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APRTC: advanced precise rapid thermal cycling in blow molding by applying fuzzy controller on thermoelectric devices for cooling and heating applications

Alireza Safaryazdi[1] · Ali Ghaffari[1]

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Abstract
This study presents an innovative approach to enhance thermal control in the blow molding production process, specifically focusing on achieving rapid and precise temperature regulation. To address the significant time consumption during mold closure, strategically deploying thermoelectric modules (TEMs) arranged according to the mold's geometry enables meticulous temperature monitoring through integrated thermocouples. The configuration forms a matrix of interconnected TEMs, thermocouples, and controllers, orchestrating precise temperature adjustments across the mold surface. The research integrates fuzzy algorithms to facilitate seamless communication between thermoelectric devices and thermocouples for precise mold temperature control. Simulation of thermoelectric devices using COMSOL Multiphysics and implementation of fuzzy controllers in Matlab, connected through a live-link, enables real-time. I have adjustments and precise control. This integrated approach allows for a comprehensive analysis and optimization of the thermal control system, ensuring effective and adaptive temperature regulation. TEMs, operating as solid-state heat pumps, offer size versatility, adaptability to diverse mold shapes, and maintenance-free operation. Leveraging individual control capabilities significantly enhances heat transfer resolution, enabling precise manipulation of heat flux. Emphasizing the reduction of cooling time and achieving high-gloss surface quality, the study introduces the Advanced Precise Rapid Thermal Cycling in Blow Molding (APRTC) method. APRTC strategically employs TEMs to expedite cooling and elevate temperature determination accuracy, guaranteeing enhanced temperature resolution on the core mold surface. Furthermore, the study optimizes energy utilization through a closed-loop fluid circulation system, harnessing waste energy from other stages. Comparative analysis highlights APRTC's superiority, revealing a remarkable 91% reduction in temperature differentials during the cooling cycle and an 89% decrease in the heating stage. These findings underscore APRTC's efficacy in maintaining minimal temperature variations throughout the entire molding process.

Keywords Blow molding · Thermoelectric · Rapid thermal cycling · Fuzzy control

1 Introduction

The blow molding industry continues to be one of the most advanced sectors globally. This production method enables manufacturers to achieve high-quality products in less time, making it economically attractive. The industry demands technical molding containers, irregular hollow shapes, industrial parts, and bottles. This has ignited fierce

✉ Alireza Safaryazdi, a.safaryazdi@email.kntu.ac.ir; Ali Ghaffari, ghaffari@kntu.ac.ir | [1]Department of Mechanical Eng., K. N. Toosi University of technology, Tehran, Iran.

competition among companies to produce their products at the lowest cost and with the highest strength-to-weight ratio. As a result, researchers have been driven to significantly improve the production technology level of the blow molding process [1].

The primary concern in the various blow molding processes (e.g., EBM, IBM, SBM, etc.) is the production cycle time. The blow molding process consists of four main phases. In the first stage, resin granules are melted in the extruder. Then, a parison in the die-head is formed, or a preform from the injection process is created. In the third stage, mold halves catch the parison, which is then blown by a blow pin. At the end of these main phases, the shaped part cools down via the molds. It's essential to note that these stages do not always occur sequentially but may sometimes overlap. The blowing stage consumes a certain amount of time, making the cooling step the longest phase in the molding cycle.

The cycle time in blow molding is relatively short, ranging from a few seconds to a few minutes. Cooling in blow molding involves the absorption of heat through cooling channels via conduction. The effectiveness of common cooling methods in blow molding depends on various factors, such as coolant temperature, cooling fluid flow rate, convective heat transfer, wall thickness, particle distribution in parts, thermal conduction in the mold, cooling channel position and size, and many other uncontrollable conditions.

One long-standing debate has revolved around the shape and proximity of cooling channels to the core mold surface in order to achieve superior thermal control on the core mold surface [2]. The space between the cooling channel and the core mold surface has a significant impact on part quality. If this distance is too short or too long, it may result in hot spots or significant shrinkage. Some areas, such as around the bottleneck or the bottom pinch-off, often require more polymer mass compared to other sections. As a result, larger molds are equipped with multiple (up to three or more) independent cooling zones to account for these disparities [3]. The varying cooling rates, wall thickness, and cooling channel distribution can also affect shrinkage, leading to undesirable deformations in plastic parts.

In recent years, researchers have shown increased interest in optimizing heat transfer in thermoplastics molds [4, 5], determining the location of cooling channels [6], the number and shape of cooling channels in injection molding [7], and flash pocket inserts [8], where fast cooling plays a critical role. They have explored the use of conformal and spiral cooling channels to control plastic mold temperatures [9], and 3D mold printing for complex geometries [10]. Infrared thermography has been employed to understand blow molding heat transfer [11]. In other areas, neural networks have been utilized for better control over parison thickness and optimized raw material expenditure [12–14].

In blow molding, the process cycle is primarily controlled by the cooling time [15]. Therefore, to increase the production rate, an emphasis should be placed on advanced technology and mechanisms. In the cooling cycle, the outer surface of the parison solidifies immediately upon contact with the cold mold wall, resulting in a final product with poor surface quality. To achieve better surface quality, manufacturers typically perform secondary surface treatments on blown parts, which are time-consuming.

Recent developments in rapid thermal cycling have allowed manufacturers to eliminate secondary surface treatment, particularly for high-gloss parts molded with engineering plastics such as ABS and PA. This approach reduces costs and enhances production efficiency. In a recently published work [16], an optimized method for rapid thermal cycling in extrusion blow molding (RTCEBM) is presented. Rapid thermal cycling for injection molds was developed in a prior studies [17, 18] and [19] has been applied to mass production in injection molding. These methods have resolved numerous issues and introduced new avenues for machinery designers to manufacture more high-quality products [20]. However, challenges persist in mold manufacturing, particularly for parts with complex geometries and in mold corners.

Reducing cooling time is highly desirable to shorten the cycle time, necessitating the design of an efficient cooling system.

Over the past decade, thermoelectric materials have seen rapid development in various industries. Thermoelectric modules (TEMs) are solid-state heat pumps without moving parts, making them maintenance-free and ensuring a long useful lifespan. Due to environmental concerns related to chlorofluorocarbon (CFC) gases, researchers have been motivated to seek new approaches and develop high-performance thermoelectric materials for energy transformation [21]. These materials have found wide applications, including coolers [22], laser applications [23], power generation [24], waste heat recovery [25, 26], solar panels [27, 28], micro coolers [29, 30]. In [31], thermoelectric modules were employed for temperature control in injection molding machines. Additionally, in [32], thermoelectric modules were used for precise temperature control in injection molds. Notably, innovative applications of thermoelectric modules in injection molding have been introduced in a recent patent [33]. In the manufacturing process, the utilization of waste heat energy through thermoelectric generators was explored. In [34] specifically investigates the application of TEGs to recycle waste heat within the steel manufacturing process and in [35] details the implementation of a recycle waste heat for cement rotary kilns through the utilization of TEGs. In manufacturing processes such as welding, TEC modules can be implemented for cooling and temperature control during the welding process [36]. These advancements have made TE modules available in a wide range of sizes and powers.

This paper presents an advanced, revolutionary method to address the aforementioned problems by applying thermoelectric modules in blow molds, achieving higher accuracy and excellent temperature control resolution on the core mold surface. With the thermoelectric effect and TE modules available in various sizes, it's possible to create more zones inside the molds for temperature control. Each module can act as an independent thermal zone, and their versatile sizes enable comprehensive coverage of every corner of the mold for precise temperature control and heat transfer.

Another advanced temperature control approach presented in this article focuses on rapid thermal cycling. The method established in this study uses thermoelectric modules to achieve rapid and precise thermal control. For effective thermal control on the core mold surface, each TE module must be under heat transfer control, as they interact with one another. This is achieved through a fuzzy logic controller, which is implemented with COMSOL Multiphysics [37] in coordination with MATLAB [38] functions containing fuzzy control algorithms. As a case study, this approach is implemented on bottle molds, one of the most common blown parts used in the industry. In Fig. 1, a schematic representation of a sample blow mold is depicted, featuring its principal zones. In the subsequent sections of this paper, we will utilize this mold, as illustrated in its overall view with labeled zones, for further discussion and analysis.

