Sensitivity analysis of conformal CCs for injection molds: 2D Transient Heat Transfer Analysis

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Research Article

Keywords: Sensitivity analysis, Conformal Cooling Channels, Injection Molding; Computer Aided Engineering

Posted Date: October 18th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-958556/v1>

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Abstract

Conformal Cooling Channels (CCCs) have gotten easier and more economical to manufacture in recent years. This was largely due to recent developments in additive manufacturing. The usage of CCCs in engineering applications involving injection molding provides for superior cooling performance than straight drilled channels, which have traditionally been utilized in injection molding. The fundamental reason for this is that CCCs are able to follow the molded geometry's trajectories. With the use of CCC's, the cooling time, total injection time, thermal stresses, and warpage can all be considerably reduced. Nonetheless, the CCC design process is more difficult than that of traditional channels. The integration of computer-aided engineering (CAE) simulations is critical for achieving an effective, cost-effective design. This paper focuses the sensitivity analysis of design variables, with the intention of implementing a design optimization methodology in the future. The ultimate goal is to optimize the placement of Cooling Channels (CCs) to minimize the ejection time and maximize the uniformity of temperature distribution. It can be concluded that the parametrization done in ANSYS Parametric Design Language (APDL), as well as the selected design variables are feasible and might be useful for future optimization methodologies.

1. Introduction

Some research has been conducted in the field of design and simulation of CCCs in injection molds. Several simulation packages have been utilized for analyzing mold and channel designs. In 2005, Moldflow analysis was utilized in I-DEAS™ by Dimla et al. for finding the best position of the channel (Dimla D et al. 2005). Using ANSYS modules for thermal analysis, ABM Saifullah and SH Masood investigated the "cooling time of the part" (Saifullah A, Masood S, 2007). The same set of researchers used MPI simulation modules for component analysis in 2009 and compared the findings for conventional and quadratic CCC profiles, concluding that conformal channels have a 38 percent faster cooling time than conventional channels (Saifullah A et al. 2009). Gloinn et al. from Ireland used a finite element model (FEM) to determine the mold temperature using ABS polymer as the molten material and a cooling water inflow (Ó Gloinn T et al. 2007). Moldflow Plastic Insight 3.1 was utilized in another study conducted in 2007 to investigate the thermal effects of CC design on the injection molding process (Au K, Yu K 2007). The authors offered a new framework for designing a uniform CC. Wang et al. used the same simulation modules to examine the advantages of a cooling cycle; the authors simply simulated the molding temperature (Wang Y et al. 2011). Using the AMI modules, Khan et al. investigated the effects of conventional, serial, parallel, and additive-parallel CCs on cooling time, total cycle time, volumetric shrinkage, and temperature variance in 2017 (Khan M et al. 2014). Researchers have developed a variety of methodologies and algorithms for the design of Conformal CCs (CCC'S) with the goal of achieving an intelligent and optimal design of CC systems (Jauregui-Becker et al. 2009; Chung C - Y 2019; Clemente M R, Oliveira Panão M R 2018). Various CC patterns have been proposed for this purpose, including spiral (Zhang Y et al. 2018), zigzag (Tuteski O, Kocov A 2018), profiled (Altaf K, Rani A M A 2015), and vascularized (Berger G R et al. 2019). The diameter of the duct, the distance between ducts, and the distance between the wall and the duct were all taken into account. Several optimization approaches

have been applied in the optimization-based studies. A few examples of optimization strategies are Simulated Annealing (SA) (Lin JC 2002), Powell's conjugate direction (Park H-S, Dang X-P 2010), evolutionary algorithms (Lam YC et al. 2004 Li XP et al. 2009), Response Surface Methodology (Lam YC et al. 2004) and CONMIN (Park SJ, Kwon TH 1998) (constrained minimization approach developed in (Haarhoff PC, Buys JD 1970). In the transient thermal analysis, the boundary element method was preferred, for improving the conventional cooling performance (Park SJ, Kwon TH 1998; Qiao H 2005; Qiao H 2006; Zhou H et al. 2009). Several optimization algorithms have been developed for improving the design of conformal CCs (Lin JC 2002; Feng S et al. 2021; Shen C et al. 2007; Wang et al 2011). Although there are many studies on the analysis of CCC, the number of studies focusing on the design parameters of CCCs for different types of designs is very limited. Most of the designs have been applied based on the experience of the designers. To the author's knowledge, mixtures of any kind and the agreement between the design parameters, section size and the corresponding experimental analyzes are rare. Nevertheless, A few preliminary information has been obtained from the literature that provides a basis for further investigation in this project. For example, a simple relationship between four parameters for the design of CCC using additive manufacturing can be found in Mayer (Mayer S 2005). From previous literature, the use of cross-sections other than circular for channels could provide better cooling efficiency. In (Au K, Yu K, 2014), research has been performed for analyzing CCs with variable spacing for tooling applications. In order to redesign the existing model, which was originally built with straight channels, with CCCs, the authors performed a study in which a comprehensive solution for conformal channel design was derived. Parameters such as duct diameter, pitch spacing, and wall-to-duct spacing were considered. In this work, ANSYS Mechanical APDL software was used for parameterization of cooling ducts and calculation of temperatures for 2D heat transfer problem by natural convection. The present work goals for evaluating the feasibility of the selected design variables for application in optimization routines by coupling MATALB and ANSYS Mechanical APDL.

