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Abstract. Because of recent advancements in additive manufacturing, fabricating conformal cooling channels (CCCs) has become easier and more economical. In the injection molding process, CCCs provide higher cooling performance than standard (straight drilled) channels. The major reason for this is that CCCs may follow the courses of the molded geometry, whereas typical channels created using traditional machining processes cannot. Using CCCs can reduce thermal strains and warpage while also improving cycle time and achieving a more uniform temperature distribution. CCC, on the other hand, has a more complicated design procedure than traditional channels. Simulations using computer-aided engineering (CAE) are critical for achieving an effective and cost-effective design. This article compares two ANSYS modules for the purpose of validating results. It can be inferred that the two modules produce similar results for models with fine mesh. As a result, the ANSYS module to work on should be chosen depending on the job's goal as well as the CAD geometry's complexity.

Keywords: conformal cooling; injection molding; computer aided engineering; Design Optimization

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1. Introduction

CCCs in injection molds have received a lot of attention in terms of design and modeling. A variety of simulation software was used to examine mold and channel designs. In 2005, Dimla et al. [1] used Moldflow analysis in I-DEASTM to find the best channel position. ABM Saifullah and SH Masood investigated the "part cooling time" using ANSYS thermal analysis modules [2]. In 2009, the same group of researchers used MPI simulation modules to evaluate parts and compare the results for conventional and quadratic CCC profiles, determining that conformal channels cool 38 percent faster than conventional channels [3]. To establish the mold temperature, Gloinn et al. from Ireland performed a FEM analysis with ABS polymer as the molten material and a cooling water inlet [4]. In the work [5], the authors investigated the thermal impacts of cooling channel design on the injection molding process using Moldflow Plastic Insight 3.1 in a 2007 study. The authors presented a ground-breaking approach for CC design consistency. The benefits of a cooling loop were verified by Wang et al. using the same simulation modules [6]. They just modeled the temperature of the component. In 2017, Khan et al. [7] examined the cooling times, total cycle times, volumetric shrinkage, and temperature variance of conventional, serial, parallel, and additive-parallel cooling channels. Despite the fact that there are many studies on CCC analysis, there are few studies on CCC design parameters for various types of designs. The designers used their past experience to implement the majority of the designs. According to the author's knowledge. Mixtures of any kind are extremely rare, as is consistency across design parameters, cross-section size, and experimental findings. Nonetheless, preliminary data from the literature was obtained, which will serve as a foundation for future research on this topic. Mayer [8] illustrates a basic relationship between four elements in the creation of CCCs using additive manufacturing. According to previous study, channel cross-sections other than circular could improve cooling efficiency. Cooling channels with variable spacing have been researched in extensively for tooling applications [9]. The authors conducted research in which they developed a complete method for conformal channel design in order to reconstruct an existing model that was originally built using straight channels using CCCs. Factors including duct diameter, pitch spacing, and wall to duct separation were considered by the writers.

This work compares the findings of a 3D transient thermal research performed with two ANSYS packages: ANSYS Steady state/Transient Thermal in Workbench and ANSYS Mechanical APDL. The two modules packages are used for a variety of purposes: Workbench is more user-friendly and CAD-friendly. Mechanical APDL is fully integrated with ANSYS Parametric Design Language, ensuring that models developed there are fully parametrizable and compatible with any optimization approaches. The purpose of this study is to determine the appropriate meshing parameters for the best results. Both modules' outcomes are cross-validated at the same time. A similar work was already done in [10]

2. Background

Injection molding is a popular advanced manufacturing technique for producing produced parts that is both cost-effective and dependable. The injection molding process consists of several steps [11]. The four steps are injection, packaging, cooling, and ejection: (1) injection, (2) packaging, (3) cooling, and (4) ejection. Injection molding is important in the plastics sector, accounting for a large percentage of total plastic usage [12]. Plastic injection molding is a versatile method for producing a wide range of complex sizes and shapes of high-quality items from thermoplastic and thermoset materials [13]. For generating a high-quality plastic product, the injection mold design, particularly the design of the mold core and cavity, is crucial. It also has a big impact on the company's financial elements. Cooling channels must be employed to ensure temperature control and cooling of the molded component. Traditionally, cooling channels were bored straight using subtractive manufacturing techniques. CCCs might be made fast and cheaply using traditional processes. The shape of CCCs, on the other hand, has significant constraints that can slow down the injection molding process. Due to the geometry of the cavity, the necessity to avoid interference between the cavity and the channel, and the drilling procedure, straight drilled channels are impossible to produce perfect cooling. In this situation, only straight holes can be bored. Figure 1 shows a comparison of a straight cooling channel and a conformal cooling channel (left). CCC inserts are depicted in Fig. 1 right.

