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Impact of Injection Mold Settings Optimization on the Thermal Performance of Plastic (Cup) Product using Response Surface Methodology

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ABSTRACT

High quality plastic cups are attainable via the careful optimization of the injection mold settings. The development of the optimal injection mold settings of the injection speed, injection pressure, mold temperature and the cooling time input parameters in order to investigate their impact on the finished polypropylene plastic cup thermal performance response variable using the response surface methodology is the focus of this research study. A cup with a good thermal performance insulates the liquid content for a longer time helping the hot drinks to retain warmth for a longer time, and keeping the cold drinks from warming up quickly. Conversely, well insulated cups minimize condensation on the cup's exterior, improving grip and comfort while preventing water rings on surfaces. Therefore, an important indicator of a plastic cup's quality is the thermal performance. The response surface methodology (RSM) design of experiment (DOE) with multiple iterations of trial test moldings while varying the selected parameters was employed in this study. The response surface methodology analysis produced the following optimal solutions for each of the input variables: injection speed – 50mm/s; injection pressure – 95MPa; mold temperature – 57℃; and cooling time – 15s. Correspondingly, the optimal solution of the response variable, thermal performance was 0.360W/mK. The global desirability (DG) of achieving the optimal solutions was 1 (100%), with a strong Coefficient of Determination (R^2) between the input parameters and the response variable value of 89.68%. The analysis of variance (ANOVA) table showed that the selected model was a quadratic model. The ANOVA model showed that the cooling time input factor has the most significant effect on the target response, together with the interactive term coefficient of injection speed and injection pressure. The optimized results will serve as a guide to manufacturers in the optimal setting of their production parameters. The economic feasibility of determining the best mold settings and materials for enhanced product quality was demonstrated in this study with the use of the DOE. The approach of this research study will mitigate a lot of wastes and defects in production and also when employed in the production of other injection mold plastic products.

INTRODUCTION

This study aims to investigate the interplay between production mold parameters and plastic cup quality, seeking to reveal insights that can lead to enhanced production efficiency, optimized mold settings, and ultimately, the delivery of high-quality plastic cups with optimized characteristics. Plastic cups, though convenient and looks simple, its production are associated with challenges related to achievement of optimal quality while ensuring efficiency and sustainability are maintained.

Production molds used in the manufacture of the plastic products (e.g. cups) are responsible for these attributes having crucial impact on the finished product (cup's) quality of strength, dimensional accuracy, thermal performance, aesthetics, and the cost of production, etc. Inadequate production mold designs result to imperfect shapes, weak points, etc., leading to leaks, cracks, premature failure, overweight, etc., which accrues to wastage of materials, prolonged cycles of production, increased energy consumption, generation of avoidable environmental burdens, and increased production cost etc.

The thermal performance of a cup hinges on the capability of a plastic cup to maintain the hotness or coldness of the temperature of the content for a longer time. Good thermal performance of plastic cup has the following advantages: (a) Insulation of the hot drinks from the surrounding atmosphere, maintaining them warmer for a longer time. Equally, insulate cold drinks, preventing them from getting warmer quickly. (b) It's a pleasurable experience for the liquid content in the cup to stay at the desired temperature for a longer time during consumption. (c) Well insulated cups minimizes condensation on the cup's outside wall, enhancing grip and comfort while preventing water rings on surfaces. The thermal performance specification of a plastic cup usually depend on the intended use: cups for hot drinks need retain heat longer and cups for cold drinks need avoid condensation to keep liquid content cold longer. When testing for thermal performance, fill tests are used with hot and cold water to measure heat loss/gain rates over time compared to desired targets. There should be a balance between thermal performance, cost and other factors like durability and ease of use when setting specifications. But insulation is a key purchasing driver. Consistent thermal performance testing ensures plastic cups maintain the desired temperature retention and insulation properties for their intended application.

The injection mold parameters combination of injection speed, injection pressure, mold temperature and the cooling time, affects the finished plastic (Cup) product/ thermal performance/ quality as defined hereafter: (1) Injection Speed: Injection speed impacts significantly on plastic cup thermal performance by affecting the internal structure, crystallinity, and residual stress. Injection speed affects the melt temperature, cooling behavior and final part quality. Here's a clear breakdown focused on plastic cups (thin-walled parts). (A) Melt Temperature and Frictional (Shear) Heating: (i) Faster Injection Speeds: Increases more friction (shear) rate, i.e. more shear heating, which occurs as the molten polymer flows rapidly through the gate and the mold channels, generating significant heat, especially at the melt front (potentially raising the melt front temperature). This increase in internal temperature can alter the finished product's crystallinity and density, impacting insulation. Faster injection speeds also helps melt stay fluid long enough to fill thin cup walls (ii). Slower Injection Speeds: Causes less friction (less shear heating), meaning less heat generated from flow, but the material (melt) cools faster against the mold walls, resulting in risks of short-shots or incomplete filling, thus, creating different internal structures.

Slower speeds can cause uneven cooling and higher crystallization, making the cup less uniform and potentially affecting how well it holds heat/cold over time, leading to variations in thermal insulation and structural integrity. (iii) Thermal Impact: High injection speed can raise effective melt temperature without increasing barrel heat, improving flow but risking overheating. (B) Crystallinity and Density: (i) Slow Injection Speeds: Allows more time for polymer chains to align and crystallize as the material cools against the mold, resulting in higher density but potentially more brittle parts and altered thermal conductivity. (ii) Moderate Injection Speeds: Often ideal, promoting uniform crystallization and better impact strength, creating a more consistent thermal barrier. (iii) Fast Injection Speed: Can lead to amorphous (less crystalline) regions if cooling is too rapid, or complex, uneven structures due to high shear, affecting how heat transfers through the cup. (C) Cooling and Solidification/ Mold Filling and Heat Distribution: (i) Slower Injection Speed: Material cools more before the cavity fills, requiring higher pressure and potentially leading to larger temperature gradients and warpage, affecting uniform insulation. The melt near mold walls cools too quickly. This can lead to uneven wall thickness and cold spots. (ii) Faster Injection Speed: Fills the cavity quicker, but the increased internal heat requires sufficient cooling time to prevent warpage and ensure uniform properties, crucial for consistent thermal performance.

Faster injection speeds leads to more uniform temperature distribution during filling, reduces premature freezing at the flow front, and better replication of thin walls. (D) Internal Stresses: High injection speeds can trap stresses altering molecular orientation, which can affect the finished cup's ability to resist temperature changes without deforming or cracking, thus impacting its thermal resilience. In summary, too slow injection speed, leads to premature cooling, higher pressures, uneven structure, higher crystallinity (potentially), and poor bonding if multi-layered, all impacting uniform thermal insulation and strength. Too fast injection speed causes excessive shear heating, potentially creating uneven densities, increased stress, and poor surface finish, which can compromise insulation and structural integrity. The optimal speed balances flow, heat generation, and cooling to create uniform density and crystallinity, resulting in a stable internal structure for consistent thermal performance and durability. (2) Injection Pressure: Injection pressure primarily affects the density, fill completeness and structural integrity of plastic cups, which indirectly impacts thermal performance by controlling wall thickness uniformity and air pockets (insulation); higher pressure ensures better fill (fewer voids/ better insulation) but too much can cause flash/ warping, while optimal pressure balances density for consistent thermal insulation against defects like short-shots (poor fill) or flash.