The aim of this study is to shed light on advanced thermal control in blow molding. The following sections describe an advanced, precise, rapid thermal cycling method in blow molding.

2 Thermoelectric effect

In order to explain applied thermoelectric modules and benefit from them in following section, thermoelectric effect and its applications are argued. Moreover, coming paragraphs justify why thermoelectric devices are used and how they work in this method.

2.1 Thermoelectric effect principle

Over the past century, applied researchers became increasingly interested in energy conversion, like mechanical energy to electric energy or other forms of energy, transforming to one another. This study needs to convert heat energy into electric energy and vice versa, by implementing thermoelectric effect. The alternation of electric voltage to temperature differences

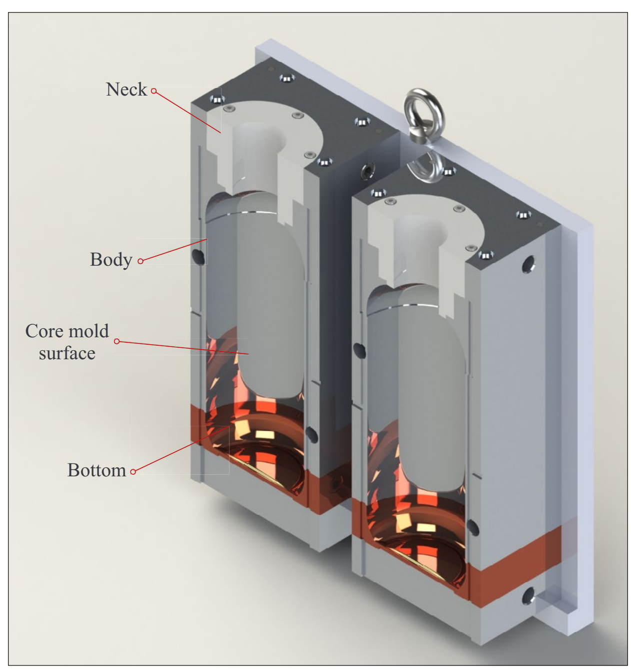


Fig. 1 Mold cavity which used in this article for analysis

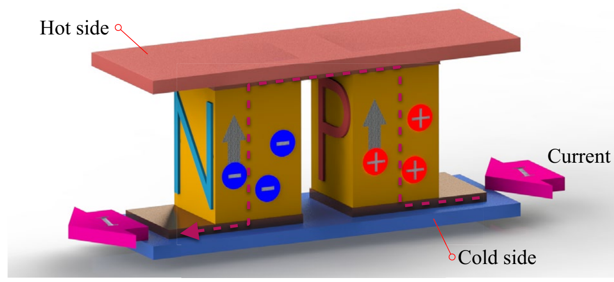


Fig. 2 Thermoelectric effect when current first inputs in P-Type semiconductor and heat transfer's direction

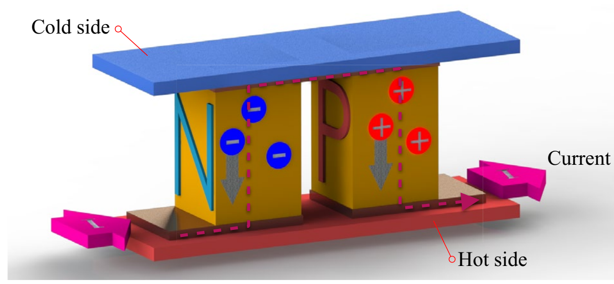


Fig. 3 Thermoelectric effect when current first inputs in N-Type semiconductor and heat transfer's direction

is known as thermoelectric effect. In the heart of thermoelectric effect lies two principles: Peltier effect and Seebeck effect. The transformation of heat energy into electric energy in form of electric current, is described by Seebeck effect. As far as these disperse processes are energy-dependent, the different carriers diffuse electric energy at different rates, and create higher density of carriers at one end of the material.

Consequently separation of positive and negative charges, increases electric field and a related potential difference: the Seebeck voltage [39], defined as follows:

$$\Delta V_S = S_{\alpha,\beta}\Delta T \tag{1}$$

where $S_{\alpha,\beta}$ is the Seebeck coefficient of the junction materials and relies on temperature.

In 1834 a french watchmaker, named Jean Peltier, observed that rising or decreasing temperature at the junction of two distinct conductors brings about electric current generation. That means, when electron particles move from a lower energy level in P-type semiconductor and pass coupling conductor to a higher energy level in N-type material, make couple to absorb heat on the cold side. This phenomenon is called the Peltier effect [21].

$$\Delta Q_P = \Pi_{\alpha,\beta}(T)I\Delta t \tag{2}$$

The alleged Peltier heat in Eq.(2) (J unit) is proportional to the time duration and the magnitude of electric current, so it can be utilized as shown in Fig. 2 & 3. This physics principle is in fact another viewpoint of Thomas Johann Seebeck concept. In other word, the concept is: by applying a temperature differential to coupled material an inverse process occurs, which causes the current to flow, thereby generates power.

Thermoelectric for cooling is defined by the equation [40]:

$$\dot{Q}_c = S_{\alpha,\beta}T_cI - \frac{1}{2}I^2R + K(T_c - T_h) \tag{3}$$

$$\dot{Q}_h = S_{\alpha,\beta}T_hI + \frac{1}{2}I^2R + K(T_c - T_h) \tag{4}$$

Here, I represents the electric current. By employing the first law of thermodynamics across the thermocouple, the input power can be characterized as

$$\dot{W}_c = \dot{Q}_h - \dot{Q}_c \tag{5}$$

The coefficient of performance (*COP*) resembles thermal efficiency, but its value may exceed 1. It is defined as the ratio of the cooling power to the input power:

$$COP = \frac{\dot{Q}_c}{\dot{W}} \tag{6}$$

Recent developments in transforming types of energy to another have led to a renewed interest in redesigning production processes from the beginning. This study has developed a new method and utilized this effect for redesigning.

2.2 Thermoelectric effect application

Usage of thermoelectric effect in industrial applications has been developed in the past few decades. Nowadays, thermoelectric modules have a significant advancements in performance, efficiency, generated temperature difference, heat transfer rate and maximum sustained temperature. By establishing electrical series connections between couples which are made of N-type and P-type Bismuth Telluride (Bi_2Te_3) thermo-elements and are thermally in parallel and in the middle of ceramics substrates, thermoelectric modules will be achieved. These couples can be used in various forms, sizes and multi-stages [29] as one module or a group.

This article leverages the benefits of these modules, which function as solid-state heat pumps with rapid response rates. The versatility of these modules, available in various sizes on the market and customizable to specific dimensions and shapes (such as flexible models, multistage, circular, ring-like, rectangular, with different thicknesses, etc.), makes them ideal choices for addressing the challenges of complex mold design.

The diverse sizes of these modules directly impact the number of controllable heat-transferring zones, thereby defining the thermal control resolution. This adaptability offers a tailored approach to thermal management in line with the specific requirements of different modules.

As modules sizes reduce, heat transfer resolution increase. Other noteworthy advantage of this approach is that each point of the mold can have precise temperature control with accuracy of ± 0.1° C and each area can separately be commanded, while in common mold cooling or in rapid thermal cycling, some thermal zones can be chosen with temperature differences.

Applying suitable inputs of voltage or current controllers on these modules and considering other thermoelectric devices simultaneously, results in uniformly chilled or heated core mold and moreover temperature difference caused by heterogenous distribution of polymers will be removed. Because thermoelectric devices pump heat, with no moving parts, they significantly require less maintenance and could have more than 100,000 h of steady-state working life time [21].

In order to have temperature feedback from particular point of the mold and the exact temperature of a desired moment, a temperature sensor should be used as a measurement device. This sensor must be fast-response and work in wide range of temperature. Using thermocouple operating under Seebeck effect.is recommended in this study.