Fig. 3. Comparison of straight-drilled cooling channels and CC channels: straight-drilled cooling channels (a) and Conformal cooling channels (b), Adapted from [14], in [15])

When it comes to fabricating CCC shapes, traditional machining processes are frequently insufficient. As a result, they are made using additive manufacturing technologies [16-18] in [15]. As a result of recent developments in 3D printing technology, the CCC manufacturing approach has become more affordable and commercial. Injection molding is a method of heat transmission that is only

temporary. It's safe to assume, though, that after a few injection molding cycles, it'll settle down (if the average mold temperature is considered constant). Heat transfer equilibrium is reached when the heat transfer rate (heat flux) from the molten polymer to the mold material matches the heat transfer rate (heat flux) from the mold material to the coolant and ambient air. Figure 2 depicts the heat movement in a simple manner.

Fig. 2 - Simplified representation of the heat flows [19].

The balance equation is defined in Eq. 1 [20] in [19]

$$\dot{Q}_m + \dot{Q}_c + \dot{Q}_e = 0 \quad (1)$$

Conduction, convection, and radiation are the three basic heat transfer methods used in injection molding. The heat transmission rate (heat flux) from the molten polymer to the mold material, as well as the heat flux inside the mold material, is determined by the conductive heat transfer mechanism. The heat flow from the mold material to the coolant is calculated using convective heat transfer. When the temperature of the mold material rises during the injection molding process, the surface temperature of the mold material rises above that of the ambient air. As a result, heat is transferred from the molding material to the surrounding air via both radiation and convection. Equations 2-4 [21,22] define the conductive, convective, and radiative heat transfer rates analytically.

$$\dot{Q}_{cond} = \int_0^{t_{cycle}} \frac{\lambda}{\delta} \cdot A \cdot \Delta T \cdot dt \quad (2)$$

$$\dot{Q}_{conv} = \int_0^{t_{cycle}} \alpha \cdot A \cdot \Delta T \cdot dt \quad (3)$$

$$\dot{Q}_{rad} = \int_0^{t_{cycle}} \sigma_0 \cdot \varepsilon \cdot A \cdot \Delta T^4 \cdot dt \quad (4)$$

In Eq. 2, λ and δ are the thermal conductivity and thickness, respectively, in Eq. 3, α and 0 are the constant Stefan-Boltzmann and emissivity, respectively, in Eq. 4. T and A stand for temperature and cross-sectional area, respectively. In order to improve the cooling performance of CCCs, maximization is commonly pursued during the cooling process. The smallest value of $\dot{Q}_e$ implies heat loss over the molding material boundary, while the biggest value of $\dot{Q}_e$ denotes the smallest value of $\dot{Q}_m$. In other circumstances, the obtained loss is less than 5%. As a result, $\dot{Q}_e$ is regarded as negligible, and the molding material boundary is assumed to be adiabatic [23,24].

When the $\dot{Q}_e$ is neglected, Eq. 1 can be rewritten as Eq. 5 [19]:

$$\dot{Q}_m + \dot{Q}_c = 0 \quad (5)$$

Rao et al [25] defines $\dot{Q}_m$ as in Eq. 6,

$$\dot{Q}_m = 10^{-3} \cdot [(T_p - T_e) \cdot C_p + i_p] \cdot \rho_p \cdot \frac{s}{2} \cdot x \quad (6)$$

where T_p and T_e are the polymer melt and demolding temperatures, C_p is the polymer's specific heat, i_p is the latent heat, ρ_p is the polymer melt density, s is the molded component thickness, and x is the cooling channel pitch difference. Furthermore, Eq. 7 [19] states:

$$\dot{Q}_c = 10^{-3} \cdot t_k \cdot \left(\frac{1}{\lambda_m \cdot Sh} + \frac{1}{\alpha \cdot 10^{-3} \cdot d \cdot \pi} \right)^{-1} \cdot (T_{mw} - T_c) \quad (7)$$

where t_k is the cooling time, λ_m is the thermal conductivity of the tool material, Sh is the form factor of the cooling channel geometry, d is the cooling channel diameter, T_{mw} is the tool material's wall temperature, and T_c is the coolant's supplied temperature

All of the parameters in equations 6 and 7 are known or assumed during the operation, with the exception of the values t_k and T_{mw} [19]. Without taking into account the effect of axial conduction, [26] can be used to express the energy equation:

$$\rho c_p V_z \frac{\partial T}{\partial z} = k \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + \mu \left(\frac{\partial V_z}{\partial r} \right)^2 \quad (8)$$