The following illustrates how pressure impacts physical properties (indirect thermal effects): (i) Better Density and Fill: Higher pressure forces melt into the mold, increasing density and ensuring complete filling, reducing internal air pockets that act as insulators, making the cup less thermally resistant (better heat transfer to hands/ lips). (ii) Reduced Shrinkage/ Warpage: Sufficient pressure (packing pressure) counteracts material shrinkage, leading to more uniform wall thickness, which is crucial for consistent heat retention/ transfer; less warpage means fewer gaps for heat loss. (iii) Structural Integrity: Proper pressure prevents voids and weak spots, ensuring the cup's structure holds up, preventing leaks and maintaining its designed insulation properties. (iv) Fewer Air Pockets (Good Insulation): If pressure is too low, you get short-shots or voids (air pockets), which can actually improve insulation if the cup is thin-walled and needs trapped air, but it's usually a defect. (v) Uniformity (Better Performance): Optimal pressure leads to uniform thickness and density, meaning heat transfers more predictably across the surface, providing consistent thermal protection. In summary: Too Low Pressure: Incomplete fill (short-shots), voids, weaker structure, poor thermal consistency, heat escapes through gaps.

Too High Pressure: Flash (excess material), warping, increased part stress, potential damage; can make the cup denser (less insulating) but might also force material into thin spots, making them more prone to heat transfer if not cooled right. In essence, you need optimal pressure for a solid, uniform cup with consistent density, ensuring it performs thermally as designed, rather than having unpredictable hot/ cold spots from defects. The Ideal pressure creates a dense, uniform cup with minimal defects, offering predictable thermal performance, usually better insulation due to optimized density and structure. Therefore, finding the "sweet spot" in injection pressure ensures a stable, well-packed cup that provides the intended thermal performance (insulation or conductivity) with maximum structural strength, balancing density, fill, and defect prevention. (3) Mold Temperature: Mold temperature significantly affects plastic cup thermal performance by controlling crystallinity and molecular structure, which dictates insulation; higher temperatures allow more ordered crystals/ crytsallization (better insulation for hot drinks, but can affect clarity/ strength), while lower temperatures freeze chains/ less-ordered structures (less crystalline, potentially clearer but less insulating, better insulation for cold), impacting heat retention, warpage, and mechanical properties like strength. It also influences density, strength, and dimensional stability, impacting the cup's overall thermal efficiency by changing wall thickness uniformity and minimizing air gaps (which degrade insulation). Optimal mold temperature balances these factors for the desired cup properties, with specific ranges depending on the plastic type (PP, PET, etc.). Key effects of mold temperature are: (A) Crystallization and Molecular Orientation: (i) Higher Mold Temperatures: Slower cooling gives polymer chains more time to align, increasing crystallinity and density, making the cup more rigid but potentially less insulating (unless for hot liquids where ordered structure helps). More crystalline structures improve a cup's ability to resist heat transfer (better insulation for hot liquids.) but can reduce transparency.

It improves surface finish but can affect dimensional stability. (ii) Lower Mold Temperatures: Faster cooling freezes molecular chains in less ordered (amorphous) states, permitting less time for alignment of polymer chains, resulting in reduced or lower crystallinity. This can trap more air (better insulation for cold drinks) but may lead to internal stresses, warping, and lower strength. This often leads to clearer cups but can decrease their thermal resistance (poorer insulation). (B) Density and Air Trapping: (i) Hotter Molds: Can lead to higher density and more uniform structure, but also higher shrinkage. (ii) Colder Molds: Can result in lower density or more trapped air pockets (if cooling is uneven), improving insulation but potentially creating weak spots or warpage. (C) Thermal Performance (Insulation): (i) For Hot Drinks: A higher degree of crystallinity (from higher mold temperatures) can create a more robust structure that withstands heat better, while controlling wall thickness improves overall thermal performance. (ii) For Cold Drinks: A less Crystalline, potentially more porous structure (from lower mold temperatures) can trap air, enhancing insulation to keep contents cold longer. Impact on Cup Quality: (a) Dimensional Stability: Poor mold temperature control leads to warping or inconsistent dimensions, creating gaps that allow heat transfer. (b) Internal Stress and Warpage: Too high mold temperature can increase shrinkage after molding, potentially causing warping and dimensional issue.

Too low mold temperature can lead to uneven cooling, trapping internal stresses, causing warpage, and making weld lines visible, weakening the cup. Rapid cooling (low temperature) freezes stress, affecting durability and how well the cup holds temperature without deforming. (c) Melt Flow and Surface Finish: Higher mold temperatures improves melt flowability, helping plastic fill the mold completely and replicate fine surface details (better finish). In essence, hotter molds yield better surface reproduction. Lower mold temperatures reduce melt flow, potentially causing incomplete filling or surface defects. Colder molds can cause defects like flow marks, impacting aesthetics and minor insulation. In essence, optimizing mold temperature balances material properties (crystalinity, density) with part geometry to achieve the desired thermal performance (insulation) and structural integrity for hot or cold applications. Manufacturers use techniques like conformal cooling channels (CCC) and design of experiment (DOE) to find the ideal/ optimal mold temperature settings that balance these properties for optimal cup quality and desired thermal insulation. (4) Cooling Time: Cooling time during injection molding process affects a plastic cup's thermal performance by influencing its molecular structure, density, and wall thickness; longer, optimal cooling allows for better crystallization, creating denser structures that improve the plastic's inherent insulating properties (low thermal conductivity), keeping hot drinks hot and cold drinks cold longer especially in thicker plastics.

Essentially, proper cooling makes a better insulator by solidifying the materials structure for optimal heat retention. In injection molding, cooling time has major impact on the thermal performance, quality, and productivity of plastic cups. Here's how it affects the process in a clear, cause-and-effect way: (A) Heat Removal and Part Solidification: (i) Cooling time is the period when the molten polymer inside the mold releases heat and solidifies. In a short cooling time, the plastic may still be soft or partially molten. In an adequate cooling time, there's uniform solidification and stable cup shape. Plastic cups are thin-walled, so heat must be dissipated evenly to avoid defects. (B) Dimensional Stability and Warpage: (i) If cooling is too short, uneven shrinkage occurs. Cups may warp, ovalize, or lose roundness. (ii) With proper cooling, shrinkage becomes more uniform. Cup dimensions remain consistent (important for stacking and lids). (C) Residual Stress and Thermal Performance: (i) Rapid or uneven cooling traps residual thermal stresses in the cup. These stresses: reduce resistance to hot liquids; increase risk of cracking or deformation during use. (ii) Controlled cooling allows polymer chains to relax, improving heat resistance and long-term durability. (D) Surface Quality: (i) Insufficient cooling can cause sink marks, gloss variations, poor rim definition. (ii) Optimized cooling improves smooth surface finish, and uniform wall thickness appearance. (E) Cycle Time and Productivity Trade-off: (i) Cooling time typically makes up 50-70% of the total cycle time. (ii) Longer cooling time results in better thermal and dimensional performance, and lower production rate. (iii) Shorter cooling time leads to higher output, and higher risk of defects and thermal weakness. (F) Material Specific Effects (Common Cup Plastics): (i) For the material of the cup used in this research study, Polypropylene (PP), the material is sensitive to cooling rate. Faster cooling rate increases stiffness, but may reduce heat resistance. (ii) Polystyrene (PS) materials, needs uniform cooling to avoid brittleness, (iii) In Polyethylene Terephthalate (PET) materials, cooling affects crystallinity, which directly impacts thermal resistance. (G) Overall Impact on Thermal Performance in Use: (i) Proper cooling time leads to cups that: maintain shape with hot liquids, have lower heat distortion, and feel more rigid and reliable to the user. (ii) Poor cooling control results in: softening with hot drinks, deformation under load, and reduced service temperature. In summary, when cooling time is: (i) Too short: warpage, weak heat resistance and defects occur; (ii) Optimal: there’s stable dimensions, and good thermal performance; (iii) Too long: there’s better quality, but slower production.