3 Simulation and controller

In order to apply APRTC and validate it, fuzzy logic is chosen as controller and computer aided engineering (CAE) software is selected for simulate processes. In the following, firstly discuss the controller algorithms and next introduce COMSOL Multiphysics as CAE software and its interaction with MATLAB functions to fuzzy controller.

3.1 Fuzzy controller

There are many complex systems, with no detailed system understanding and do not match the accurate traditional standard system models. Due to the fact that there is no way to determine the exact threshold to express their complex boundary, modern controller is used. However, obtaining exact mathematical model of the system is too complex, and for non-linear systems, simplifying and linearization equations are also required, but, for fuzzy controller, linearization is not necessary. Fuzzy inference parameters are tuned by the knowledge of experts who control the same process or understanding the physics rules underlying the system from approximated equations. in short terms, the fuzzy parameters include membership function shapes, positioning, number and type of rules that making rule base.

As Previously stated, fuzzy logic has advantages over pure mathematical approaches, the present method uses two *TC*0 sensor as feedback instead of one as shown in Fig. 4. In some cases higher thermal control resolution on, three or more thermocouple can be used, as shown as in Fig. 4, is named *TC*1, details of installation TEMs is explanations in section 4.

The main goal of current study is to have uniform distribution of temperature all over the core mold surface. Each module should act as a member of system and interact with others, in other words, each one should not be con- trolled independently. For this aim the average temperature of all thermocouples is measured and is used as data for second control algorithm's input. Fuzzy logic has an attractive feature for temperature control systems which is the power of taking system dynamics qualitatively, and turn this qualitative dynamics into a real-time state.

Two inputs have been given to thermoelectric module controller: each thermoelectric temperature and total average temperature, in fact both are the same, because, if the temperature of each TE module is available, the average is available too. to make this concept simpler following explanation is chosen. As explained earlier, owing to to thermocouples efficiency and ease of installation, they are installed between each two TEM. As far as controlling the temperature of each module is concerned, the mean measured temperature from surrounding sensors is used as a feedback for the controller.

For every thermoelectric module, temperature set point can be separated selected but in general application they are set the same. First input signal, that is named $Error_1$ is calculated with differences between the real time module temperature and the set point, Second one, named $Error_2$, is determined from the differences between total average temperature and the real time module temperature. Real time module temperature is average temperature of surrounding thermocouples measurement (See Fig. 5). Figure 5 just shows the control algorithm for one TEM as an example.

For fuzzy controller utilizing Mamdani fuzzy inference [41], and "minimum" for "and" is chosen. The input variables in a fuzzy control system are mapped by sets of membership functions, Fig. 6 illustrates inputs membership functions for changing a real scalar value into a fuzzy value is called fuzzification. The computation stage is based on a bank of logic rules in the form of If-Then statements, which the IF part is called the antecedent and the consequent named for THEN part. Table 1 presents a 25-rule FLC rule base, which *VCold* means very cold, *SCold* means little cold and for *Hot* the same applys. *NNv* indicates big negative voltage, whereas *Nv* negative voltage and for positive voltage, the same rules are applied for made linguistic variables. Defuzzification takes the fuzzy inference to make output of the rules and generates a real scalar value used in control input of the plant, figure 7 shows membership function for output of the controller, centroid method has been used for defuzzification.

In this paper, MATLAB script is used to implement a fuzzy logic temperature control system and interacts with a model in COMSOL Multiphysics as described in 3.2.

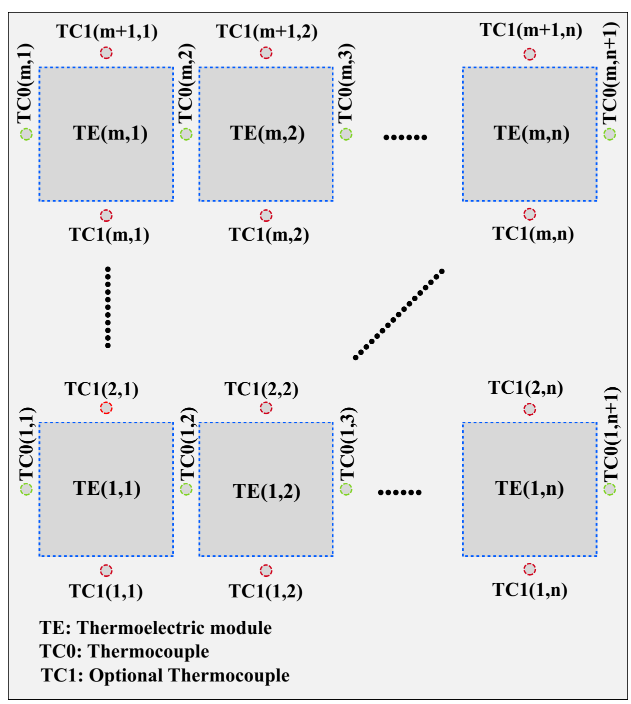


Fig. 4 Scheme of thermoelectric and thermocouple arrangement, applying for APRTC method

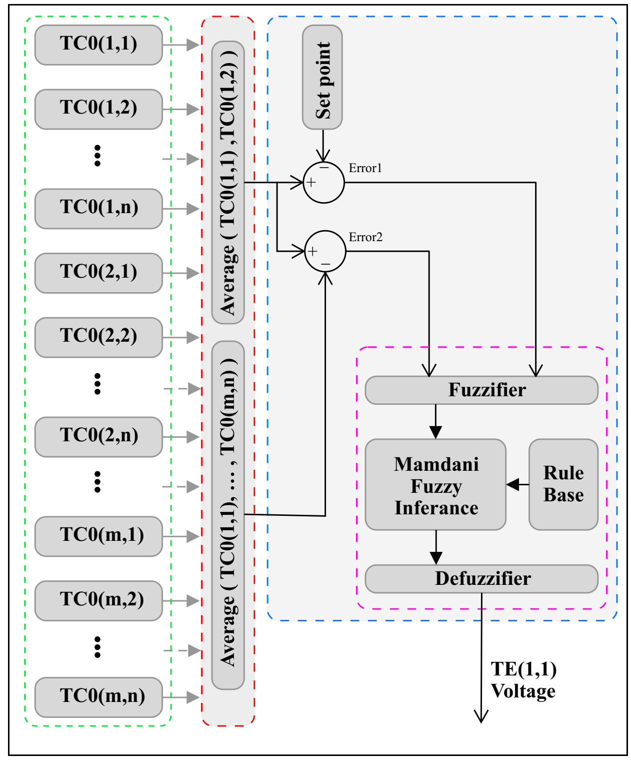


Fig. 5 Diagram for controlling input voltage of one thermoelectric module *TE*(1, 1) with considering all measured thermocouples value *TC*0(*i*, *j*)

Table 1 Fuzzy rule base

		$Error_1$				
		VCold	SCold	Zero	SHot	VHot
$Error_2$	VCold	NNv	NNv	Nv	Nv	Zero
	SCold	NNv	Nv	Nv	Zero	Pv
	Zero	Nv	Nv	Zero	Pv	Pv
	SHot	Nv	Zero	Pv	Pv	PPv
	VHot	Zero	Pv	Pv	PPv	PPv