The phenomena of heat transmission at the interface between the mold cavity and the molten polymer is complex. There are several factors to consider, including surface roughness, geometry, mold coating, and polymer composition. The most commonly cited criterion for the contact heat transfer rate is that the heat flux must be maintained across the discontinuity [27]:

$$q^{\parallel} = h(T_{melt} - T_{mould}) \quad (9)$$

The thermal contact resistance coefficient, h , is calculated experimentally [27]. After determining temperature and velocity profiles for any z -axis position, the average melt temperature can be calculated using the mixing cup temperature idea [29]. The associated equation is as follows:

$$T_{avg} = \frac{\int_0^R \rho \cdot 2 \cdot \pi \cdot r \cdot dr \cdot V_z \cdot c_p \cdot T}{\int_0^R \rho \cdot 2 \cdot \pi \cdot r \cdot dr \cdot V_z \cdot c_p} \quad (10)$$

Theoretical considerations of heat transport are critical in injection molding. An important equation is the energy balance. energy balance can be written using Equation 11 [29]:

$$\rho_m C_m l_m \frac{dT_m}{dt} + \frac{h \pi D K_m}{2 K_m W + h \pi D l_m} = \frac{\rho_p C_p l_p (T_{melt} - T_{eject})}{t_{cycle}} \quad (11)$$

The tool's active component is the area between the surface and the cooling lines. The first term in equation represents the tool's thermal mass and the build-up of heat as the tool temperature rises (18). The second part in equation represents heat transmission through conduction through the tool and then convection into the coolant (18). The right-hand side of the equation represents the heat source (18). The heat source is assumed to be the cooling of the plastic. A first-order ordinary differential equation having a solution in the form of equation (12) [29] is represented by equation (11).

$$T_m(t) = T_{m0} + (T_{ms} - T_{m0}) e^{\frac{-t}{\tau}} \quad (12)$$

where T_{ms} is the system's time constant and is the steady-state cycle-averaged tool temperature.

Equations (13) and (14) represent the cycle-averaged tool temperature and time constant, respectively. Conformal cooling (CC) is now formally defined as being smaller than or equal to the injection cycle time [29]:

$$T_{ms} = T_c + \frac{\rho_p C_p l_p (2K_m W + h\pi D l_m)(T_{melt} - T_{eject})}{h\pi D K_m t_{cycle}} \quad (13)$$

$$\tau = \frac{\rho^m C^m l_m (h\pi D l_m + 2K^m W)}{h\pi D K^m} \quad (14)$$

The expression for the time constant in equation (14) [29] is reduced to the form provided in equation (15) when heat transport is considered to be lossless:

$$\tau = \frac{\rho_m C_m l_m^2}{K_m} \quad (15)$$

Equation 15 considers the case where the heat transfer coefficient is infinite, which is the same as supposing that heat transport to the molten liquid is 100% efficient [29].

3. Procedure

3.1 Geometry and sets

The geometry of the analyzed 3D model is presented in Figure 3. All the dimensions were scaled to half of the original mold [30-32], due to the need of reducing the computation power required to solve the numerical analyses.

Fig. 3–Set drawing: simplification of the 3D model, also presented in [33,34]

The components of the geometry (Fig. 1), are shown in Fig. 4.

Fig. 4. – Components of the assembly, represented by numbers from 1 to 10

The components of the geometry are explained in Table 1:

Table 1 –Components of the geometry used in the simulations

Component ID	Quantity	Description
1	1	Part
2	8	Channels
3	1	Mold

Water in the liquid phase was used for the cooling channels, which are represented by circles and numbered from (1) to (8) in Fig. 4. The injected component is polypropylene (PP), while the mold cavity is considered to be made of p20 steel.

3.2 Materials

In the simulations, performed in ANSYS Mechanical APDL 2020 R2, water was used for the cooling channels and PP was used for the injected component. P20 steel was utilized for the mold. Only water is considered as a fluid; PP and steel, on the other hand, are regarded to be solid. The properties of the materials used are listed in Table 2.

Table 2 - Properties of water, PP and P20 steel [30-34].

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

3.3 Numerical procedure

The meshing parameters are shown in Table 3.

Table 3 - Meshing parameters

	Esize [mm]	Mesh type
Cooling channels and mold	2.5	Quadrilateral free mesh
Part	0.07	

Both modules employed the identical mesh parameters. Fig 5 top and bottom show the mesh in Mechanical APDL and Workbench, respectively.

a)

b)

Fig.5 – Mesh in ANSYS Mechanical APDL (a) and in ANSYS Workbench (b)

The boundary conditions implemented in ANSYS Mechanical APDL 2020 r2 are listed in Table 4.

