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Die Casting Thermal Diffusion Study Using the Rao and Schumacher Theory

This study investigates the cooling process' efficiency in high-pressure die-casting molds, focusing on key parameters such as the thermal conductivity of the mold material, the cooling channels' diameter, the distance between the channels, and the distance from the mold to the channels. The mold material's thermal conductivity (λst) was the most influential factor, with a cooling time variation between 30%-35%, followed by the distance from the mold to the cooling channels (20%-35%). The cooling channels' diameter showed a moderate influence (7%-20%), while the distance between the channels had the least impact (5%-15%). The analysis suggests that cooling efficiency can be significantly improved by optimizing thermal conductivity and minimizing the distance from the mold to the cooling channels.

Keywords: *Die Casting, Improvement, Molds, Zamak, Thermal diffusion.*

1. INTRODUCTION

Thermal diffusion studies in high-pressure die-casting processes for Zamak alloys play a crucial role in determining the properties and quality of final products. Research has shown that factors such as mold temperature significantly influence the solidification process and the properties of Zamak alloys, with corrosion and mechanical resistance being linked to porosity defects in regions that solidify last. Additionally, investigations into the melting temperatures of Zamak 5 have revealed that higher temperatures result in larger grains and increased microhardness due to lower solidification rates while also highlighting the absence of porosity defects in the samples [1-4].

Modeling studies by Bounds et al. [1] and Pinto et al. [5] have also been conducted to estimate heat transfer coefficients in high-pressure die-casting processes, emphasizing the importance of accurate predictions for casting defects and thermal behavior. These studies provide valuable insights into optimizing the die-casting process by understanding the thermal interactions and their impact on the final product quality. Accurate modeling of heat transfer coefficients is crucial for predicting and mitigating defects such as porosity and for ensuring consistent mechanical properties in cast components.

Among the products resulting from high-pressure die casting, lock terminals used in the manufacturing of Bowden cables are predominantly produced through this process, with the injection of Zamak alloy (Zn-Cu) into molds. This system is crucial as all components are essential for carrying out the mechanical energy conversion process, resulting in two forms of energy: kinetic, related to movement, and potential, related to storage, which connects the system to peripheral components [5].

Although studies focus on optimizing the die-casting process to increase strength, improve process efficiency, and extend mold life, little discussion is given to heat transfer and cooling during the process. However, these are crucial factors that reduce mold life and affect the produced items' physical properties [6,7].

This study continues and concludes a project initiated in 2017 focused on optimizing casting molds for the automotive industry [8-10] by applying CFD (Computer Fluid Design) processes to study and validate the injection of metallic material (Zamak) into the mold. In 2019, another study [5] focused on mold optimization, utilizing the same CFD process used in the initial studies.

For this study, a theory proposed by authors Rao and Schumacher [11] for plastic injection was validated in the context of metal injection. Additionally, an agile calculation method was developed to design molds for the automotive industry. This study's practical application is the feasibility and application of the concept by Natti S. Rao and Gunter Schumacher regarding the transition from plastic injection to metal injection (Zamak 5), which represents the innovation of this work.

2. LITERATURE REVIEW

Studies on Bowden cables have been conducted in previous works [12,13], concluding that new equipment concepts for assembling these components have drastically reduced the labor required for this task, ensuring higher quality and reducing setup and cycle times. These concepts also apply to the production phase of parts by injection molding, where new production and mold handling methods allow for reduced cycle times for incorporating new designs into the assembly line, optimizing production [14].

The casting industry, therefore, exhibits significant activity, with products applied in diverse fields. High-pressure die-casting is a manufacturing process that produces precise, dimensioned metal parts with smooth or textured surfaces [15,16]. The process involves

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Received: September 2024, Accepted: October 2024
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doi: 10.5937/fme2404681P

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injecting molten metal at high pressure and velocity into a reusable steel mold [8]. The automotive sector is one ofthe primary markets for parts produced by this process. Still, many other markets consume a large number of parts made through high-pressure die casting in lightweight alloys due to their excellent mechanical properties, low surface roughness, and shape very close to the desired final form, as well as shorter production times [X5, X6]. Reusable molds, called dies, are used for this process [12].