Inasmuch that a lot of researches has been conducted previously on the improvement of the efficiency of the production mold and the finished product quality through the optimization of the injection molding process and it’s parameters, no previous work has dwelt on the novel field of the improvement of the efficiency of the injection molding process for the resultant finished product’s enhanced quality through the optimization of the mold settings for enhanced finished product’s thermal performance. Injection molding is a complex process regulated by many factors (injection speed, injection pressure, melt temperature, mold temperature, and others) (Sortino et al., 2014). Injection molding is used to make things such as housewares, toys, automobile components, furniture, packaging items, appliances, and medical disposal syringes (Bhardwaj et al., 2024). Injection molding is based on a process in which a molten polymer is injected into a cavity that contains the microchip channel architecture, once the liquid polymer has filled the cavity; the temperature is lowered, causing polymer solidification (Pitingolo and Nastruzzi, 2023). The optimization of the process parameters of the injection molding of the inner panel of the car door was completed by Yang et al. (2022). In the research, the mold temperature, melt temperature, cooling time, holding pressure, and holding time were selected as the influencing factors, and volume shrinkage and warpage deformation were selected as the evaluation indicators to design and complete the orthogonal test. The test data were simulated by Moldflow, and the optimal combination of process parameters was determined by range and variance analysis.

The BP neural network model related to the molding process parameters, volume shrinkage, and warpage deformation was built, and the trained network model was optimized with the ant colony algorithm. The optimal parameter combination was: mold temperature 76^{0}C, melt temperature 205^{0}C, cooling time 23.8s, holding pressure 54.7MPa, and holding time 22.1s. The simulation results showed that volume shrinkage was 13.2% and warpage deformation was 4.315mm. In the research of Li et al. (2023), hydrogen storage cylinder lining was taken as the research object. Moldflow was utilized for analysis to determine the best combination of injection molding process parameters. The effects of injection process parameters (melt temperature, mold temperature, holding pressure, holding time and cooling time) on the evaluation index were analyzed by orthogonal experiment L_{16} (4^5). The multi-objective optimization problem of injection molding process was transformed into a single-objective optimization problem by using the grey correlation analysis method. The optimal parameters such as melt temperature 270^{0}C, mold temperature 80^{0}C, packing pressure 55MPa, packing time 20s and cooling time 13s were obtained. Aslam et al. (2025) presents an experimental design technique aimed at minimizing warpage and weight in Polyethylene Terephthalate (PET) preforms weighing 45g. Five important process parameters were identified through initial screening; they're, melting temperature, injection time, molding temperature, cycle time, and cooling time. Taguchi L_{27} (3^5) array design was used to conduct the experimental design. The ANOVA and signal-to-noise (S/N) ratio were used to discover the optimal parameter levels and evaluate their effects on warpage and weight. The results showed a reduction in warpage by 4.75% and weight by 2.05% under the optimized settings. A validation test established the potency of the Taguchi method at the optimal parameter levels, to show consistency with the experimental findings.

Jou et al. (2025) delivered an innovation in sustainable injection molding and uniquely combined a back propagation neural network (BPNN) with particle swarm optimization (PSO) in order to overcome traditional optimization challenges. The BPNN's exceptional proficiency to learn complex non-linear relationships between six key process parameters (including melt temperature and holding pressure) and product quality is improved by PSO's intelligent search capability, which efficiently navigates the high dimensional parameter space. The hybrid approach achieves what neither method could accomplish alone: the BPNN accurately models the complex process-quality relationships, while PSO swiftly converges on optimal parameter sets that simultaneously meet strict quality targets (66-70g weight, 3-5mmthickness) and reduce energy consumption. Experimental verification established that the optimized factors minimized energy use by 28% and material waste by 35%, while consistently producing parts within specifications. The analysis of the heat transfer during the stage of cooling permits the study of the optimal arrangement of the cold sources and their intensities. Chaabene et al. (2022) developed a systematic approach used to replace traditional channels in an injection molding tool with conformal cooling channels. They simulated to develop a numerical model that illustrated the heat transfer and predicts the cycle time of both the optimal and traditional designs. They made a numerical comparison between the conventional and conformal cooling to reveal the advantageous influence on minimizing the manufacturing cycle and improving part quality.

Gaspar-Cunha et al. (2025) reviewed the optimization methodologies in injection molding, with emphasis on integrating advanced modeling, surrogate models, and multi-objective optimization techniques to improve efficiency, quality and sustainability. Important stages such as plasticizing, filling, packing, cooling, and ejection are analyzed, each presenting unique optimization challenges. The review study highlights the significance of cooling, which accounts for 50-80% of the cycle time, and studies new strategies, such as conformal cooling channels (CCC's), to improve uniformity and reduce defects. Various computational tools, such as Moldex3D and Autodesk Moldflow were discussed due to their roles in process simulation and optimization. Also, optimization algorithms such as evolutionary algorithms, simulated annealing, and multi-objective optimization methods were explored. The combination of surrogate models, such as Kriging, response surface methodology, and artificial neural networks, has shown capacity in addressing computational cost challenges. Upcoming directions highlight the need for adaptive machine learning and artificial intelligence techniques to optimize molds in real time, offering more innovative and sustainable manufacturing solutions. Mold temperature control is an essential part of the injection molding process having an influence on cooling time, surface quality and inner structure (Zhang and Zhou, 2013). Beside mold temperature, thermal conductivity of the mold material is a relevant factor. Mold materials for serial production are available with thermal conductivity in the range of 15W/mK to above 150W/mK (Reddy and Panitapu, 2017 and Liu, 2014).

The theoretical basis of this research study is centered on the application of response surface methodology (RSM) design of experiment (DOE) to analyze and to investigate the effects of the optimal injection mold parameters on the finished plastic (Cup) product thermal performance. RSM is a popular statistical and mathematical tool deployed in optimizing systems, product quality, and in investigating the common relationships among the variables (input and output) of systems, etc. Existing literatures has given a foundation for this study, several researchers having used the application of response surface methodology (RSM) to optimize the injection mold system for enhanced product quality. This research study will contribute to knowledge in building on the existing literatures for the optimization of the injection mold system for improved product quality and performance.

Optimizing injection mold settings (like mold temperature, injection pressure, injection speed, and cooling time) for plastic cups is crucial because it directly controls the final part's density, crystallinity, and wall thickness uniformity, which dictates it's insulation (thermal performance), strength, and leak resistance, leading to better hot/ cold retention, reduced material waste, lower costs, and a superior, more consistent consumer product. The key significance in the optimization of mold settings for thermal performance of plastic cups are: (a) Density and Crystallinity: Mold temperature and injection pressure affect how quickly the molten plastic cools and solidifies, influencing molecular alignment (crystallinity) and density, which are key to insulation. Higher density often means better heat retention. (b) Wall Thickness Uniformity: Optimized settings prevent warpage and sink marks, ensuring even wall thickness. Uniform walls provide predictable and consistent heat transfer, crucial for keeping drinks hot or cold. (c) Reduced Defects: Proper settings minimize air traps, weld lines, and voids that act as thermal bridges, allowing heat to escape or enter, and degrading performance. The key mold settings and their impacts are as follows: (a) Mold Temperature: Controls cooling rate; affects surface finish, crystallinity, and part shrinkage. (b) Injection Pressure/ Speed: Impacts part density, minimizing voids, and ensuring complete mold filling, especially for thinner cups. (c) Cooling Time: Must be optimized with mold temperature for efficient cycle time and proper part solidification, preventing warpage. The overall benefits of optimization of the mold settings includes: (a) Improved Insulation: Cups retain temperature longer, enhancing user experience. (b) Enhanced Strength: More uniform structure means better tensile strength and durability. (c) Cost Reduction: Less scrap, faster cycles, and better material usage. (d) Consistent Quality: Predictable performance and appearance across millions of units.

Inasmuch a lot of previous researches has been conducted on the improvement of the efficiency of the production mold and the finished product quality through the optimization of the injection mold process and it's parameters, but no previous research has delved into the novel ground of the improvement of the efficiency of the injection molding process for the resultant finished product's enhanced quality with emphasis on the optimization of the mold settings for improved finished product's thermal performance. The optimization of the injection mold parameter combinations of the injection speed, injection pressure, mold temperature and the cooling time as input parameters in plastic cup production, in order to investigate the impact of the optimized input parameters on the finished plastic (cup) product thermal performance as the response variable, using the response surface methodology (RSM) for analysis is the basis of this novel and innovative research study.