2. Procedure

The optimization was done using ANSYS Mechanical APDL, in which a 2D transient thermal analysis was performed. The geometry that was object of study can be seen in section 3.1. The material properties used can be seen in section 3.2. and the conditions applied in ANSYS can be seen in section 3.2.

2.1 Geometry

The geometry of the analyzed 2D model is presented in Figure 1

To perform the optimization, 16 variables/geometric parameters were defined in ANSYS Mechanical APDL. Eight of these variables are horizontal and eight are vertical, as shown in Table 1.

Table 1
Information regarding variables and components

Component	Designation	Component ID	Direction, as in Fig. 1.
CCs	VAR1	1	Horizontal
	VAR2	2	
	VAR3	3	
	VAR4	4	
	VAR5	5	
	VAR6	6	
	VAR7	7	
	VAR8	8	
	VAR9	1	Vertical
	VAR10	2	
	VAR11	3	
	VAR12	4	
	VAR13	5	
	VAR14	6	
	VAR15	7	
	VAR16	8	
Part	-	9	-
Mold	-	10	-

Table 2 shows the lower and upper bounds of the design variables set by ANSYS considering the defined initial variables.

Table 2
Limits of geometric variables Variable

designation	Lower Bound [mm]	Initial Value [mm]	Upper Bound [mm]
VAR1	0	10	20
VAR2	0	10	20
VAR3	0	10	20
VAR4	0	10	20
VAR5	0	10	10
VAR6	0	10	20
VAR7	0	10	20
VAR8	0	10	20
VAR9	0	5	25
VAR10	0	5	20
VAR11	0	5	20
VAR12	0	5	20
VAR13	0	5	6
VAR14	0	5	12
VAR15	0	5	12
VAR16	0	5	12
Only lower and upper bounds were assigned in MATLAB, with no equality nor inequality constraints.			

2.2 Materials and conditions

The materials used in the simulations were water, for the CCs, polypropylene for the injection molded part and steel P20 for the mold cavity.

Table 3
– Properties of Water, PP and P20 steel, used in the simulations

Material	Water in liquid state	Polypropylene, with 10% mineral	P20 steel
Application	Cooling channels (inside)	Injected part	Mold
Density [(kg/m ³)]	998.2	1050	7861
Specific heat [J / (kg.°C)]	4182	1800, Considered constant	502,48
Thermal conductivity [W/ (m.K)]	0.6	0.2 Considered constant	41,5

Of the materials shown in Table 3, only water is assumed to behave as fluid, i.e. PP and steel are assumed to behave as solids. The properties of the used materials are shown in Table 3. The boundary conditions implemented in ANSYS Mechanical APDL can be seen in Table 4.

Table 4
– Thermal conditions applied (Silva et al., submitted)

Condition	Component ID (Fig. 1)	Value [°C]	Application
Initial Temperature, varies with time	9	210	Part, 1 area
	1-8	40	Cooling channels, 8 areas
Temperature, constant	10	40	Mold, 1 area
	10	23	Boundary, 4 lines
With respect to the cooling channels, the water inside them is assumed to have a constant temperature of 40 [°C].			

4. Results

Due to different scales, value IDs were used in the horizontal axis. Table 5 presents the correspondence between Value ID and values for each variable.

Table 5
Value of each point, in millimeters, for all the 16 variables.

Var ID	1	2	3	4	5
Var1	5	7,5	10	12,5	15
Var2	5	7,5	10	12,5	15
Var3	5	7,5	10	12,5	15
Var4	5	7,5	10	12,5	15
Var5	2,5	3,75	5	6,25	7,5
Var6	5	7,5	10	12,5	15
Var7	5	7,5	10	12,5	15
Var8	5	7,5	10	12,5	15
Var9	7,5	10	12,5	15	17,5
Var10	5	7,5	10	12,5	15
Var11	7,5	8,75	10	11,25	12,5
Var12	5	7,5	10	12,5	15
Var13	1	2	3	4	5
Var14	2	4	6	8	10
Var15	2	4	6	8	10
Var16	2	4	6	8	10

Figures 1-3 show the Maximum, Average, Minimum temperatures in the injection molded part, respectively. Fig. 4 shows the temperature amplitude.