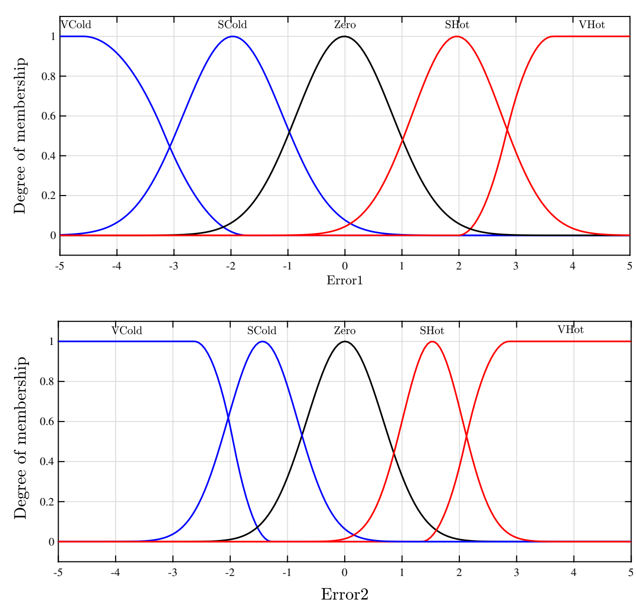


Fig. 6 Fuzzy input membership function for $Error_1$ and $Error_2$

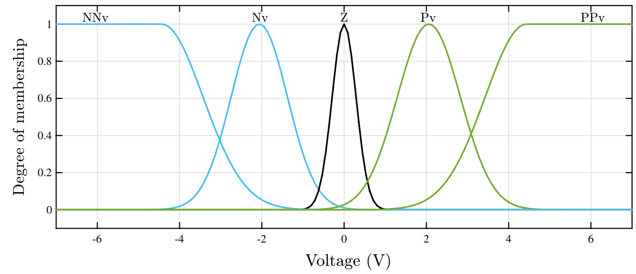


Fig. 7 Fuzzy output membership function for thermoelectric module voltage

3.2 Simulation software

To verify the cooling performance of the APRTC, the CAE simulation tool is employed in this study. in design and developing blow molding process or blown part using CAE software is prevalent. to simulate and confirm this introduced method, an advanced analyzer is needed. Because Multiphysics simulation includes electrical devices, heat transfer, thermoelectric materials and flowing fluid, COMSOL Multiphysics is used. In this study COMSOL Multiphysics is a cross-platform finite element analysis, solver and Multiphysics simulation software which is able to simulate coupled processes involving more than one occurring physical fields simultaneously. Validated COMSOL Multiphysics simulations of thermoelectric materials and devices are presented in [42–45].

To design the fuzzy controller and implemented on Multiphysics model, MATLAB coding and scripting controller function is needed. Seamlessly integrating COMSOL Multiphysics with MATLAB to extended modeling with scripting programming in the MATLAB environment as shown in Fig. 8. Leads COMSOL server to create an environment to interact with MATLAB function and the model applied in COMSOL Multiphysics. each time COMSOL sends each thermocouple measured temperature to MATLAB and after putting values in function, thermoelectric module voltage will be returned for COMSOL Multiphysics.

4 Utilizating of thermoelectric modules in blow molds

Determining the blow molding cycle time is crucial, with mold cooling being a key factor. To increase both production quantity and quality, mold makers should explore new or optimized methods such as parallel channels, multi-zone cooling, conformal cooling channels, and more. However, various limitations exist in mold manufacturing, preventing the implementation of any desired shape of cooling channels, and they may not cover the entire core mold surface. Another significant challenge is the non-uniform distribution of cooling channels and varying heat transfer rates during the blow molding process, resulting in uneven temperature distribution across different points on the mold surface.

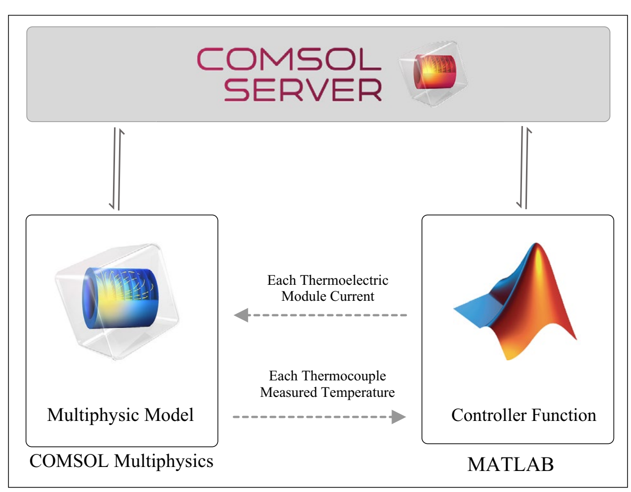


Fig. 8 Interaction between software under Livelink protocol, that includes COMSOL Multiphysics, MATLAB and COMSOL Server

This diverse temperature distribution on the core mold surface leads to differences in part shrinkage and undesirable geometric dimensions.

It's crucial for the blow mold halves to be controlled effectively, ensuring rapid solidification of parts after they catch the parison and are inflated by the blow pin. The application of different designs and methods has a substantial impact on process control and part quality.

To reduce cooling time, some mold designers tend to increase the fluid flow rate and decrease the coolant temperature. However, as the fluid temperature decreases, the heat transfer with the surrounding environment increases due to machine equipment and air thermal exchange, potentially leading to water condensation on mold walls. Therefore, when a high-gloss surface quality is required, it becomes necessary to rapidly cool down the mold with uniformly distributed heat transfer, a concept discussed in the 4.2.2 section through the introduction of the rapid thermal cycling method.

In summary, achieving a faster cycle time while maintaining acceptable quality allows for the production of more parts in less machine time, ultimately reducing overall costs. This study effectively addresses the aforementioned problems, either completely solving them or significantly improving their impact. Furthermore, it introduces additional capabilities to enhance the production of high-quality products. The following section provides a detailed report on the solutions to these problems and the utilization of thermoelectric modules in blow molds.

4.1 Installation thermoelectric modules

As mentioned before, each thermoelectric module is composed of numerous set of thermoelectric couples and there are two ceramics plates installed on both sides, which heat exchange happens through them. According to manufacturer's production standards, cooling and heating sides are defined by current direction input.

By the specified voltage for element input which is shown in red and black wires, the initial heat transfer direction is determined, as illustrated in Fig. 9. To prevent any mistake in assembling, all modules are settled from one side and cold standard surface is positioned out toward core mold surface.

As illustrated in Fig. 10, the thermoelectric module used in this study measures $8mm \times 8mm \times 1.8mm$ and comprises 28 couples of thermoelectric elements. This module is analogous to the commercial model 9502/031/018 from Ferrotec company [46] in terms of size. The Thermoelectric (TE) device is affixed to the blow mold using methods like adhesive attachment, mechanical fastening, embedded integration, or custom mounting structures. Special consideration is given to insulation and thermal interface materials, with the flexibility to employ conformal TE modules for contoured surfaces. The choice of attachment method depends on factors such as mold geometry, thermal conductivity needs, and ease of installation, ensuring a reliable thermal connection for optimal performance in the blow molding process.In this study, thermal compound securely attaches Thermoelectric (TE) modules to the blow mold. Small holes facilitate precise placement of thermocouples for accurate temperature monitoring. The thermocouples are glued to mold sections in direct contact with the polymer, and another mold part stabilizes the TE module position during molding.

As previously stated, thermoelectric modules are available in various sizes and power ranges, hence there is several choices for blow mold designers to eliminate former limitations. Some mold points which are in the corner or the ones

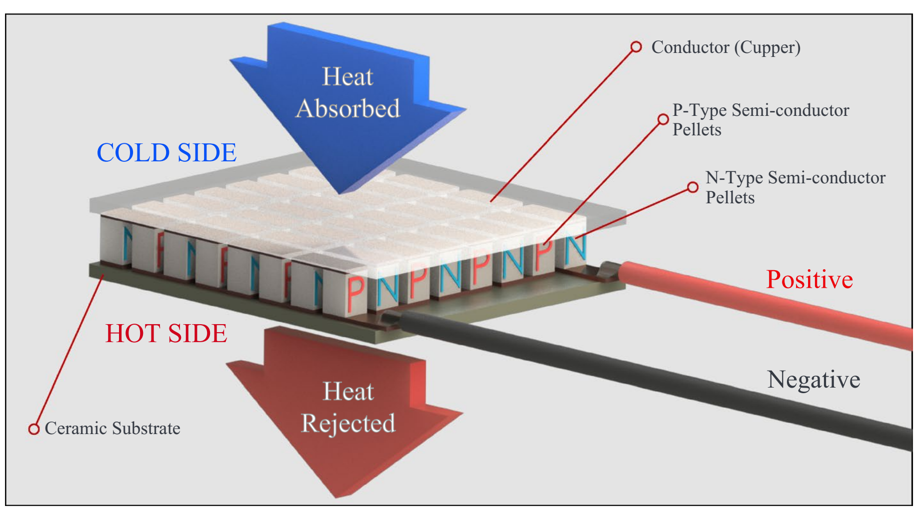


Fig. 9 Thermoelectric module scheme in detail with standard wiring and heat transfer direction