METHOD

The beginning of this research study involved the identification of the fundamental plastic cup qualities which were adopted from the perspective of the user-experience and structural and durability features. The identification of the fundamental injection mold factors impacting the fundamental cup qualities follows. This is followed by conducting experimental trials with variations of mold factors to examine their performance, and then, evaluate the impact of the variations of the mold factors on the quality and efficiency of the finished polyethylene plastic (Cup) product. Following is the investigation of the interactions between the different mold parameters against the quality metrics as against the individual parameters. Thermal performance significantly impact plastic cup's quality, influencing it's potentials to insulate and retain desired temperatures. The key mold parameters selected for optimization based on their anticipated impact on the plastic cup quality attribute of concern are: injection speed, injection pressure, mold temperature, and cooling time. These factors were selected based on the general knowledge of injection molding dynamics and their relevance in affecting the desired cup quality of interest. Their selection put into consideration the probable interactions between the settings of these parameters. The experimental design and response modeling focused on these selected parameters, the purpose was to efficiently identify the process settings most critical to optimizing the specified cup quality variable.

Table 1: Input and Response Variables under Investigation

MOLD SETTINGS (INPUT VARIABLES)	**PLASTIC CUP QUALITY METRICS (RESPONSE VARIABLES)**
Injection Speed (mm/s) Injection Pressure (MPa) Mold Temperature (^{0}C) Cooling Time (sec)	Tensile Strength (MPa) Thermal Performance (W/mK) Weight (g)

Table 2: Central Composite Design (CCD) Matrix of the Experimental Results and Data

INPUT VARIABLES				**RESPONSE VARIABLE**
Injection Speed (mm/s)	**Injection Pressure (MPa)**	**Mold Temp. (^{0}C)**	**Cooling Time (sec)**	**Thermal Performance (W/mK)**
70	80	60	16	0.21
50	90	80	25	0.33
80	70	50	15	0.2
50	50	70	20	0.15
60	70	60	15	0.23
70	60	50	18	0.2
110	90	80	30	0.3
70	60	50	15	0.22
80	75	80	25	0.27
50	60	70	23	0.24
80	90	60	17	0.26
55	95	50	15	0.35
70	80	50	18	0.27
50	70	60	20	0.22
60	50	50	16	0.2
80	60	70	19	0.24
60	90	80	30	0.3
70	90	50	17	0.28
60	50	60	19	0.22
100	70	60	21	0.25
70	70	50	23	0.23
90	80	90	30	0.35
50	80	60	16	0.27
70	90	70	27	0.36
50	**95**	**57**	**15**	**0.36**

This study used the Minitab Statistical Software (version 20.3.0) for the analysis. It is a powerful statistical tool used for data analysis, process improvement, and Six Sigma projects. It has a user-friendly interface, thus, easy to use by both statisticians and non-statisticians. It is a valuable tool for optimizing processes and products using RSM. It is equipped with comprehensive RSM features, excellent data visualization potentials, making it a global option in various environments. It is popularly used in environments such as engineering, production, research, etc., to analyze and optimize processes, product quality, cost reduction, etc. It offers numerous pre-defined experimental designs such as Central Composite Design (CCD), Box-Behnken Design (BBD), and Doehlert Design (DD), adequate for various objectives and constraints. These designs could be customized by specifying parameters, levels and center points. The experimental runs would be automatically generated by the Minitab software, saving the analyst time and effort. The Minitab will help analyze data generated from experimental runs efficiently. Minitab offers various regression analyses to fit the models of the data, including the Linear, Interactive and Quadratic models generally used in the RSM analysis. The model's fit could be easily assessed using the diagnostic plots and the statistical tests. The Pareto chart was also used for the data analysis in this study. Pareto chart enables a cursory visual concept of the most significant variable and the interactions affecting the response of interest. The Pareto chart permits swift identification of the vital few variables that have the greatest impact on the response of interest being analyzed. The chart bars are well-arranged from the most significant to the least of the variables and their interactions that impacts on the response of concern. Pareto chart permits the assessment of the relative significance and the statistical significance of effects on the response. It also allows for the identification of the vital few factors to focus on for the response variable. Table 1 is the table of the plastic cup quality metrics (response variables) against the mold settings (input variables) under investigation.

RESULT AND DISCUSSION

The response surface technique employed for the data analysis in this research study indicated a result that the selected models are more of the quadratic types. For flexibility and simplicity of model analysis, the Central Composite Design (CCD) expert suggests more of quadratic models. In order to find the significance and impact of the input variables against the response variables, the response surface technique compares the input variables (mold settings) against each quality response, namely: weight, thermal performance, and tensile strength. In the response surface analysis, the coded coefficient table is used to identify the impacts that are positive or negative using the coefficient (coeff.) column. A positive coefficient value shows that the variable is directly proportional to the response (i.e. an increase in the input variable leads to an increase on the response). Likewise, a negative coefficient value shows an inverse relationship or impact of the variable on the response (i.e. an increase of the input factor leads to a decrease on the response). The regression analysis of the response variable, thermal performance (W/mK) against each of the input variables, namely: injection speed (mm/s), injection pressure (MPa), mold temperature (^{0}C), and cooling time (sec) and their results are following.

Table 3: Coded Coefficient Table for Thermal Performance Response Variable

Term	Coeff.	SE Coeff.	T-Value	P-Value	VIF
Constant	0.2842	0.0225	12.63	0.0000	
Injection Speed (mm/s)	-0.0057	0.0269	-0.21	0.838	3.14
Injection Pressure (MPa)	0.0021	0.0300	0.07	0.946	1.80
Mold Temperature (°C)	-0.0274	0.0488	-0.56	0.589	3.86
Cooling Time (s)	0.0905	0.0595	1.52	0.036	0.88
Injection Speed (mm/s)*Injection Speed (mm/s)	-0.0420	0.0409	-1.03	0.331	3.70

Injection Pressure (MPa)*Injection Pressure (MPa)	0.0272	0.0201	1.35	0.209	1.55
Mold Temperature (°C)*Mold Temperature (°C)	-0.0699	0.0589	-1.19	0.266	3.64
Cooling Time (s)*Cooling Time (s)	-0.0606	0.0481	-1.26	0.239	1.33
Injection Speed (mm/s)*Injection Pressure (MPa)	-0.0373	0.0298	-2.93	0.017	3.38
Injection Speed (mm/s)*Mold Temperature (°C)	-0.0112	0.0815	-0.14	0.894	2.33
Injection Speed (mm/s)*Cooling Time (s)	0.0307	0.0810	1.00	0.345	2.86
Injection Pressure (MPa)*Mold Temperature (°C)	-0.0024	0.0412	-0.06	0.955	3.36
Injection Pressure (MPa)*Cooling Time (s)	-0.0118	0.0511	-0.23	0.823	3.94
Mold Temperature (°C)*Cooling Time (s)	0.1111	0.0909	1.22	0.249	3.35

From the above table, it can be seen that three of the linear/constant term coefficients (independent) variables have no significance on the response (thermal performance) variable, but the cooling time input variable has a high significant impact on the response variable with high significance of P- value of 0.036. The quadratic (square) term coefficients of the independent variables also demonstrate no significant effect on the response variable (thermal performance). But the interactive (2-way) term coefficient of the independent variables, the Injection Speed*Injection Pressure shows a remarkable significant effect on the thermal performance response variable with high significance of P- value of 0.017, though the impact of the coefficient is inverse (negative) on the response.

