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DESIGN OF A LOW-COST AUTOMATED CONTROL DEVICE FOR CHOCOLATE MOLDING PROCESS

Suzana Nature Silveira Nunes
Tames Fernandes Mariano
Neylor Makalister Ribeiro Vieira
Eduardo José Lima
Antonio Augusto Torres Maia
Universidade Federal de Minas Gerais, Department of Mechanical Engineering, Av. Pres. Antônio Carlos, 6627 - Pampulha, Belo Horizonte - MG, 31270-901
suzana.nature.nunes@gmail.com, tamesfernandes@gmail.com, neylormakalister@yahoo.com.br, eduardo@demec.ufmg.br, aamaia@ufmg.

Abstract. *The process of melting and molding chocolate is a technical challenge, especially when conducted in large scale. The complexity comes from the fact that the substrate is a solution composed of different cocoa fats that require one specific polymorphic form to retain the shape, appearance and texture expected in the final product. Each fat has its own melting, crystallization and degradation temperature. To achieve the desired polymorphic form the substrate must undergo a tempering process. In this process the temperatures are controlled both during the heating and the cooling in a way that the correct crystallization order happens and the solidification happens has expected. Small deviations in the temperatures during the tempering process can turn entire batches of substrate unusable. That leads to the need for an automated temperature control system. The traditional food industry uses several automated controllers for theirs production, the most commonly used automatic controller in the industry is the Proportional Integral Derivative (PID) controller. The algorithm has sufficient flexibility to produce excellent results in a wide variety of applications. In recent years we have been seeing a great number of small industries joining this market, but this small producers do not have access to the same control solutions as the traditional producers once they are of high prices and usually not accessible to small plants. To solve their problem a cheap and robust solution needs to be developed. This solution can be achieved by using low value accessible microcontrollers with easily customizable settings. This work presents an accessible PID temperature solution for small chocolate industries with computer and mobile interfaces*

Keywords: *PID Control; Microcontroller; Thermodynamic system; Crystallization; Cocoa butter.*

1. INTRODUCTION

The manufacturing of chocolate in solid form such as bars and other molded forms requires careful and precise control of the melting and solidification process. The reason is that the temperatures involved in the molding process have significant influence in the chocolate properties both rheological properties of chocolate which determine the workability in the production processes, and physical properties of end products such as gloss, snap, texture, heat resistance, fat bloom stability, etc. (Hachiya et al, 1989), (Murray, 1978), (Musser, 1973).

That way, the main goal of the manufacturing chocolate confectionery is to achieve the best crystalline structure of the constituent cocoa butter. The major constituent of solid fat in chocolate is cocoa butter, and that makes the physical properties allied to its polymorphism. Despite ix polymorphs of cocoa butter have been identified (Wille, 1966), (Aronhime et al, 1988), Forms I, II, III, IV, V and VI, only one, Form V is the desirable one. This form is preferred in chocolate manufacture as its melting point is high enough for the solid to be relatively firm and glossy at room temperature, yet low enough to melt in the mouth (Tewkesbury et al, 1999)

However, the Form V is not easy to be obtained. Generally the production of chocolate in the industry employs a tempering phase prior to the molding using a carefully controlled shear and temperature software that generates seed crystals in Form V. According to Stapley, Tewkesbury and Fryer (1999) the final crystalline form depends mainly on the shear time process that the material underwent. The tempered chocolate is then deposited in molds and cooled so that subsequent crystal growth occurs upon the existing seed crystals. Currently, the two-state crystallization processes are applied in the production of chocolate; Pre-crystallization and mass crystallization (Nelson, 1988), (Martin, 1982) and (Cook, 1982).

The large-scale solution to the tempering process is the use of computer controlled heating and cooling devices. This industries controls the temperatures to generate the seed crystals in Form V (Stapley et al. 1999). This ensures that large amounts of chocolate reach Form V and preserve a homogeneity of characteristics as well as avoids the loss of raw material due to degradation resulting from an incorrect crystallization process. Unfortunately for small producers the costs of such solutions do not fit their financial reality.