However, due to the demands of most markets, time and quality are increasingly common requirements. The companies involved can belong to large corporations, such as the capital-intensive giants in the automotive industry, or they may be small businesses with little room for economic maneuver, where the reality is entirely different. In certain cases, they are small manufacturing units where operations are carried out manually in countries with lower labor costs. In this scenario, production relies on intensive human labor rather than technology-intensive processes [17].

On the other hand, competitiveness has demanded an increase in process automation, progressively shifting from a labor-intensive system to a capital-intensive one, especially in developing countries where there is a trend for wages to rise more rapidly and the required level of quality is incompatible with the variability associated with human behavior [18]. Currently, companies must possess the processes, materials, people, and technology necessary to ensure timely production of the quantities, products, and/or services requested by customers. The ultimate result lies in customer loyalty and increased market share [9,10]. In conjunction with Lean tools, work studies enable any industry to achieve increased production, better quality, and reduced costs, ultimately translating into higher profits and greater levels of customer satisfaction [19].

These studies are often conducted with the aid of sophisticated computer programs, which provide a very close insight into the intended objective's reality. However, due to the high cost of these programs, not all companies can afford to use these resources. Therefore, there is a need to develop new tools so that less sophisticated companies with fewer financial resources can remain competitive. It is in this context that the content of this work stands out.

2.1 The High-Pressure Die Casting Process

The high-pressuredie-casting process involves obtaining hollow shapes by pouring liquid metal into a cavity defined by a set of elements made from appropriate metallic materials that compose the mold. Upon solidification, the molded part is obtained [20]. This process is characterized by a hydraulic power source that displaces liquid metal at high speed and pressure, ensuring rapid filling of metallic mold [4]. The main advantage of this process is its high production rate of identical parts at reduced costs, with levels of precision that cannot be achieved by any other method [21]. The mold absorbs the stress injection and dissipates the heat from the metal, facilitating the removal of the molded part and initiating a new cycle. The hydraulic power, which controls the actuator's position, speed, and acceleration, also generates injection pressures ranging from 70 to 3500 bar (7 to 350 MPa) [22].

The physical process of injection results from the flow of liquid metal into a cavity, evacuation of gases from this cavity, interaction between the molten metal and the hydraulic system, and heat loss during injection. This enables work with different types of alloys, including those based on Al, Zn, Mg, Cu, and, to a lesser extent, Pb alloys, brass, and ferrous alloys [23].

2.2 Cooling and the Cooling Cycle

Cooling begins precisely at the moment when the injection of liquid metal into the mold cavity ends and the mold starts cooling. Its main characteristic is temperature control within the mold, which regulates the cooling process [24]. However, other indirect factors influence the process, such as mold and part temperatures, as well as mold opening speed and times, cooling and part extraction times, and production rate [24-26]. Therefore, the cooling cycle involves six main points to be considered, which are:

- Mold temperature control;
- Mold closing speed;
- Cooling period;
- Mold opening speed;
- Delay in ejector advance;
- Mold opening time.

3. METHODOLOGY

3.1 Definition

The studies mentioned in previous articles aimed to enhance produced parts by reducing gas porosities and shrinkage. While they succeeded in the former aspect, optimizing the latter still requires new measures. In this regard, an innovative approach to thermal study was adopted, inspired by the concept used by Rao and Schumacher [11] for plastic injection and applied to the injection of liquid metal.

The study of cooling and thermal diffusion focuses on analyzing the region that encompasses the mold and its structure. It aims to investigate how the cooling time after injecting metal into the mold cavity influences the type and quantity of defects a part may exhibit. The likelihood of shrinkage development increases with the duration that the molding is kept at temperatures above the solidification temperature.

Therefore, the research aims to apply cooling formulas developed by Rao and Schumacher [11] in the cooling of metallic alloys. It is crucial to assess how modifying certain cooling parameters, such as the distance required for thermal conduction flow, can prevent the formation of typical defects in this process. This study seeks to foster the development of new methods and solutions to enhance future molds.