Table 4: Model Summary Statistics for the Thermal Performance Response Variable

S	**R^2**	**Adj. R^2**	**Pred. R^2**
0.0278	89.68%	73.62%	0.00%

The model summary statistics table 4 above shows that the standard error of regression (S) value of 0.0278 is reasonable low, which signifies a good fit between the model predictions and the actual data points. The R^2 value of 89.68% shows that the model explains 89.68% of the variance in the response. The relatively high R^2 value is indicative that the model fits the data to a very good extent and hence can be used to predict and as well as model the response variable of thermal performance. The Adj. R^2 value of 73.62% is high but lower than the R^2 value suggesting that the model is not over-fitting the data. A higher R^2 and Adj. R^2 values are always desirable. When the variance between the R^2 and Adj. R^2 values is large, or when the Adj. R^2 value is significantly small compared to the R^2 value, it shows that there’s an existence of possible error in the values of the data of the variables obtained. The error values need to be properly checkmated or replaced entirely if need be. The Pred. R^2 is surprisingly low; a value of 0.00% indicates that the model would not be adequate to predict future outcomes of the response variable. Generally, the model is statistically significant and explains a large percentage of the variance in the thermal performance response variable.

Table 5: ANOVA Table for Thermal Performance Response Variable

Source	df	Seq. SS	Contribution	Adj. SS	Adj. MS	F-value	P-value
Model	14	0.060589	89.68%	0.060589	0.004328	5.59	0.007
Linear	4	0.049270	72.92%	0.023840	0.005960	7.69	0.006
Injection Speed (mm/s)	1	0.000585	0.87%	0.000034	0.000034	0.04	0.838
Injection Pressure (MPa)	1	0.033409	49.45%	0.000004	0.000004	0.00	0.946
Mold Temperature (°C)	1	0.013867	20.52%	0.000243	0.000243	0.31	0.589
Cooling Time (s)	1	0.001409	2.09%	0.001792	0.001792	2.31	0.036
Square	4	0.002781	4.12%	0.000943	0.000943	1.22	0.369
Injection Speed (mm/s) * Injection Speed (mm/s)	1	0.000034	0.05%	0.000818	0.000818	1.06	1.06
Injection Pressure (MPa) * Injection Pressure (MPa)	1	0.000880	1.30%	0.001417	0.001417	1.83	0.209
Mold Temperature (°C) * Mold Temperature (°C)	1	0.001694	2.51%	0.001090	0.001090	1.41	0.266
Cooling Time (s) * Cooling Time (s)	1	0.000173	0.26%	0.001231	0.001231	1.59	0.239
2-Way Interaction	6	0.008538	12.64%	0.001423	0.001423	1.84	0.198
Injection Speed (mm/s) * Injection Pressure (MPa)	1	0.005883	8.71%	0.006648	0.006648	8.58	0.017
Injection Speed (mm/s)* Mold Temperature (°C)	1	0.001221	1.81%	0.000015	0.000015	0.02	0.894
Injection Speed (mm/s) * Cooling Time (s)	1	0.000732	1.08%	0.000769	0.000769	0.99	0.345
Injection Pressure (MPa)* Mold Temperature (°C)	1	0.000025	0.04%	0.000003	0.000003	0.00	0.955
Injection Pressure (MPa) * Cooling Time (s)	1	0.000041	0.06%	0.000041	0.000041	0.05	0.823
Mold Temperature (°C) * Cooling Time (s)	1	0.000637	0.94%	0.001461	0.001461	1.89	0.203
Error	9	0.006974	10.32%	0.000775	0.000775		
Total	23	0.067562	100.00%				

The model as revealed from the ANOVA table above indicates a high significance value with a P-value of 0.007. The contribution 89.68%, explains the percentage of the total variation in the model that can be explained (i.e. the R^2). This very high P-value value signifies that the model is good and fit for the data and for the statistical modeling of the thermal performance response variable. From the table, it is also shown that the linear term coefficients has a total contribution of 72.92% to the model and shows significance with a P-value of 0.006, which depicts that each of the input variables has a statistically significant linear relationship with the model. The quadratic (Square) term coefficients indicate a low contribution of 4.12% to the model with the significance or P-value of 0.369. From the table it is also shown that the input factor that has the most significant impact on the thermal performance response variable is the cooling time having high significance with a P-value of 0.036. From the interactive term coefficients, the ANOVA indicates that the interaction between the injection speed and the injection pressure has a high significant impact on the thermal performance response variable having high significance with P-value of 0.017, and a contribution of 8.71% to the overall interactive source model. The unexplained variation or error in the overall model of the thermal performance response variable amounts to 10.32% as seen from table 5 above. Generally, the ANOVA table reveals that the RSM model is good and fit for the data analysis and for the adequate modeling of the thermal performance response variable, with the cooling time input factor and the interactive term coefficient between the injection speed and the injection pressure indicating the most significant factors impacting on the thermal performance response variable.

Regression Model for the Actual Factors of the Thermal Performance Response Variable

The final equation in terms of the actual factors in the regression model of the thermal response variable is as follows:

Thermal Performance (W/mK) = -0.483 + 0.0083 Mold Temperature (°C)
+ 0.00989 Injection Speed (mm/s)
+ 0.00457 Injection Pressure (MPa)
- 0.0150 Cooling Time (s)
- 0.000175 Mold Temperature (°C)*Mold Temperature (°C)
- 0.0000047 Injection Speed (mm/s)*Injection Speed (mm/s)
+ 0.000054 Injection Pressure (MPa)*Injection Pressure (MPa)
- 0.001077 Cooling Time (s)*Cooling Time (s)
- 0.0000019 Mold Temperature (°C)*Injection Speed (mm/s)
- 0.0000005 Mold Temperature (°C)*Injection Pressure (MPa)
+ 0.0000741 Mold Temperature (°C)*Cooling Time (s)
- 0.0000129 Injection Speed (mm/s)*Injection Pressure (MPa)
+ 0.0000359 Injection Speed (mm/s)*Cooling Time (s)
- 0.0000070 Injection Pressure (MPa)*Cooling Time (s)

Pareto Chart for Thermal Performance

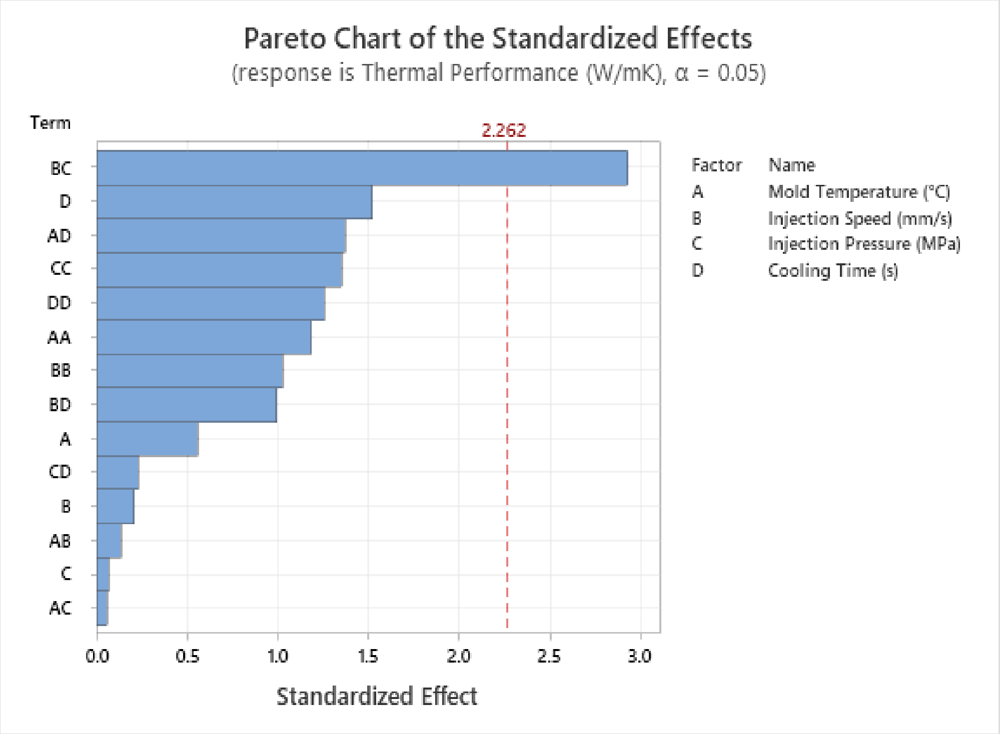

Fig. 1: Pareto Chart for the Thermal Performance Response Variable.