This works proposes the development of an cheap but reliable solution to meet the needs of the small producers of chocolate. The proportional-integral-derivative controller (PID), the industry's most popular method, and responsible for 97% of existing industrial controllers (Yu, 2006) it is only natural to look for it in this solution. To pair with the industry high budget solutions the microcontrollers available in the market can be low cost and effective in the implementation of a temperature control system.

1.1 Chocolate Temper

Chocolate is made up mainly of cocoa butter. This fat can have up to six different crystalline forms, as exemplified by Fig. 1.

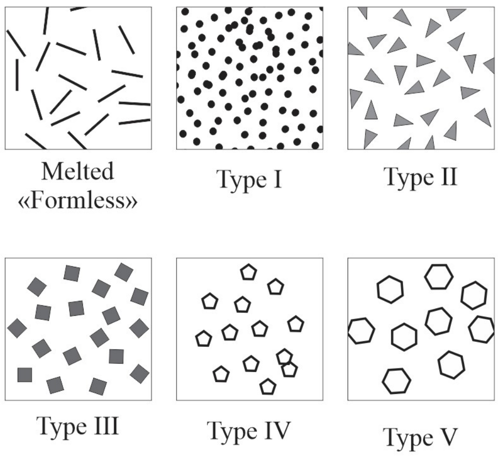

Figure 1. Representation of the 6 cocoa butter crystallization forms

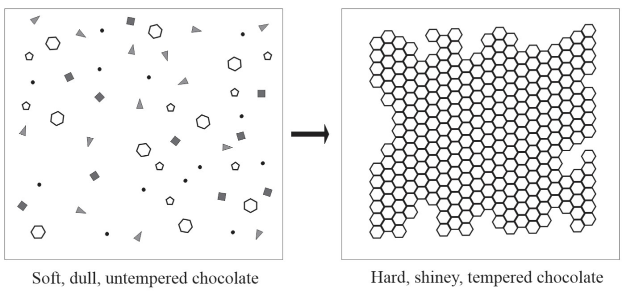

Figure 2. Representation of the correct before and after of an temper process.

To achieve the optimum configuration we need the final molded chocolate to only retain Form V crystals. To achieve that we must heat it up to the melting point of each form without affecting the Form V crystals.

Even though for each raw material one must use the manufacturer's information, in average one can work with some tabulated values as shown in Table 1 (Nanci, 2016).

Table 1 – Different melting temperatures for each type of fat

Fat Form	Melting Temperature ºC
I	17.3
II	23.3
III	25.5
IV	27.5
V	33.8
VI	36.6

The process in then to melt the chocolate until the limit temperature, preserving the Form V crystals and melting the other ones. Fig. 3a-d shows the process.

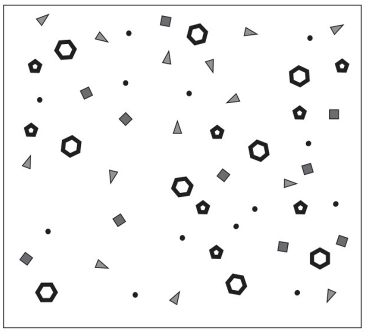

Figure 3a. Raw chocolate, compose of the 6 Crystal forms in random concentration.

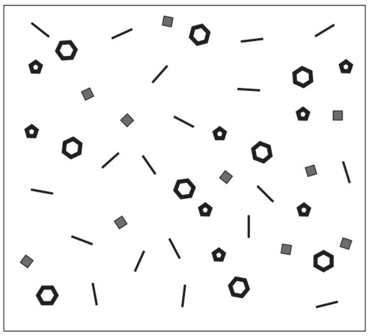

Figure 3b. When the melting process start the lowest temperature melting form disappears.