3.2 Calculation for analysis

Rao and Schumacher [11] argue that the heat supplied to the mold by the molten metallic material (Zamak) is governed by Equation 1:

$$Qw = 10^{-3} * tk * \left(\frac{1}{\lambda st} + \frac{1}{\alpha * 10^{-3} * 2 * \pi * R} \right)^{-1} * \tag{1}$$
$$* \left(Tw - T\left(H_2O \right) \right)$$

where:
Qw: Heat transferred from the molten metal to the cooling medium [kJ/m];
tk: Cooling time [s];
λst: Thermal conductivity of mold material [W/(m.K)];
Se: Form Factor [adm];
α: Heat transfer coefficient of coolant [adm];
R: Radius of cooling channels [mm];
Tw: Exit temperature of coolant (water) [ºC];
T(H_2O): Inlet temperature of coolant (water) [ºC].

The *Se* form factor helps understand how heat distributes and dissipates within the mold, influencing the cooling efficiency and the time required for solidification of the injected metal, as presented in Equation 2:

$$Se = \frac{2 * \pi}{\ln \left[\frac{2 * x * \sinh\left(\frac{2 * x * y}{x} \right)}{\pi * d} \right]} \tag{2}$$

where:
Se:Form Factor [adm];
x:Distance between cooling channels [mm];
y:Distance from the cavity contact surface to the axis of cooling channels [mm];
d:Diameter of cooling channels [mm];
sinh: Hyperbolic sine function.

The heat transfer coefficient "α" in Equation 1 is obtained through Equation 3, and the Reynolds number of coolant (water) through Equation 4:

$$\alpha = \frac{0.031395}{d} * \mathrm{Re}^{0.8} \tag{3}$$

$$\mathrm{Re} = 10^{-3} * u * \frac{d}{v} \tag{4}$$

where:
u: Coolant velocity [m/s];
d: Diameter of cooling channels [mm];
v: Kinematic viscosity of coolant [m²/s].

The heat removed from the mold is influenced by the cooling liquid used (in most cases, and in the present study, water), as shown in Equation 5:

$$Qab = 10^{-3} * \left[\left(Tm - Te \right) * Cps + im \right] * \rho m * \frac{S}{2} * x \tag{5}$$

where:
Qab: Heat extracted from the mold by the cooling fluid [kJ/m];
Tm: The metal temperature at the time of injection [ºC];
Te: Mold release temperature [ºC];
Cps: Specific heat capacity of casting metal [kJ/(kg·K)];
im: Latent heat of fusion of casting metal [kJ/kg];
ρm: Foundry metal density [g/cm³];
S: Thickness of cavity of the part to be molded[mm];
x: Distance between cooling channels [mm].

The required cooling time is obtained by applying Equation 6:

$$tk = \frac{s^2}{\pi^2 * a} * \ln \left[\frac{4}{\pi} * \left(\frac{Tw - Ta}{Tw - Tb} \right) \right] \tag{6}$$

where:
tk: Cooling time[s];
Tw: Constant temperature from plate to surface [ºC];
Ta: Initial temperature[ºC];
Tb: Average plate temperature at time tk[ºC];
a: Thermal diffusibility[cm²/s];
s: Plate thickness[mm].

3.3 Analysis method description

The theory by Rao and Schumacher [11] is based on the equations presented in Section 2 and the principle that the thermal equilibrium of heat input into the mold by the molten metal must be equal to the heat removed from the cavity by the coolant (Figure 1), expressed by the equality in Equation 7.

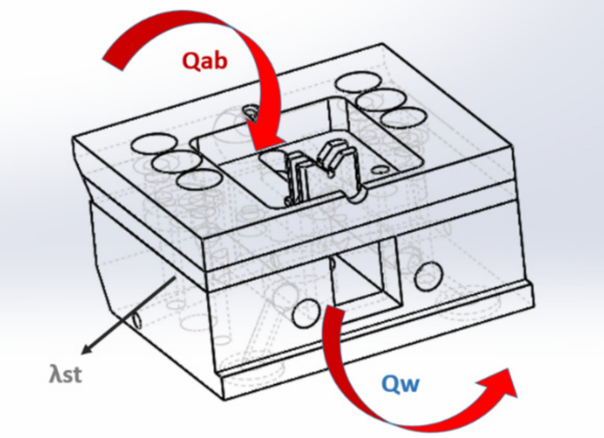

Figure 1. Heat transfer in a mold structure.

$$Qin = Qout \Leftrightarrow Qab = Qw \tag{7}$$

The principle of development, therefore, aims to obtain the required cooling time "tk" to remove the heat introduced by the molten metal "Qab" to the desired ejection temperature "Tw". This varies with dimensions d, x, and y (Figure 2) and the thermal conductivity of mold metallic material "λst". Since dimensions directly impact the shape factor "Se" and thermal conductivity directly affects the extracted heat "Qw". The cooling time is determined by equating Equation 7 and solving Equations 1 and 5 for "tk", assigning the shape factor "Se" to a plate. These operations were also conducted for two different values of λst, 29 W/(m•K) for AISI H-13 steel and 45 W/(m•K) for steel with higher conductivity.