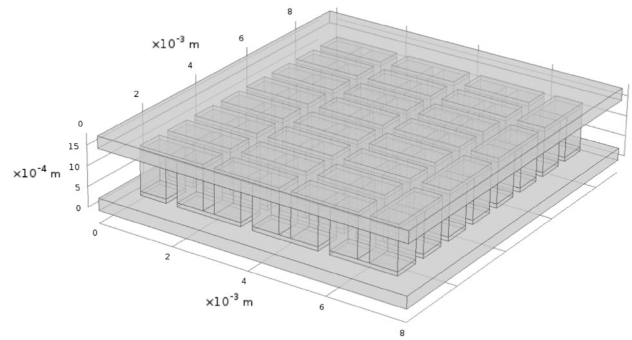


Fig. 10 Dimensions of thermoelectric module which used in this study with 28 couple of N-type and P-type semiconductor

which belongs to a mold with complex geometry, unevenly transfer heat leading to temperature difference between parts' zones and eventually temperature difference in different zone of blown part, causes unwanted deformation, that makes undesired product characteristics. Based on the importance of temperature resolution control and accuracy of heat transfer, number of modules can be determined.

On the hand, water flowing in mold loses the heat created by hotter side, in the cooling mode (See Fig. 11), for high surface quality rapid thermal cycling is needed. To achieve this goal, the thermoelectric voltage input is reversed as the heat transfer magnitude changes simultaneously with current, and the fluid flowing through channels cools down. To avoid wasting energy, fluid circulation in closed loop the same cool fluid employed in the first stage is used in the next. Next section, explains APRTC method which first is heated rapidly before solidification process and then begins the mold cooling mission.

To measure temperature of a specific point on the model, thermocouples are used. Some advantages of employing thermocouples are that they are accessible in wide range of sizes and temperature and those are highly responsive in the system. In the current study, to determine the temperature of all mold points, a temperature has been put among each thermoelectric modules by thermocouples and the thermal controller has take advantage of it.

One item noticed in this study is the mechanical behaviors of thermoelectric materials. Bismuth telluride Bi_2Te_3, which is the most common thermoelectric material used in TEM devices, demonstrate elastic modulus values close to common engineering metals. For thermoelectric materials, in [47] and [48] modulus of elasticity thermoelectric materials was reported in the range between 40 GPa and up to 200 GPa and for common Bi_2Te_3 materials it is from 50 GPa to 55 GPa (in comparison with 70 GPa for Aluminum alloys). In mold life time, the mechanical properties of mold's materials have particularly important role. To improve mechanical properties and thermal isolation, for both sides of TEM in contact with mold materials such as aluminum alloys, heat resistant materials with great mechanical properties should be used. In this study steel pins are used for this purpose.

Figure 4 presents arrangement of thermoelectric and thermocouple devices schematically, $TE(i, j)$ is the label of thermoelectric devices, $TC0(i, j)$ is the label of required thermocouple devices for measuring temperature and for more accuracy $TC1(i, j)$ can be installed between each rows of thermoelectric devices. i and j are indexes of row and columns of this array. It is clear this two dimension array is just as an example to explain following works but higher dimensions the number of indexes in each row will be different because of different sizes of modules.

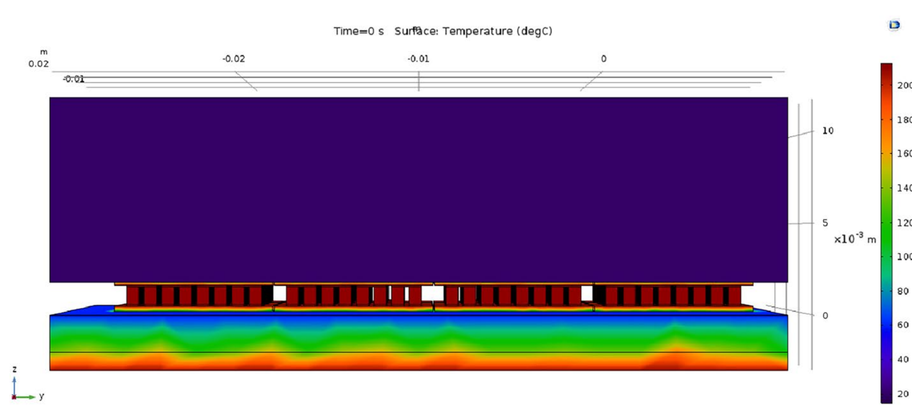


Fig. 11 A flat model simulated with Comsol in $t = 0s$

4.2 Applications

The primary objective of this paper is to reduce production cycle time while achieving rapid, precise, and uniform temperature control across the entire core mold surface. To accomplish these goals, the Advanced Precise Rapid Thermal Cycling (APRTC) method is introduced. In the blow molding process, after the parison is extruded, it begins by clamping mold halves and subsequently inflating them using a blow pin. In the final stage of the process, the mold solidifies the polymer and opens. Throughout this process, the mold cools the plastic parts by circulating a cooling fluid inside the mold cooling channels, a thermal mechanism known as mold cooling. In specific production scenarios where enhanced surface quality is required, an additional thermal mechanism is necessary. In this process, the core mold surface is first heated, followed by a cooling cycle. This additional step is referred to as rapid thermal cycling.

As shown in Fig. 12. in each row of this mold, seventeen thermoelectric modules and eighteen thermocouples sensors are employed for temperature measuring in this study (TE arrangements shown previously in Fig. 4). In addition, seven drilled cooling channels are embedded in this mold which in cooling stage absorb heat from hot side of modules and do the opposite in heating stage. High density polyethylene (HDPE) is chosen as the polymer with 1.5*mm* thickness at 185 ° C is set for initial temperature (HDPE die-head temperature range is from 160 ° C to 210 ° C) [1] and water used as coolant fluid flowing inside the mold.

4.2.1 Cooling cycle

Fast heat transfer is of utmost importance, because cooling step time controls the length of the blown parts production time. Efficient heat transfer leads to rapid cooling, and rapid cooling means more products blown per hour, causing less amount of money to be paid. To control dimensions and surface appearance, it is essential to have control over the cooling quality of parts as much as possible. Coolant flow rate is the major factor in heat removal and cycle time. In traditional blow molding, the global flow pattern affects the features of parts in addition to flow rate.

Some mold areas, such as thicker wall sections, may remain viscous while the thinner wall sections solidify when the item is ejected from the mold halves. Additionally, differences between the inlet and outlet flowing fluid temperatures in each zone can lead to thermal instability in the mold. It's evident that maintaining uniform temperature control is crucial during the cooling cycle.

To accommodate the production of geometrically complex parts with varying thermal flow rates and thickness differences, an advanced temperature control mechanism is necessary. This means employing controllable non-uniform heat transfer to ensure uniform temperature control across the core mold surface. If certain areas require more heat transfer or absorb more heat than others, the APRTC method will be introduced to bring all areas under control.

To absorb the heat generated on the TEM's hot side, cooling channels are integrated into the mold, which are subsequently cooled by a radiator in a closed loop. This closed-loop system is installed in an outdoor environment and eliminates the need for mechanical devices such as chillers. The coolant used is water, which circulates in a closed loop and maintains an ambient temperature.

Common method to designing the cooling channels inside bottle molds (as shown in Fig. 13) is to place it in parallel with drilled cooling channel.

Table 2 illustrates variables and the value of both mold is analyzed in this study.