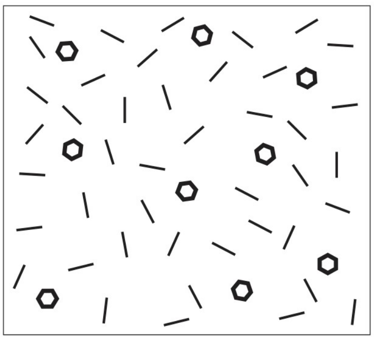

Figure 3c. After some time all the crystal forms disappear leaving Form V.

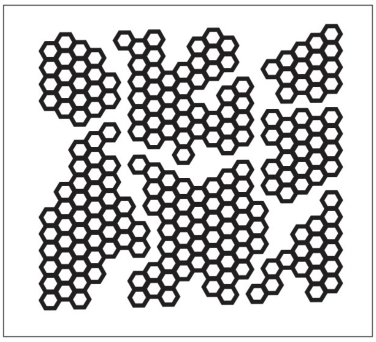

Figure 3.d Now the cooling process can begin and the melted cocoa butter will solidify following the Form V seed.

The tempered chocolate is then deposited in molds and cooled so that subsequent crystal growth occurs upon the existing seed crystals. And to control the temperature in this process we can employ a vast number of computational systems.

1.2 Microcontrollers

In the large-scale industry the use of expensive equipment is not only necessary but also justifiable given the large amount of raw material that must be maintained homogeneously. However for smaller producers such costs are not feasible and large solutions are not necessary since the material volume is low.

With the evolution of electronics we currently have available diverse options of low cost computational solutions, one being the microcontrollers. A microcontroller is nothing more than a bundle of an processor, memory and input and output peripherals on a single chip. They are originally designed govern a specific operation in an embedded system, but new models can offer as many options as computers. it's easy to find microcontroller options from the simplest PICs to the more complex ones like Arduinos, Raspberry Pi's and Beaglebones. Its main advantages are the low cost of acquisition and the simplicity of implementation.

For this work we first worked with a PIC Controller however given the limited memory available we opted for the Arduino Uno in the final design..

2. EXPERIMENTAL PROCEDURES

Since one of the main goals for this solution, is to be low-cost and practical. The proposed device consists of an electrical resistance controlled by an Arduino Uno Microcontroller. The temperature sensor used is a type K thermocouple and a digital dimmer is used to control the voltage input has shown in Fig 4 . The entire setup is small and easy to assemble in any chocolate melting device, including domestic versions.

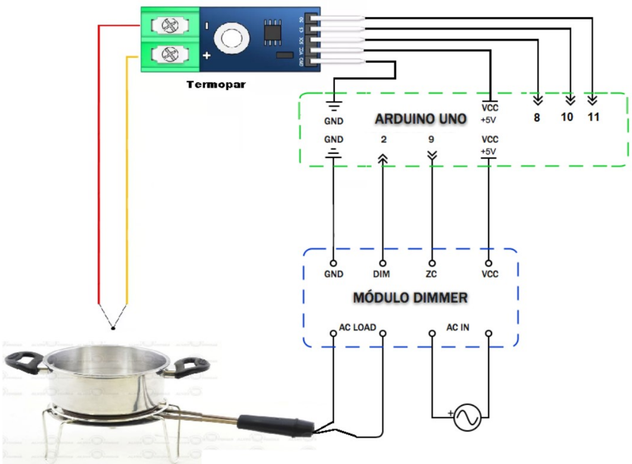

Figure 4. Hardware setup.

The Arduino board does not operate directly with AC loads nor with the voltage range of 110V coming from the power grid, which leads us to use an external circuit to complement it - in this case, an Arduino Dimmer Module that can be connected directly to 110V electrical installation.

2.1 System Identification

The transfer function of this system was obtained experimentally. Since chocolate must be heated indirectly, by transferring heat from a container with water and its melting also does not occur evenly given its viscosity, we choose, for better results, to determine the system by the measurement of water heating.

The chocolate container was kept in contact with the water of the second vessel in order to obtain the melting. Fig. 5 shows the response of the system to a step of 100 ° C.