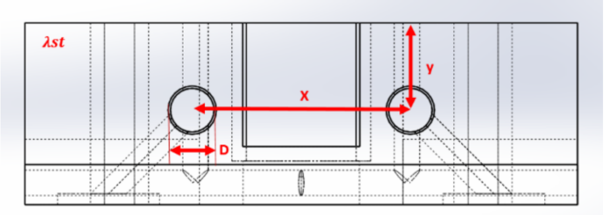

Figure 2. Mold structure variables description.

The parameters used and their respective values for the calculations are presented in Tables 1 and 2.

Table 1. Values applied in the equation Qab.

Symbol	Value	Units
Tm	430	□C
Te	120	□C
Cps	0.39	kJ/(kg·K)
im	130	kJ/kg
ρm	6.6	g/cm^3
S	5	mm
x	25	mm

Table 2. Values applied in the equation Qw

Symbol	Description	Units
λst	Variable	W/(m·K)
Se	Variable	adm
α	23324.214	$(W/(m^2 \cdot k))$
R	2.5	mm
Tw	95	□C
$T(H_2O)$	17	□C

4. RESULTS AND DISCUSSIONS

The mold cooling time values "tk" were obtained from the parameters used in Tables 1 and 2, and these results are presented in Tables 3, 4, 5, 6, and 7. There are variations due to changes in mold metallic material and consequently in thermal conductivity (λst), cooling cha–nnel diameter (d), distance between cooling channels (x), and distance from the cavity contact surface to the centerline of cooling channels (y).

Table 3. Test results for: λst: 29 W/(m·K); d: 5 mm; y: 10 mm

λst W/(m.K)	d (mm)	x (mm)	y (mm)	tk (s)
29	5	10	10	46.08
29	5	15	10	33.78
29	5	20	10	28.24
29	5	25	10	25.25
29	5	30	10	23.47
29	5	35	10	22.32

Table 4. Test results for: λst: 29 W/(m·K); d: 10 mm; y: 10 mm

λst W/(m.K)	d (mm)	x (mm)	y (mm)	tk (s)
29	10	10	10	41.04
29	10	15	10	28.73
29	10	20	10	23.19
29	10	25	10	20.21
29	10	30	10	18.42
29	10	35	10	17.27

Table 5. Test results for: λst: 29 W/(m·K); d: 5 mm; y: 25 mm

λst W/(m.K)	d (mm)	x (mm)	y (mm)	tk (s)
29	5	10	25	75.21
29	5	15	25	52.54
29	5	20	25	41.61
29	5	25	25	35.28
29	5	30	25	31.23
29	5	35	25	28.44

Comparative graphs were created (Figures 3, 4, 5, and 6) to facilitate understanding of the results. Based on these properties and characteristics, the objective was to assess the behavior of cooling time "tk" required to remove introduced heat into the molds.

Table 6. Test results for: λst: 29 W/(m·K); d: 5 mm; y: 30 mm

λst W/(m.K)	d (mm)	x (mm)	y (mm)	tk (s)
29	5	10	30	137.6
29	5	15	30	94.79
29	5	20	30	74.01
29	5	25	30	61.91
29	5	30	30	54.08
29	5	35	30	48.67

Table 7. Test results for: λst: 45 W/(m·K); d: 10 mm; y: 10 mm

λst W/(m.K)	d (mm)	x (mm)	y (mm)	tk (s)
45	10	10	10	27,73
45	10	15	10	19,80
45	10	20	10	16,23
45	10	25	10	14,31
45	10	30	10	13,16
45	10	35	10	12,42

It should be noted that this study includes only two values of thermal conductivity, "λst," as these are the two existing steels used for mold execution. Similarly, the values of "d" are limited because it is not feasible to create channels in structures with diameters greater than 10 mm. The red arrows indicate the variation in the plotted graphs.