The Pareto chart above shows that the interaction between the injection speed and the injection pressure input factors and the cooling time input factor are the most significant influencers on the thermal performance response variable and the length of their bars confirms their statistical significance on the thermal performance response variable.

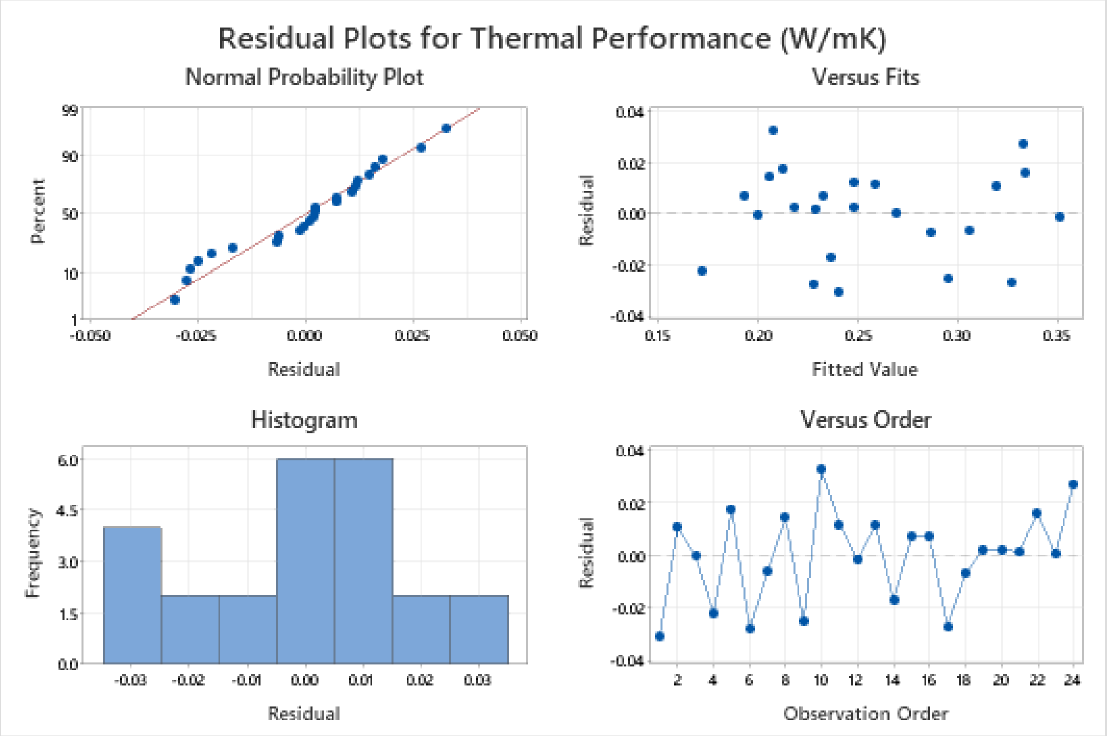

Figure 2: Residual Plots for Thermal Performance Response Variable.

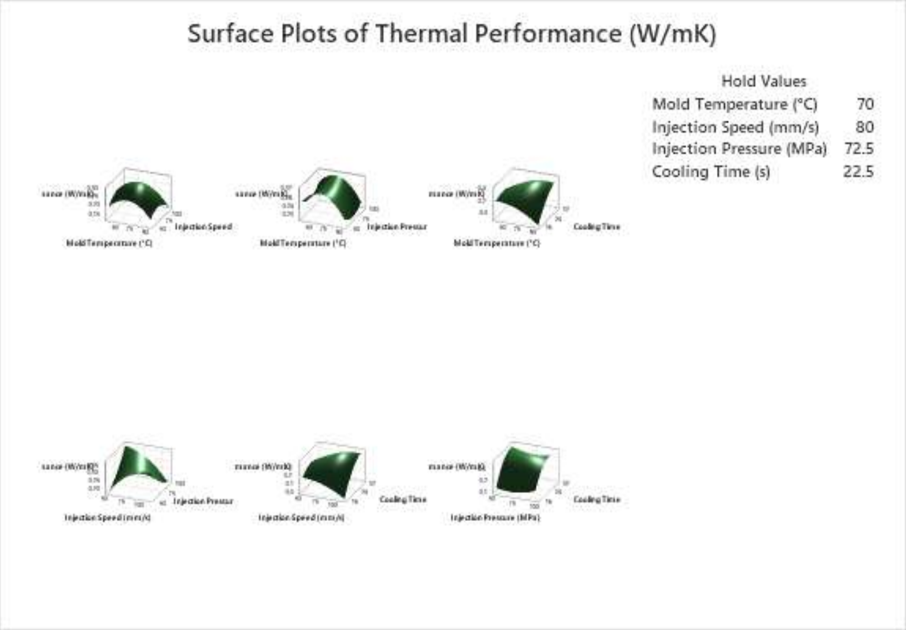

Figure 3: Surface Plots for Thermal Performance Response Variable.

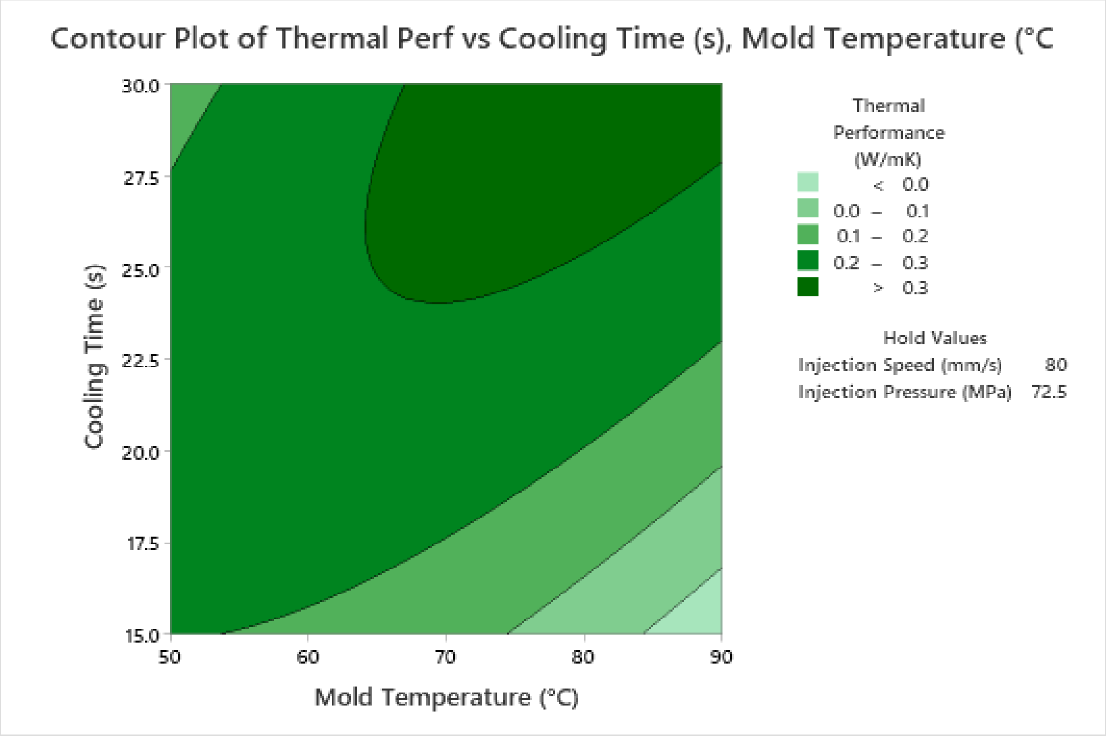

Figure 4: Contour Plot of the Thermal Performance Response Variable: Cooling Time versus Mold Temperature.