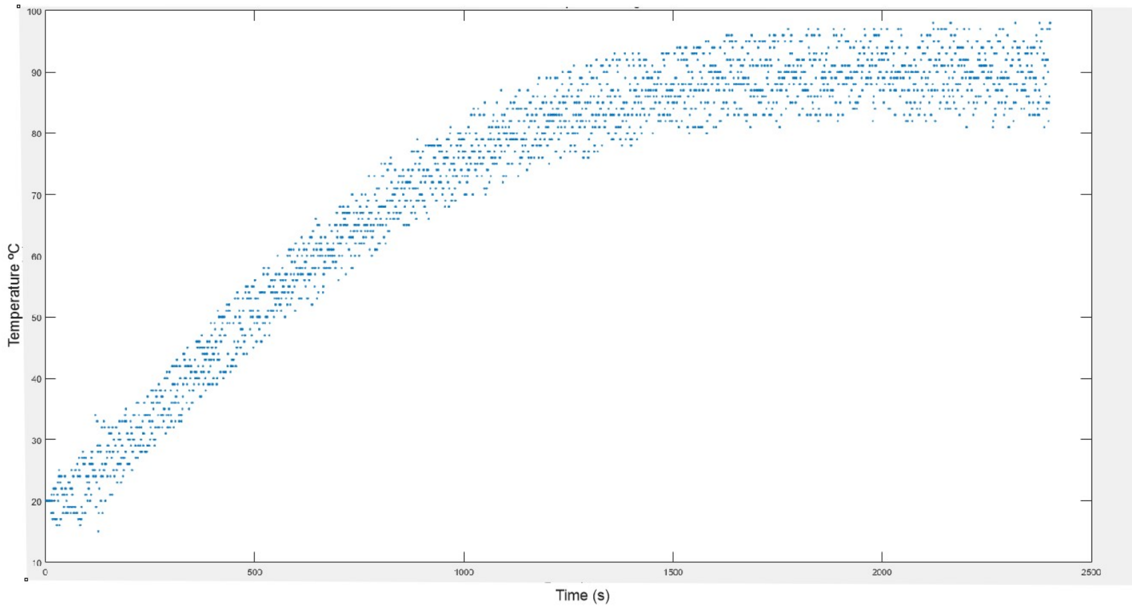

Figure 5. Step response of the system.

The cloud of points obtained can be explained by the process of convection of the liquid. Therefore, a filter was applied in which the average temperature was calculated at each instant of time, as can be seen in Fig 6.