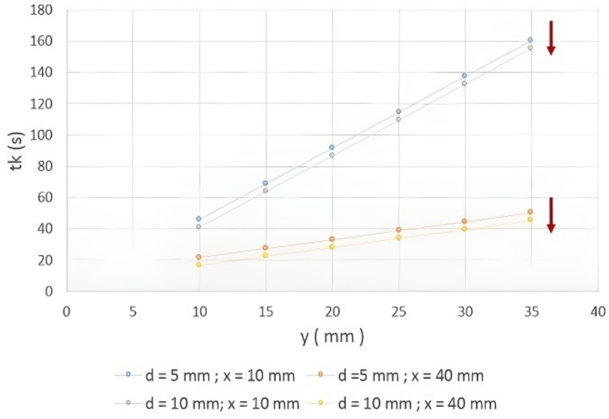

Figure 3. Comparison Graph of Cooling Time for λst: 29 W/(m·K) and Variable y.

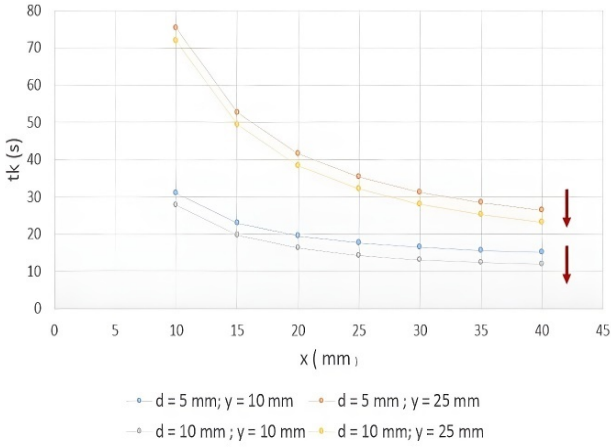

Figure 4. Comparison Graph of Cooling Time for λst: 29 W/(m·K) and Variable x.

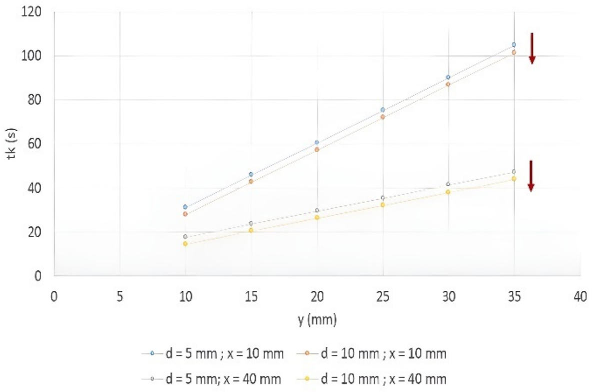

Figure 5. Comparison Graph of Cooling Time for λst: 45 W/(m·K) and Variable y.

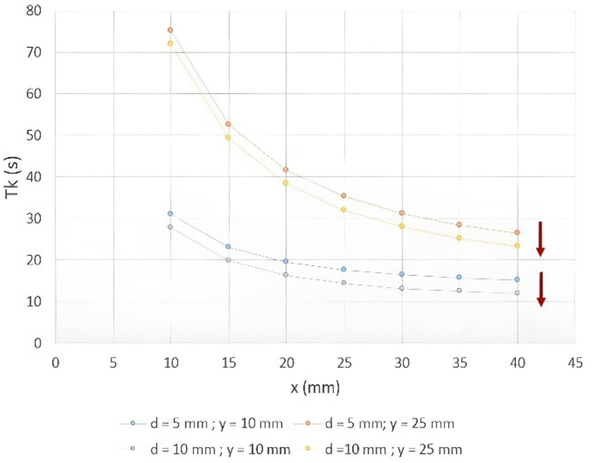

Figure 6. Comparison Graph of Cooling Time for λst: 45 W/(m·K) and Variable x.

From the analysis of tables and graphs obtained, it is observed that the reduction in cooling time of a casting varies based on the following characteristics:

I) Increase in the diameter of cooling channels;
II) Decrease in the distance from the cooling channels to the mold cavity;
III) Increase in the distance between the cooling channels;
IV) Increase in the thermal conductivity of mold material.

