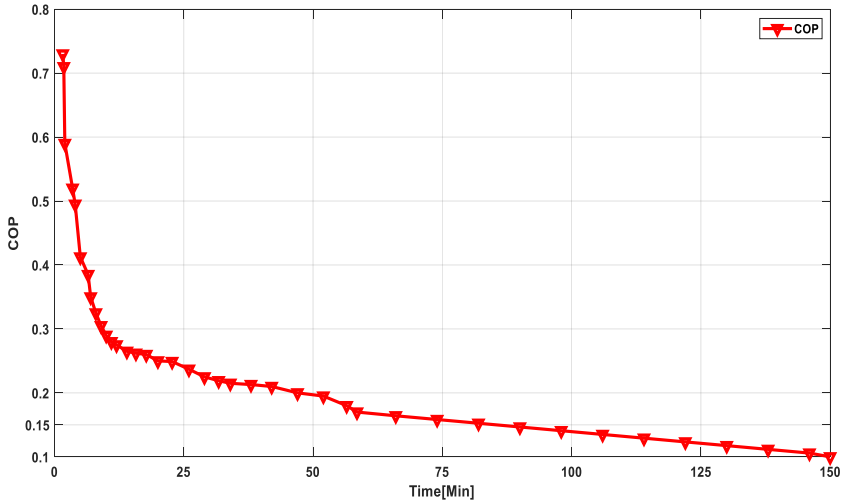


Fig. 8. COP variations during test time.

decreased rate of 1.5 °C/min. The minimum temperature has reached −10.1 °C.

The TEC's lower-cooling behavior at temperature differences between the inside and outside surfaces of the Peltier Module (or fins), has driven to a gradually decreases in the associated coefficient of performance (COP) as shown in Fig. 8. The COP value changes from 0.73 to 0.1 during the experiment. We have found that COP value of refrigerator are notably low. Moreover, it was seen that the COP value of the whole system are better to the similar studies in the literature.

In Fig. 9 we illustrate the variations of cold side temperature and hot side temperature inside thermoelectric modules, as well as the ambient temperature versus time for 1 L/min flow rate. From Fig. 9, we can see that the cold side temperature of the thermoelectric cooling unit decreases quickly during the first 30 min then it stays steadily below −5.0 °C after 2 h.

After 10 min, hot temperature T_h has approached to 46.01 °C. After 14 min have elapsed, it was rather constant. As for Tc, it has got closer to −5.0 °C after 30 min (refer to Fig. 9). The ambient temperature has been varied between 30 °C and 31 °C during the experiment. The temperature span between the two sides of the TEC has reached 51.01 °C after only 30 min.

As it can be seen in Fig. 10, the water temperature of the internal water block increases to 46.01 °C after 20 min then it drops to 15 °C after 90 min. After 120 min, the temperature of the external cooling water block reaches about 5.0 °C. As for the volume of water in the tank, it is constant during the experiment. We can see that the temperature of the water in the tank increases from 30 °C to 40 °C in 20 min and then drops to around 12 °C after 90 min.

6. Conclusions

The notion of stability under operating constraints is a delicate step for thorough an appropriate behavior of the TE refrigerator. In

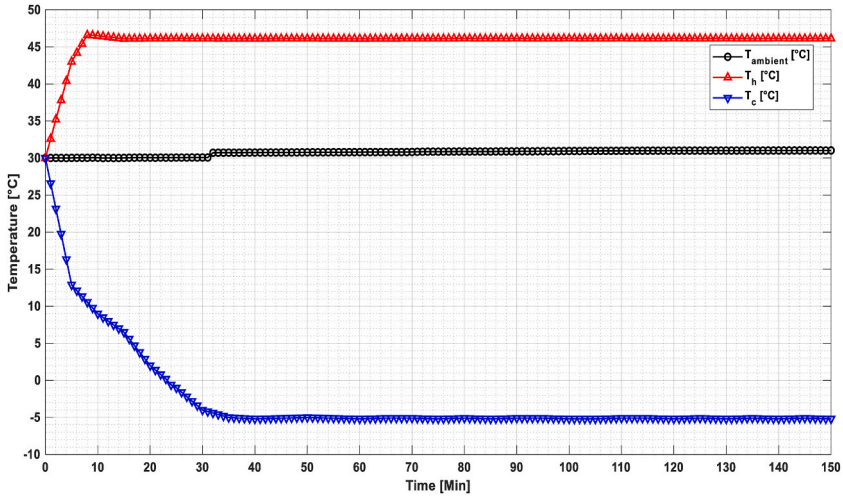


Fig. 9. Experimental relationship of time and temperatures of T_c, and T_h and ambient temperature $T_{ambient}$.