Optimization Analysis

The twenty-four (24) experimental trials produced optimal solutions for both the input and response variables. The optimal solutions for the input variables show that the optimal solution for Injection Speed is 50mm/s; Injection Pressure is 95MPa; Mold Temperature is 57.2727°C and Cooling Time is 15s. The optimal solution for the response variable, Thermal Performance is 0.36W/mK. Moreover, the Desirability of achieving the Optimum solution results is 1 (100%).

Table 6: Optimization Solution Table.

Solution	1
Injection Speed (mm/s)	50
Injection Pressure (MPa)	95
Mold Temperature (°C)	57.2727
Cooling Time (s)	15
Tensile Strength (MPa)	31.43
Thermal Performance (W/mK)	0.360
Weight (g)	32.06
Composite Desirability	1

Predictive Analysis

To test the accuracy of the models in actual application, conformity test were conducted by assigning different values for process input variables within their working limits but different from the design matrix. When settings were input for the four mold parameters, guided by the experimental data trends, the regression equations of the response surface methodology predicted the corresponding values of each of the response variables. To test the ability of the response models, an injection speed value of 105mm/s, injection pressure value of 85Mpa, mold temperature value of 75^{0}C, and cooling time value of 28s was used and inputted into the response models. The results of the models predicted optimal solutions for each of the responses to be: Tensile Strength – 45 Mpa; Thermal Performance – 0.36W/mK; and Weight - 45grams, for the resultant plastic cups.

Table 7: Mold Settings Values to be Predicted

Process Input Variables	Settings
Injection Speed (mm/s)	105
Injection Pressure (MPa)	85
Mold Temperature (°C)	75
Cooling Time (s)	28

Table 8: Prediction of the Thermal Performance Response Variable.

Fit	SE Fit	95% CI	95% PI
0.364645	0.158083	(0.0070354, 0.722254)	(0.00153, 0.7278) XX

XX denotes an extremely unusual point relative to predictor levels used to fit the model

DISCUSSION OF RESULTS

This research study centers on the employment of the design of experiment (DOE) of the response surface methodology (RSM) to optimize injection/ production mold settings for a polypropylene (PP) plastic (cup) production. The objective of the optimization process is to determine the most appropriate percentage combination of the thermal performance (process response variable), with the optimum values of each of the mold settings (process input variables), namely: injection speed (mm/s), injection pressure (MPa), mold temperature (°C), and cooling time (s) that will adequately optimize the thermal performance ratio of the finished polypropylene plastic cup product. The overall target of the optimization model was to determine the most appropriate percentage combination of each of the response variables, namely: tensile strength, thermal performance, and weight in the finished polypropylene plastic (cup) product, with the optimum values of each of the process input variables, namely: Injection Speed, Injection Pressure, Mold Temperature, Cooling Time needed to adequately optimize (maximize) the tensile strength and thermal performance response variables of the finished plastic (cup) product, and adequately optimize (minimize) weight response variable content in the finished polypropylene plastic (cup) product.

This study utilizes response surface design of experiments (DOE) with multiple iterative test molding trials while varying the selected process input factors. Experimental trials were conducted while varying the mold settings to access their performance followed by the evaluation of the impact of the varied mold settings (parameters) on the quality and efficiency of the finished polypropylene (PP) plastic cup. In the course of the experimental trials, ranges of the values of the input variables (mold settings) and response variable (thermal performance) were measured and recorded, which make up the experimental data for the analysis. A statistical design of the experiment (DOE) using the central composite design (CCD) was developed. Due to practical limits, only twenty-four (24) experimental trials were conducted. An experimental matrix consisting of twenty-four (24) experimental trials was generated. The process input variables (variations of each of the mold settings) and the response variable values make up the experimental matrix for the analysis. The RSM tool used for the design of the experiment (DOE) is the Minitab Statistical Software (version 20.3.0). Central Composite Design (CCD) was used in this study because of its simplicity and flexibility to variable adjustment and analysis of process interactions relating to process factor combinations.

For the analysis, the software used full quadratic model as suggested by the software to be the best model to fit the data and analysis. The optimal solution of the response surface methodology analysis revealed that the optimal solution of each of the process input variables (mold setting factors) are: injection speed – 50mm/s; injection pressure – 95MPa; mold temperature – 57.2727^{0}C; and cooling time – 15s. Correspondingly, the optimal solution of the response variable, thermal performance was 0.360W/mK. The global desirability (DG) of achieving the optimal solutions was 1 (100%). The model as revealed from the ANOVA table indicates a high significance with a P-value of 0.007. The contribution 89.68%, explains the percentage of the total variation in the model that can be explained, i.e. the Coefficient od Determination (R^2). This very high P-value value signifies that the model is good and fit for the data and for the statistical modeling of the thermal performance response variable. The model indicates from the ANOVA table that the cooling time input factor has the most significant effect on the target response, thermal performance, having high significance with a P- value of 0.036. From the interactive term coefficients, the ANOVA indicates that the interaction between the injection speed and the injection pressure has also a high significant impact on the thermal performance response variable with high significance of P- value of 0.017, and a contribution of 8.71% to the overall interactive source model. Generally, the ANOVA table reveals that the RSM model is good and fit for the data analysis and for the adequate modeling of the thermal performance response variable.

This research study has successfully demonstrated and established that a response surface methodology (RSM) can be used efficiently to optimize injection mold settings/ variables. This research study employed the use mold settings (process input variables) design to determine the optimal solutions of each of the response variables of the polypropylene plastic (cup) product. To test the accuracy of the models in actual application, conformity test were conducted by assigning different values for process input variables within their working limits but different from the design matrix. When settings were input for the four mold parameters (process input variables), guided by the experimental data trends, the regression equations of the response surface methodology predicted the corresponding values of each of the response variables. To test the ability of the response models, an injection speed value of 105mm/s, injection pressure value of 85Mpa, mold temperature value of 75^{0}C, and cooling time value of 28s was used and inputted into the response models. The predictive analysis produced the optimal solutions of the predictive model for each of the responses to be: Tensile Strength – 45 Mpa; Thermal Performance – 0.36W/mK; and Weight - 45grams for the resultant plastic cup. See table 7 and table 8 above.

CONCLUSION

This study conducted experimental trials and data analysis to elicit the optimization models that will demonstrate the optimal values of tensile strength, thermal performance, and weight, which are the polypropylene (PP) plastic (cup) product response variables from injection speed, injection pressure, mold temperature, and cooling time as the input parameters (injection mold settings) in injection molding process using response surface methodology (RSM). The thesis is: "Optimization of Production Settings and their Effects on the Finished Plastic Product Quality." The title of this research study is: "Impact of Injection Mold Settings Optimization on the Thermal Performance of Plastic (Cup) Product using Response Surface Methodology."

This study centers on finding the optimal mold settings for producing high-quality polypropylene plastic cups from injection molding process. Response Surface Methodology (RSM) was used in optimizing different combinations of four vital mold settings: (1) The Injection Speed: How fast the molten polymer (plastic) is injected. (2) The Injection Pressure: The applied pressure/ force on the molten polymer during the injection process. (3) The Mold Temperature: The hotness of the state of the mold itself. (4) The Cooling Time: The duration of the cooling of the molten polymer (plastic) in the mold. Many experimental trials were conducted to explore all possible combinations of these settings. Different qualities of the plastic cups produced were measured, thus: (1) Tensile Strength: How strong the produced cups were. (2) Thermal Performance: How well and long the produced cups retained/ maintained the temperature of the contained liquid. (3) Weight: How much the cup weighed.