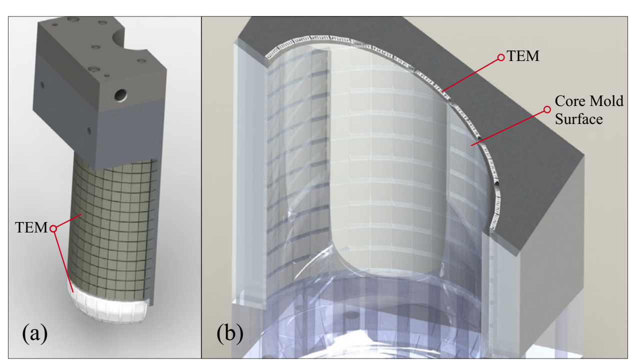


Fig. 12 Cross-section of the bottle blow mold with thermoelectric module which used in this study: (a) show mold without the exterior part, (b) cross-section of mold

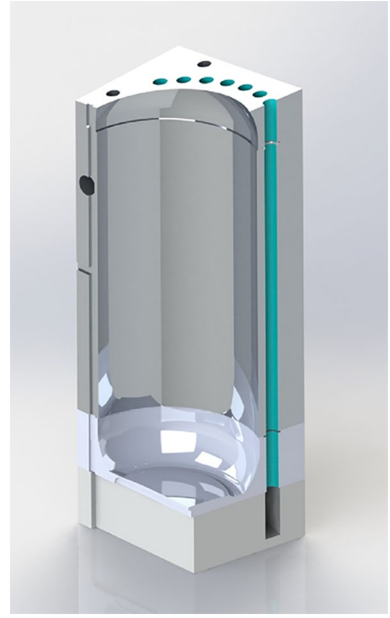


Fig. 13 Mold with two cross-section plates and cooling channel

Figure 15 compares four TEM samples that electric current runs through them in different points of the mold, they significantly act differently in time, as an example, a fourth thermoelectric module is installed in difficult heat transfer, that means extra need for heat pumping. Figure 16 illustrates maximum and minimum temperatures of inner and outer surface of a blown part's surface along the mold was close.

In Fig. 15, around the 5-second mark, fluctuations in current are observed. These fluctuations stem from the controller's endeavors to reach the set point temperature. Moreover, variations manifest in different regions due to smaller temperature differences, and the current and power of each thermoelectric module vary based on their respective positions within the mold. As seen in Fig. 16, the temperature of the outer surface of the polymer does not noticeably change after the 5-second mark. However, the thermoelectric modules continue to work towards reducing the overall temperature of the entire polymer, consequently influencing the inner surface temperature as well.

Graphical results of the analysis are shown in Fig. 14, in which a completely uniform temperature distribution over time is seen while on the other side of TEM non-uniform temperature distribution is observed. As illustrated in Figs. 16 and 17, in classical method, temperature differences between maximum and minimum is increasing in time, in contrast, APRTC method keeps the differences at the lowest level as possible. For more details see table 3 which compares two methods and reports maximum temperature differences between inner and outer surfaces of the bottle. In comparison to the findings presented in [9] and illustrated in Table 4, the results obtained in this study showcase significant improvements. The referenced article discusses a conformal cooling method with an approximate 62% enhancement, and another method, SLDCC, with a 25% improvement in temperature differences. In contrast, our paper reports a remarkable 91% enhancement, underscoring the efficacy of the proposed approach in achieving superior thermal control in the blow molding production process.

As previously mentioned, the primary objective of this study is to enhance both the quality and quantity of production. As discussed in [3, 9, 15], the temperature distribution during the cooling stage in blow molding significantly impacts production, affecting factors such as shrinkage and the uniformity of the final product shape. In this study, the application of Thermoelectric (TE) modules, thermocouples, and fuzzy controllers is employed to mitigate temperature differences

Table 2 Mold initial variables for analysis

Parameter	Classic meth.	APRTC	Unit
Inlet water temp	5	30	°C
Flow rate	98	70	lit/min
Mold temp	10	10	°C
HDPE temp	185	185	°C
CC diameters	9	9	mm

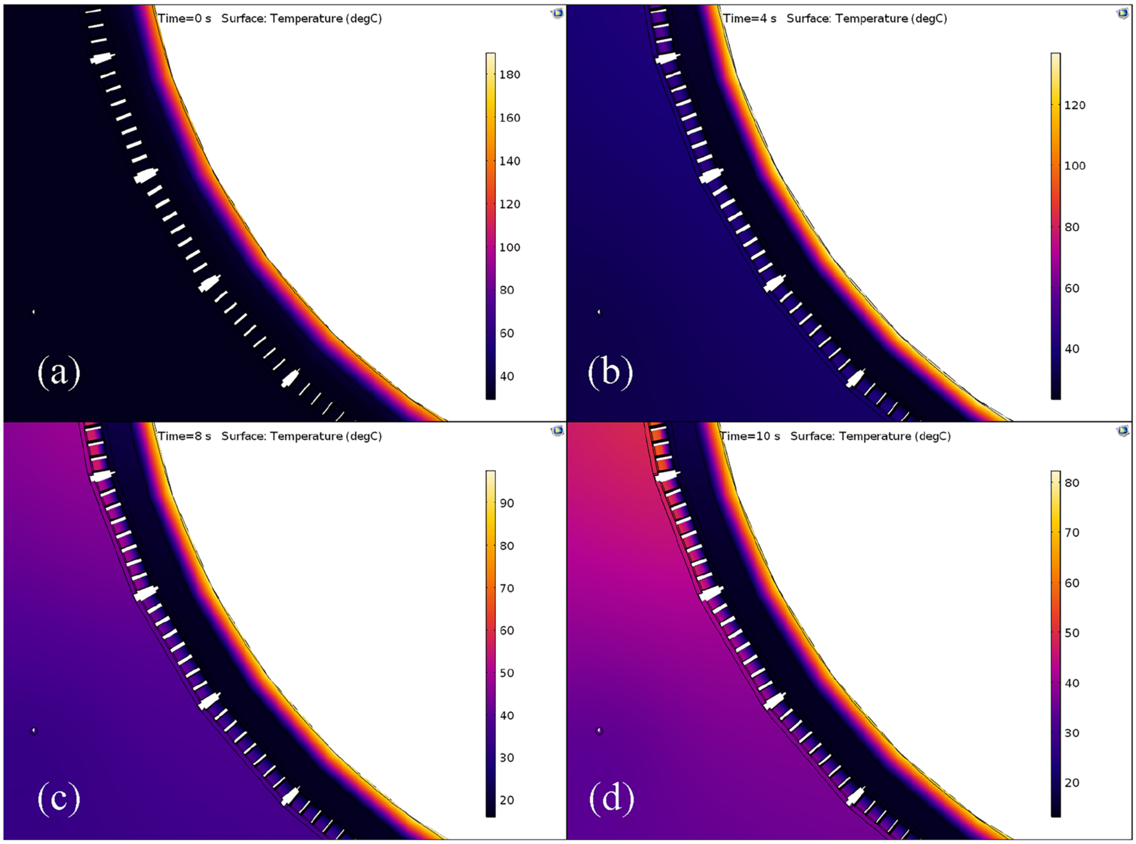


Fig. 14 Temperature field across the analyzed cross section of mold core at cooling application: (a) at $t = 0s$, (b) at $t = 4s$, (c) at $t = 8s$ and (d) at $t = 10s$

Fig. 15 Current pass through thermoelectric module in cooling mode

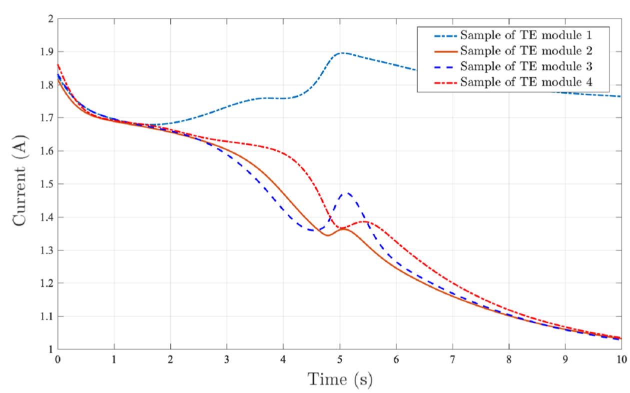
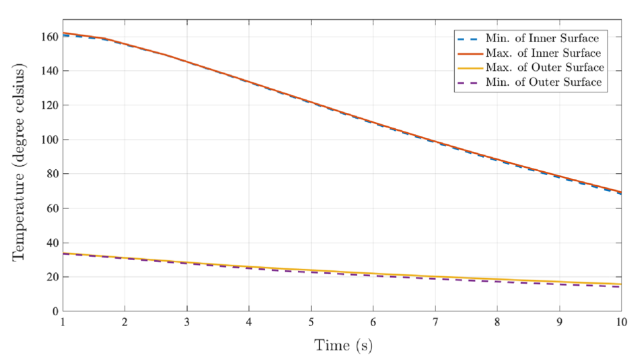