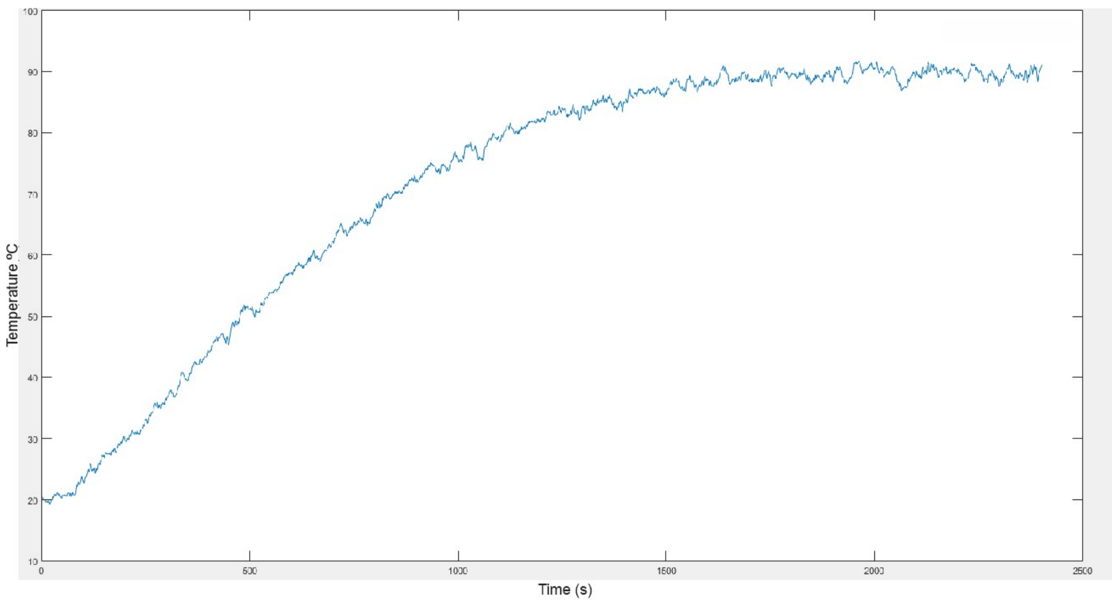

Figure 6. Filtered system response

Using the Ziegler-Nichols curve analysis technique we were able to define the transfer function as

$$G(s) = \frac{0.69}{708s + 1} \tag{1}$$

The tuning was also done by the Ziegler-Nichols method where the values of Kp, Ti and Td found were, respectively 22.35, 156 and 39.

2.2 PID controller

Proportional-Integral-Derivative (PID) controllers are used in most industry-wide automated process control applications today to regulate flow, temperature, pressure, level and many other variables of industrial processes. PID is the most widely used control algorithm in the industry and has been used worldwide for industrial control systems. The popularity of PID controllers can be attributed in part to its robust performance in a wide range of operating conditions.

The equation of PID, Equation (1), can be divided into 3 components: Proportional, Integral and Derived (Astrom & Hagglund, 1995). As can be seen in Eq. 2.

$$u_{(t)} = K_P * e(t) + K_i \int_0^t e(t)\,dt + K_d * \frac{de(t)}{dt} \tag{2}$$

The PID controller was implemented in the Arduino Uno with the tuning previously obtained...

3. RESULTS AND DISCUSSIONS

The developed interface allows the selection of the quantity and type of chocolate, since these parameters directly influence the temperature control. The melting temperatures used in the work were:

White Chocolate 28ºC
Milk Chocolate 29ºC to 30ºC
Dark Chocolate 31ºC

Fixed amounts of 500g of chocolate for each type. The processes were realized in Cool (18ºC), Environment (24ºC) and Hot (27ºC). The tests were done with manual and automatic temperature control of melting and forming. After being placed in silicone molds the solidification occurred at a fixed temperature for all cases in a freezer.

The controller was able to maintain the fixed temperature throughout the process of chocolate melting and tempering with variations below 1 ° C.

In all automatic control tests, chocolate formed in the expected manner, with few variations in texture and appearance. In the manual control tests there was no complete solidification in one instance and appearance of a fat layer in another instance as well as not ideal textures, as can be seen in tables 2 to 7.

TABLE 2 – White Chocolate

	Full Solidification	Texture	Apearance
Manual Control	Yes	Crumbly	Matte
PID Control	Yes	Firm	Glossy
Desired Result	Yes	Firm	Glossy

TABLE 3 – Milk Chocolate

	Full Solidification	Texture	Apearance
Manual Control	No	Too Soft	Glossy
PID Control	Yes	Firm	Glossy
Desired Result	Yes	Firm or Soft	Glossy

TABLE 4 –Dark Chocolate

	Full Solidification	Texture	Apearance
Manual Control	Yes	Too Soft	Presence of Fat Layer
PID Control	Yes	Crunchy	Glossy
Desired Result	Yes	Crunchy	Glossy

4. CONCLUSIONS

This preliminary results show that the temperature control has a significant impact on the results of the chocolate molding process. A study was carried out to control the temperature of chocolate in order to maintain properties such as gloss, hue, firmness and texture.

Although control techniques are already applied in the large industry, it was proposed to develop a low-cost solution that is easy to implement to meet the needs of small producers. What could lead to waste and more precise production process.

The solution presented was satisfactory but there is room for improvement. The implementation costs can be reduced by adopting a cheaper microcontroller, and the application of other tuning processes may present an even more precise controller. The next steps also include the encapsulation of the system in order to obtain a simpler equipment for the consumer's use.

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6. RESPONSIBILITY NOTICE

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