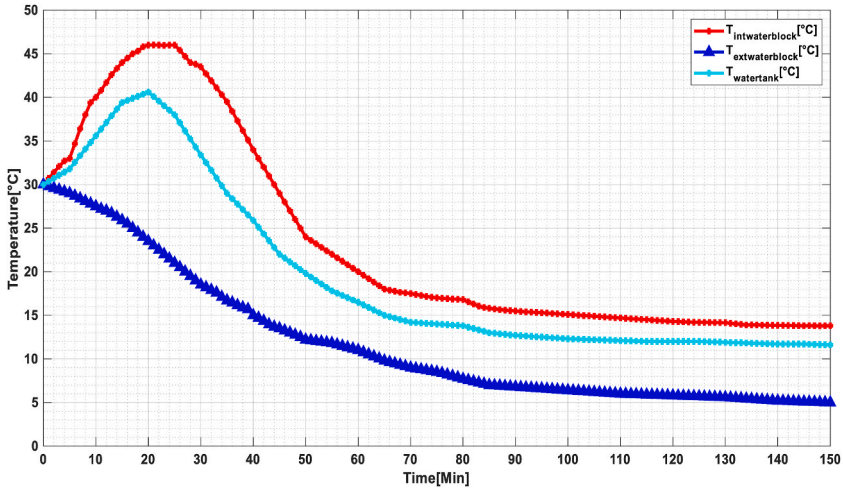


Fig. 10. Experimental relationship of time and temperatures of internal water block $T_{int_water_block}$, external water block temperature $T_{ext_water_block}$, and water tank temperature T_{water_tank}.

this paper, a PID control technique has been proposed to force the user-desired refrigeration temperature gradient on a TE refrigerator. The Ziegler-Nichols method has been adopted to set the parameters of the controller. The component derived from the controller has not been used, so the controller functions have been utilized as PI controller. Even in this case, the transient characteristic has a relatively small overshoot and a short stabilization time, especially with a large decrease in the recipient temperature.

In this study, the TEC has been used for direct temperature control on the inside of a TE refrigerator and cooling water circulates in two water aluminum blocks. The influences of heat sink temperature, flow rate, and current have been analyzed by calculation. The highest COP has been obtained as 0.73. The COP value has decreased over time during the cooling period and to get closer to zero, which means that these systems work in time-dependent conditions.

The proposed control system has been validated by the Matlab/Simulink model which has proved its ability to keep the operating temperature profile constant following the modification of the supply DC current. The cold side reference temperature chosen as equal to direct current form, where $T_{c_ref} = 5\ ^{\circ}C$.

The results of simulations in the case of using PID controller have shown its performance in terms of stability. The response time for the various tests is for the variations of PID controller parameters on one hand, and on the other hand, the change the power supply profile of the TEC. Through the different simulation results with PID controller, for $k_p = 0.9$, $k_i = 0.15$, $k_d = 0$, the proposed controller has reached an error of 0.1 °C with minimal overshoot less than 20 s. In the experimental results, the cold side temperature of the thermoelectric cooling unit has decreased quickly in the first 30 min then it remained steady below −5 °C after 2 h.

In the worst case, the controller effect exhibits a cooling temperature slight overshoot of 5 °C. Generally, the temperature fluctuates only by a value corresponding to the resolution bit of the analog-digital converter. The PID method is useful for remedying transient

heat transfer issues, where response time is as important as heat transfer.

Author statement

Abdelkrim Kherkhar: Conceptualization, Methodology, Software, Writing-Original draft preparation; Younes Chiba: Writing, Supervision, Investigation; Abdelhalim Tlemçani: Visualization, Investigation, Supervision; Hayati Mamur: Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Nomenclature

α: peltier effect
COP: coefficient of performance
DC: direct electric current
$_{\Delta T}$: temperature difference, °C
$_{e}$: error
$_{A}$: ampère
$_{I}$: electric current, A
$_{K}$: controller coefficient
κ: rate of thermal conductivity, $W.m^{-1}.K^{-1}$
$_{P}$: input electric power, W
$_{PC}$: personal computer
$_{Q}$: heat transfer rate, W
$_{R}$: resistance of TEC, Ω
$_{S}$: Seebeck coefficient of module
$_{T}$: temperature, °C
$_{t}$: time, s
TE: thermoelectric
TEC: thermoelectric cooler
$_{U}$: DC voltage, V
$_{V}$: voltage
VDC: direct electric voltage

Subscripts

ambient: ambient temperature of refrigerator
c: cold-side
c_actual: actual temperature
c_ref: desired cold side temperature
d: derivative action
ext_water_block: external water block temperature
h: hot-side
i: integral action
int_water_block: internal water block temperature
int: internal space
j: Joule effect
max: maximum value
p: proportional action
PID: proportional-integral-derivative control
water_tank: water tank temperature