Fig. 16 AHPRTC method at cooling application: Comparison of maximum and minimum temperature of outer and inner polymer's surface



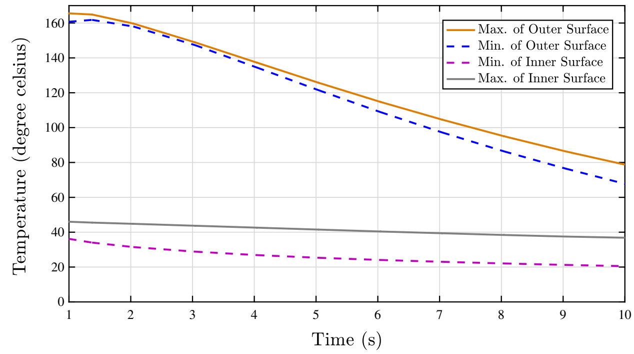


Fig. 17 Classic method at cooling application: Comparison of maximum and minimum temperature of outer and inner polymer's surface

Table 3 Comparison between two methods in cooling application

Parameter	Classic meth.	APRTC
Inner Δ T / ° C	11.7	0.97
Outer Δ T / ° C	16.32	1.50
Cooling time *sec*.	9.91	8.89

Table 4 Comparison between methods in cooling application presented in [9] and APRTC

Parameter	Classic Method	SLDCC Method	CCC Method	APRTC
Δ T / ° C	16.32	12.21	6.24	1.5
Improvement	-	25%	62%	91%

across different zones in the mold. This approach aims to reduce shrinkage, enhance product quality, and, by minimizing cooling time, increase the overall quantity of productions.

4.2.2 Advanced precise rapid thermal cycling in blow molding

From the very beginning, when mankind started to build things to present, products quality has dramatically improved. In recent decades along with the industry progress, production time must be enhanced in parallel with production quality. classic EBM cycle is a fast manufacturing method for hollow parts, but they have poor surface quality. In some cases, like bottles, car spoilers and etc. high-gloss surface quality is needed. in the past to achieve surface quality, blown parts require a new process that is time consuming.

Common blow molding process as previously described, have some stages after parison extrusion in production cycle, first when parison reaches the desired length, it is captured by mold halves, next a hollow pin, blows the parison and forms as the shape of mold, after that mold starts cools the polymer and completely solidifies the molded part, finally mold opens and ejects the part. Rapid thermal cycling in extrusion blow molding adds a new stage before mold cooling starts. The core mold surface should be rapidly heats up to 10°C higher than heat deflection temperature (HDT) of the molded polymer before parison inflation and stay at this temperature for 30*sec*. [16] in this temperature. The HDT for HDPE is 85°C and rapid thermal cycling should increase mold temperature to 95°C (Fig. 18 shown the heating process in step times). Figure 19 illustrated current pass through four thermoelectric element installed on different positions inside the mold in heating cycle.

Immediately after this stage, the parison quickly cools down by reversing input modules voltage. in the previous method, two different channel types were used, one groups for flowing coolant fluid and the others for heated fluid. To explain in details, in the first stage the heated fluid, flows through hot channels and heats the surface, when heating process ends, coolant fluid starts to run cooling channels instead and solidifies the mold. In APRTC method, when TEMs heats the core mold surface, the water which runs through the mold channels on the other side of modules will be cooled. when the heating time is over, the TEM should absorbs the heat from the polymer very quickly and pump the water for

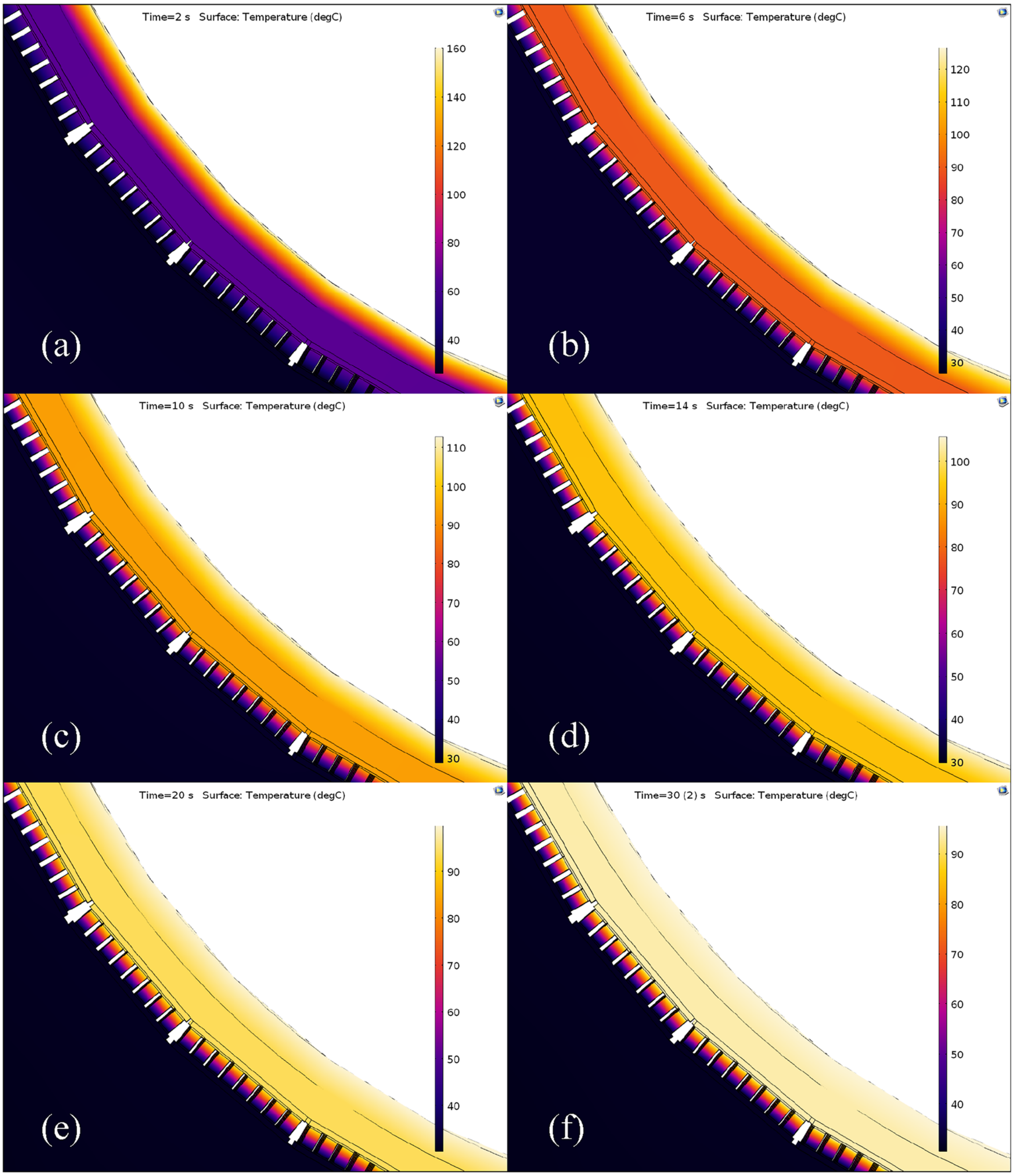
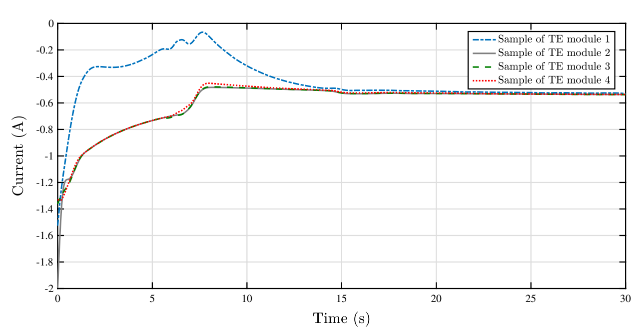


Fig. 18 Temperature field across the analyzed cross section of mold core at heating application: (a) at $t = 2s$, (b) at $t = 6s$, (c) at $t = 10s$, (d) at $t = 14s$, (e) at $t = 20s$ and (f) at $t = 30s$

Fig. 19 Current pass through thermoelectric module in heating mode



cooling stage. That is, water will be cooled in the first stage and then is used in cooling process as the coolant fluid. In other words, the energy consumed for heating is used for the next stage and makes rapid thermal cycling more efficient.