In Fig. 2 It can be see that the values of the temperature are close for every value ID, for all variables, with exception of Var10 for Value ID of 5. The maximum temperature ranges from slightly lower than 45.68 to close to 45.71 [°C].

From Fig. 3, it can be seen that the values of the average temperature range from close to 42.5 [°C] for Var10 and for a value ID of 1, to close to 43.2 [°C] for Var10 and Var3, for value ID of 2 and 4, respectively. There is a significantly larger amplitude of temperature compared to the results of the maximum temperature (Fig. 2)

From Fig. 4, it can be seen that the values of the minimum temperature range from close to 23.05 [°C] for Var13 and for a value ID of 4, to close to 23.8 [°C] for Var3, for value ID of 4. There is a similar amplitude

of temperature compared to the results of the average temperature (Fig. 3), with the value of the maximum value subtracted by the minimum value close to 0.7 [°C].

In Fig. 5, the values of the Tmax-Tmin (maximum temperature minus minimum temperature) ranging from close to 21.9 [°C] for Var3 and for a value ID of 4, to close to 22.65 [°C] for Var13, for value ID of 4.

For the results shown in Fig. 6 and 7, the Var ID 3, of Table 6, was considered as the reference point. Then, the Tmax (Fig. 6) and Tavg (Fig. 7) results for the other Var IDs were compared with the reference model, using Eq. 1.1 and 1.2.

$$vaTM[\%] = Maximum \left(\frac{T_{M_x} - T_{M_{ref}}}{T_{M_{ref}}} * 100 \right) \quad (1.1)$$

$$vaTA[\%] = Maximum \left(\frac{T_{A_x} - T_{A_{ref}}}{T_{A_{ref}}} * 100 \right) \quad (1.2)$$

For x=1,2,4 and 5.

In Fig. 6, It can be seen that the sensitivity of the maximum temperature for all variables is very low, except for VAR13. For VAR13, there is a variation of 0.269%, for the maximum temperature. For the other variables, values range from $2.19 \cdot 10^{-3} \%$ to $1.75 \cdot 10^{-2} \%$.

In Fig. 7, It can be seen that the sensitivity of the maximum temperature for all variables is also very low. The maximum value is close to $1.45 \cdot 10^{-1} \%$, for VAR10 and the minimum is $3.51 \cdot 10^{-2}$. In Fig. 7, the values of the average temperature show lesser differences for the different variables than for the maximum temperature, shown in Fig. 6.

5. Conclusions

The main conclusions of this work are:

- The chosen design variables are relevant for the case studied, since the values of the temperatures vary when changing the values of the variables.
- This case, studied in 2D, enabled the elimination of geometric constraints, in comparison with a 3D case, which enabled the implementation of more geometric variables.
- The parameterization performed to the ANSYS input file is proven to be effective for the determination of the influence of the design variables on the temperatures of the studied case.

Declarations

Acknowledgments

This research was supported by the Research Grant number POCI-01-0247-FEDER-024516, co-funded by the European Regional Development Fund, by the Operational Programme "Competitiveness and Internationalization", in the scope of "Portugal 2020"

a. Funding

This research was supported by the Research Grant number POCI-01-0247-FEDER-024516, co-funded by the European Regional Development Fund, by the Operational Programme "Competitiveness and Internationalization", in the scope of "Portugal 2020"

b. Conflicts of interest/Competing interests

There are no declared Conflicts of interest/Competing interests

c. Availability of data and material (data transparency)

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

d. Code availability

Not applicable

e. Ethics approval

Not applicable

f. Consent to participate

Not applicable

g. Consent for publication

Not applicable

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Figures

Figure 1

Set drawing for 2D analysis (Silva et al., submitted)

Figure 2

Maximum temperature for 5 points and for all the variables.

Figure 3

Average temperature for 5 points and for all the variables.

Figure 4

Minimum temperature, for 5 values of Value ID and for all the variables.

Figure 5

Temperature amplitude, for 5 values of Value ID and for all the 16 variables.

Figure 6

Maximum value for Tmax, for all the variables, according to the methodology described.

Figure 7

Maximum value for Tavg, for all the variables, according to the methodology described.