The design of the experimental matrix for the process input variables using central composite design (CCD) for the RSM analysis was done for twenty-four (24) experimental trials using the Minitab Statistical Software (version 20.3.0). Both the input and the response variables make up the experimental matrix. Multiple iterative test molding trials while varying the selected process input factors was implemented. The results recorded from the experimental trials conducted with the polypropylene (PP) plastic cup make up the experimental data for the analysis. The RSM analyses suggested only the Quadratic models for each of the three responses. The RSM analysis elicited the optimal solutions for each of the process input variables, which are: injection speed – 50mm/s; injection pressure – 95MPa; mold temperature – 57.2727^{0}C; and cooling time – 15s, and the optimal solutions for each of the process response variables, which are: tensile strength – 31.43MPa; thermal performance – 0.36W/mK; and weight – 32.06g. The global desirability (DG) of achieving the optimal solutions was 1 (100%). The models have a high significance with the P-values of all the three response variables less than 0.05 (i.e. $p < 0.05$), and all the three response variables possessed Variance Inflation Factor (VIF's) that is less than 4 (i.e. $VIF < 4$). This confirms that the models have a high goodness of fit (GOF).The contribution 89.68%, explains the percentage of the total variation in the model that can be explained, i.e. the Coefficient of Determination (R^2). This very high value signifies that the model is good and fit for the data and for the statistical modeling of the thermal performance response variable.

The findings from this study also underscore part of the innovative and novel aspect of this research study, and it hinges on the optimal solutions and the results of the RSM analysis, and the desirability of achieving the optimal solutions as demonstrated by the analytical tool employed in this research study. The findings indicates from the RSM analysis the optimal solutions for each of the process input variables, which are: injection speed – 50mm/s; injection pressure – 95MPa; mold temperature – 57.2727^{0}C; and cooling time – 15s, and the optimal solutions for each of the process response variables, which are: tensile strength – 31.43MPa; thermal performance – 0.36W/mK; and weight – 32.06g. The global desirability (DG) of achieving the optimal solutions was 1 (100%). Another key finding from the research study is that the cooling time input factor has the most significant effect on the target response, thermal performance, with high significance of P- value of 0.036, as seen from the ANOVA table, table 5. In the same vein, the interactive term coefficients indicates that the interaction between the injection speed and the injection pressure has also a significant impact on the thermal performance response variable with high significance of P- value of 0.017, as seen from the ANOVA table, table 5.

Conclusively from this research study, the optimization of the response surface models indicated that simultaneously maximizing tensile strength and thermal performance while minimizing weight could be achieved at an injection speed of 50mm/s, injection pressure of 95MPa, mold temperature of 57°C, and cooling time of 15 seconds. The quality response that could be reached using these optimized mold settings are Tensile strength – 31.43Mpa, Thermal performance – 0.36 W/mK and Weight – 32g. We also created charts and plots showing how changing the settings affect the cup quality. These pictures helped us find the best setting or range of settings to meet various quality criteria. This method could be used to make better quality cups from other plastics too, like polystyrene and polyethylene terephthalate. Overall, this study showed that using science, technology and careful testing we can make much better plastic cups and other plastic products that make comfort maximized in our world.

Recommendation

The innovations from this research study pave the way for producing stronger, lighter, and faster-produced cups, demonstrating the potential of this approach for improving quality and efficiency in the plastic cup industry. This study successfully showed how optimizing injection mold settings can improve plastic cup manufacturing. While this research was an effective demonstration, more work can be built on it. The authors acknowledged the limitations of their study, having primarily focused on a single cup design and single material. They encouraged further research on optimizing diverse cup configurations and plastic types to expand the applicability of their findings. The limitations in the research scope and the areas of the study that needed improvement and further research on include: (i) only polypropylene plastic was tested. Other plastics may have different optimal settings; (ii) only a few mold factors and cup properties were included. Expanding these could give more comprehensive models; (iii) the number of experimental trials was small due to practical limits.

Some interactions may have been missed; (iv) the lab-scale process may not capture all real-world production considerations; (v) other plastics like polystyrene should be tested to find their ideal parameters - include more mold factors and cup properties in the optimization, run larger experimental designs to catch more interactions between variables; (vi) scale up experiments to simulate commercial production conditions. (vii) Further research is needed to explore the optimization of settings for different plastic materials and cup designs. We also need to test these settings in real factories to make sure they're practicable and work. (viii) Investigating the economic feasibility of implementing optimized settings and balancing quality with cost and environmental impact is crucial for widespread adoption. (ix) Developing standardized quality measures and guidelines for plastic cups could benefit both manufacturers and consumers. By addressing these limitations, future research can advance injection mold optimization across more materials and production scales. This will help plastic manufacturers improve quality and efficiency. From the findings of this research study, the authors make the following recommendations for both the manufacturers and the consumers:

(1) Manufacturers should implement the optimal solutions produced from this research study in their real-time production, i.e. for injection speed – 50mm/s; injection pressure – 95MPa; mold temperature – 57^0C; and cooling time – 15s. Adjusting their mold settings to these values to achieve the desired quality attributes of tensile strength, thermal performance and weight.

(2) Manufacturers should implement these optimal settings determined from this research study over longer production runs to assess their impact on reducing variability and increasing process capability over time.

(3) Manufacturers should consider implementing the design of experiments (DOE), response surface methodology (RSM), as used in this research study, or other similar methods to further fine-tune settings for specific materials, cup designs, and other products and quality targets.

(4) Manufacturers should investigate more mold process parameters beyond just injection speed, injection pressure, mold temperature, and cooling time and include them in future optimizations using RSM technique.

(5) Manufacturers should evaluate additional cup quality metrics other than tensile strength, thermal insulation and weight as responses. Properties such as thermal stability, surface finish, dimensional consistency and optical clarity would provide further insights.

(6) Manufacturers should endeavor to validate the process models at full industrial production rates and scales. When the production volume is high, additional dynamics among variables not observable on laboratory scale molding may emerge.

(7) Manufacturers should invest in mold modifications; explore incorporating design attributes like ribs or double walls to boost strength and insulation without significantly increasing weight.

(8) Manufacturers should consistently assess cup quality and production efficiency, introducing modifications to the mold settings as needed to maintain optimal performance.

(9) Hybrid modeling techniques and other alternative analytical techniques like artificial neural network (ANN) could be explored and compared to the response surface methodology (RSM) in terms of accuracy and predictive proficiency.

(10) Consumers should choose brands and products that prioritize quality whether by investing in mold optimization techniques, use of environment-friendly materials or making use of sustainable processes and practices.

(11) Consumers should share their experiences on cup quality and express their preference for products made with optimized settings and sustainable materials. This would also keep the manufacturers informed and to improve their processes.

By implementing these recommendations, manufacturers can produce higher-quality plastic cups that are more durable, efficient, and environmental friendly, while consumers can make informed choices that contribute to a sustainable future.

Contribution to Knowledge

Additional proficiencies of the response surface methodology (RSM) for optimization were discovered in this research study. These are:

(1) RSM can aim not just only on minimizing or maximizing a target response, but can also achieve a desired target range for the response quality. This provides more aptness and control over the optimization.

(2) Constraints can be placed on factors during optimization. For example, a factor can be held at a specific value or within a specified range or limit. So RSM can optimize quality while respecting real-world equipment constraints on the factor settings.

In summary, RSM offers flexible optimization abilities beyond just maximizing or minimizing a response. Quality target ranges and factor constraints can be incorporated to better match real-world process limitations. This demonstrates RSM's versatility for practical process optimization applications.

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