In Table 5, the values presented are the results of the research in [16], where heating pathways have been optimized using various methods and compared with conventional traditional methods. In the first method, optimized power density is utilized, while in the second method, optimized heat pathways are employed. The proposed method in the paper involves optimization conducted by the authors using the presented algorithm.

As discussed previously regarding Figs. 15 and 16 and the observed fluctuations around the 5-second mark, a similar pattern is observed in Figs. 19 and 20. However, due to the differences in temperature between these two processes, when reaching the designated temperature, the fluctuations are different compared to the cooling process. The achievement of the setpoint becomes evident around the 8-second mark, as depicted in the figures.

Rapid thermal cycling can start when the mold closes, as shown in Fig. 20 and Fig. 21 In the heating stage, temperatures are completely uniform over time. When compared to the classical method, differences in thermal distribution are reduced from 25.05$^\circ C$ to 2.84$^\circ C$, which represents an 89$\%$ improvement in temperature variation. Should be mentioned that inner surface temperature is not important for rapid thermal cycling. Figure 22 shown temperature distribution on *x* axis in mold cross section.

The observed wavy curve in this figure is attributed to the presence of heating/cooling channels. The non-uniform distribution of temperatures in the mold is influenced by their specific positions, resulting in the observed fluctuating pattern. However, when utilizing TE devices and applying a controller to regulate temperature, the distribution becomes uniform, presenting as a straight line. However, all the previously mentioned methods suffer from some serious limitations, which which causes the thermal control to distribute non-uniform temperature thus products suffer uniform high-gloss surface.

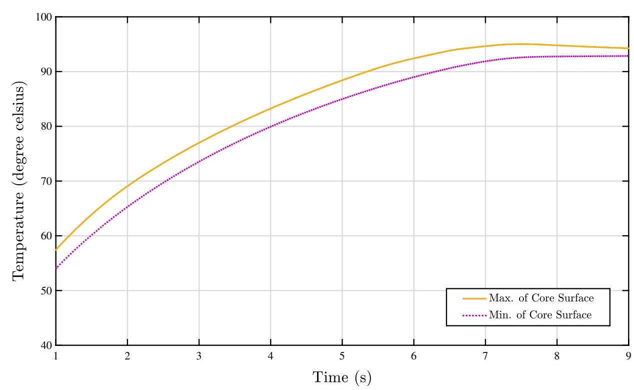


Fig. 20 APRTC method at rapid thermal cycling (heating stage) application: Comparison of maximum and minimum temperature of core mold surface

Table 5 Comparative analysis of heating methods was presented in [16] and APRTC

Parameter	Classic Meth.	P-design Case	L-design Case	Optimal Design	APRTC Design
ΔT / °C	22.06	13.00	16.52	5.05	2.84
Improvement	-	41%	25%	77%	89%

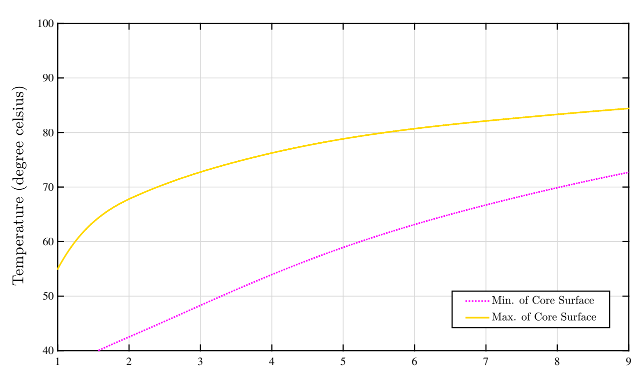


Fig. 21 Classic method at rapid thermal cycling (heating stage) application: Comparison of maximum and minimum temperature of core mold surface

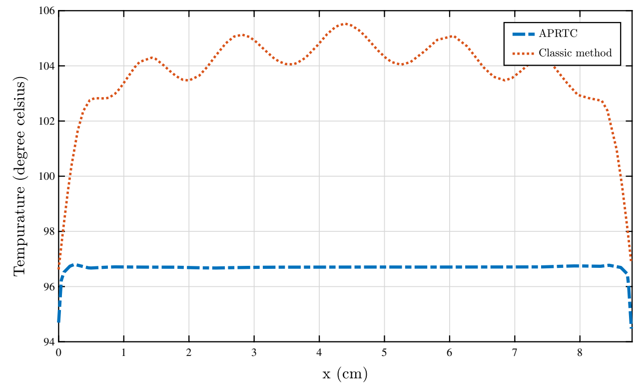


Fig. 22 Rapid thermal cycling (heating stage) application in steady state: Comparison APRTC method and classic method of core mold surface temperature

5 Conclusions

The state-of-the-art of APRTC technology using thermoelectric modules, thermocouple devices and fuzzy logic control together create a comprehensive solution for rapid thermal cycling in blow molding which is precise and accurate in controlling temperature. This is the first study integrating thermoelectric modules with blow molding production methods. Based on the results, the following conclusions can be drawn:

- The use of thermoelectric modules in this study expands the boundaries of mold design and eliminates thermal control limitations. The APRTC method can effectively cover corners, edges, and surfaces of molds with complex geometries by leveraging the thermoelectric effect. This enables precise temperature control over all points of the mold surface, surpassing what was previously achievable and significantly reducing the temperature difference across the core mold surface from 11.7°C to 0.97°C.
- The APRTC technology utilizes thermoelectric modules as solid-state heat pumps, which do not have any moving parts, making them maintenance-free. In this method, the use of a chiller is unnecessary in the process. Furthermore, because thermoelectric modules reduce temperature differences between the pipe and the environment, they significantly decrease heat waste along the pipes.
- Water circulates in a closed loop, and heat losses are minimized by the radiator in the cooling application. The use of water at ambient temperature prevents the mold from reaching the dew point, thereby improving the machine's useful lifespan. Furthermore, the rapid thermal cycling application can recover waste energy, using it to cool the water in the next stage, which, in turn, aids in cooling the hot side of the thermoelectric modules.
- Fuzzy logic control and other mechanisms such as measuring methods which are employed in APRTC, fabricate an advanced method to control the whole mold by making each TEM as a member of the entire system. This method obviously controls the surface temperature over time, and the maximum core surface temperature difference is reduced by 91% in the cooling cycle and 89% improvements in rapid thermal cycling heating stage.

The outcomes and insights gained from this study have direct applicability in manufacturing and mass production, promising enhancements in production quality for both cooling and rapid thermal cycling processes. However, a notable challenge in implementing these improvements lies in the initial cost associated with mold investment. Choosing a more cost-effective chiller could potentially offset these initial expenses over time, making the approach economically viable in the long run.

In the future, the findings of this study can be extended and applied to industrial molds characterized by complex geometries. The implementation of a Compensatory Adaptive Neuro-Fuzzy Inference System (CANFIS) could serve as a reliable and precise controller for handling the intricacies of complex molds. This advancement has the potential to enhance the adaptability and efficiency of the cooling processes, further contributing to the overall improvement in production quality for molds with intricate designs.

Author contributions AS authored the main manuscript, Professor AG provided guidance for the research and made additional contributions. All authors reviewed the manuscript.

Data availability The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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