The analysis indicates that the spacing between the cooling channels exhibits an exponential decrease in its effect on reducing cooling time as the distance increases. On the other hand, the proximity of cooling channels to the mold surface shows a linear relationship, with shorter distances resulting in more efficient cooling.

Studies emphasizing the importance of optimal cooling channel design to enhance thermal management and reduce cycle times in die-casting processes corroborate these findings [27, 28].

It is also noted that the thermal conductivity of mold, determined by the type of alloy used, significantly influences the cooling time ofthe system, as observed in other studies. Research has shown that increasing the thermal conductivity of mold alloy can accelerate the cooling rate significantly, thereby reducing the total cycle time. Hamasaiid *et al.* [29], through an analytical model to predict thermal conductance at the casting/ mold interface, found that mold thermal conductivity affects the heat transfer rate at the casting interface, directly impacting molten metal's solidification and cooling time.

Other studies also support this study's observation, emphasizing the importance of mold alloy thermal conductivity in the thermal performance of the die-casting process [30-32].

Table 8 shows the variation of parameter values in this study and their respective significances in heat transfer.

Table 8. Value variation and its importance in thermal cooling

Property	Cooling time variation (%)	Importance
Thermal conductivity (λst)	30-35	High
Diameter (d)	7-20	Average
Distance between cooling channels (x)	5-15	Low
Distance from molding to cooling channels (y)	20-35	High

Although the channels' diameter (d) influences thermal cooling, increasing the diameter has practical limitations, such as mold design constraints and fluid flow efficiency, as noted in the literature [33].

Although the distance between cooling channels shows an exponential trend in cooling time, its influence diminishes at a certain point due to saturation. Beyond this point, increasing the distance between the channels does not result in significant improvements in cooling time, as noted in studies by Kan *et al.* [34]. Optimizing the arrangement of cooling channels can enhance process efficiency but within certain limits.

Another crucial factor is the distance between the mold and the cooling channels. The smaller this distance, the more efficient the heat transfer, resulting in shorter cooling times. This variable exhibits a linear trend, indicating that reducing it has a direct and proportional impact on reducing cooling time [32,34,35].

5. CONCLUSION

Based on the analysis of the tables and graphs obtained, it is concluded that the reduction in cooling time during molding varies according to four main characteristics: increased diameter of the cooling channels, decreased distance from the cooling channels to the mold cavity, increased distance between the cooling channels, and increased thermal conductivity of the mold metallic material. The concept developed by Natti S. Rao and Gunter Schumacher was essential for the theory and application of equation 1, which justifies the heat supplied to the mold by the molten material. In this study, the Zamak alloy (Zn-Al-Cu) was used, and the results indicate that the distance between the cooling channels shows an exponential trend, with a decreasing impact on cooling time reduction as this distance increases.

On the other hand, the distance from the cooling channels to the mold surface shows a linear trend, resulting in shorter cooling times as the distance decreases. The thermal conductivity of the mold metallic material also stands out as a crucial factor in reducing cooling time, as demonstrated by comparing graphs with different values of this property. In future studies, it would be interesting to explore the application of other materials to validate a universal model and broaden the scope of the conclusions obtained.

ACKNOWLEDGMENT

Foundation Coordination for the Improvement of Higher Education Personnel (CAPES), number 88881.933644/2024-01.

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СТУДИЈА ТЕРМИЧКЕ ДИФУЗИЈЕ ЛИВЕЊА ПОД ПРИТИСКОМ КОРИСТЕЋИ РАООВУ И ШУМАХЕРОВУ ТЕОРИЈУ

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Ова студија истражује ефикасност процеса хлађења у калупима за ливење под високим притиском, фокусирајући се на кључне параметре као што су топлотна проводљивост материјала калупа, пречник канала за хлађење, растојање између канала и растојање од калупа до калупа. канали. Топлотна проводљивост материјала калупа (λст) била је најутицајнији фактор, са варијацијом времена хлађења између 30%-35%, праћено растојањем од калупа до канала за хлађење (20%-35%). Пречник канала за хлађење је показао умерен утицај (7%-20%), док је растојање између канала имало најмањи утицај (5%-15%). Анализа сугерише да се ефикасност хлађења може значајно побољшати оптимизацијом топлотне проводљивости и мин имизирањем удаљености од калупа до канала за хлађење.