Table 4 – Thermal conditions applied [30-34]

Condition	Value [C]	Application
Tini	210	Part, 1 volume, component (9)
Tini	40	Cooling channels, 8 volumes, components (1) to (8)
T	40	Mold, 1 volume, represented by (10)
T	23	Boundary, outer areas of (10) (Total of 6 areas)

The temperature of 210 [C] is an approximation of the processing temperature of PP. It is assumed that the water in the cooling channels is at a constant temperature of 40 [C]. The methodology used in this study was to compare and validate numerical findings using two different software modules from the same suite, in this case, ANSYS. A flowchart depicting the process is shown in Figure 6.

Fig. 6 -Methodology developed for the validation of the numerical results.

Geometry construction, meshing, specifying beginning and boundary conditions, and solution are all standard phases in a Finite Element analysis. However, there are two major distinctions between the two approaches: in both modules, the geometry was constructed natively, implying that the geometry environment is different. Another distinction is due to the meshing. Different meshing results from the same mesh settings, with considerable variances in the number of components. This could be because Workbench meshing has a lot more meshing choices than Mechanical APDL. In all settings that are present in Workbench but not in Mechanical APDL, the default value was retained.

4. Results and Discussion

4. Results

4.1. Contours

The aim of this work is to get the temperature distribution for the time where the temperature is lower than the ejection temperature of 70 C. Considering time steps of 0.5 s in the simulation, for $t=2$ s, the first global results whose maximum temperature is lower than 70 C, are obtained. Contours were, therefore, obtained for t from 0 to 2 s with steps of 0.5 s. These are shown in Fig.7-10

a)

b)

Fig.7 – Temperature contours for both ANSYS APDL (a) and Workbench (b), $t=0.5$ s

a)

b)

Fig.8 – Temperature contours for both ANSYS APDL (a) and Workbench (b), $t=1$ s

a)

b)

Fig. 9– Temperature contours for both ANSYS APDL (a) and Workbench (b), $t=1.5$ s

a)

b)

Fig.10 – Temperature contours for both ANSYS APDL (a) and Workbench (b), $t=2$ s

4.2 Comparison

Fig. 11 shows the maximum temperature T_{max} in function of time, for both Mechanical APDL and Workbench.

Fig. 11-Maximum temperature in function of time, for both Mechanical APDL and Workbench

One can see in Fig. 11 that results by Workbench are very close to those of Mechanical APDL. In most cases, workbench show values of maximum temperature slightly higher than APDL. Fig. 12 shows the average temperature Tavg in function of time, for both Mechanical APDL and Workbench.

Fig. 12 -Minimum temperature in function of time, for both Mechanical APDL and Workbench

It can be seen in Fig. 12 that Mechanical APDL presents a higher value than Workbench for the majority of the cases. However, the differences between both

software modules decrease along time. Fig. 13 presents the average temperatures vs time.

Fig. 13 -Average temperature in function of time, for both Mechanical APDL and Workbench

The errors regarding the results shown in Fig. 13 (T_{avg}) are shown in Fig. 14. The errors were calculated using (16)

$$|Error|_{[%]} = \frac{|T_{wb} - T_{APDL}|}{T_{wb}} * 100\% \quad (16)$$

Fig. 14- Error between Mechanical APDL and Workbench, in function of time, for average temperature

As it is shown in Fig. 14, the error in function of time fits an exponential function, in the case of the average temperature T_{avg} and a 3rd degree polynomial function, in the case of the maximum temperature T_{max} . The value of the

quadratic correlation is very close to 1, as is shown in Fig. 13. The temperature distribution shows some differences in the two software modules for all the studied substeps, shown in Figs. 11 and 12. However, it is possible to conclude that the values of the temperature are close in both ANSYS Mechanical APDL and ANSYS Workbench. The contours show some difference in the color distribution, as a characteristic of the assumptions of the software modules. It is possible to see that for $t=2$ s the temperature distribution shows a better agreement than for $t=4$ s and $t=2$ s. This is also shown in Fig. 13, for the maximum and average values of the temperature

5. Conclusions

It may be determined that, for the condition under consideration, a mesh of 0.07 mm is fine enough to obtain satisfactory precision. Analytical models for temperature prediction over time, totaling four, were obtained in the form of 2nd degree quadratic equations, as shown in Figs. 11 and 12. Despite best attempts, there are some changes in module settings between the two programs employed, limiting the goal of duplicating exact simulation conditions, particularly in terms of meshing properties. In fact, element type and mesh details were shown to be the most significant distinctions. Because of this, there may be a divergence between the two modules for coarse meshes, whereas a good agreement is established for the most refined mesh. As a result, the variances in characteristics of the meshing modules in the two software packages, mainly in what relates to the elements specifically and to the mesh, in general, are the primary causes of the observed numerical discrepancies. In the future, the errors between the two software packages might be fit into two alternative equations. These equations can be used to determine whether additional mesh refining is worth the extra computational work.

Declarations

a. Funding

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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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