2D Heat Transfer Simulation of an Injection Mold: Comparison Between ANSYS Workbench and ANSYS Mechanical APDL

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2D Heat transfer Simulation of an injection mold: comparison between ANSYS Workbench and ANSYS Mechanical APDL

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Abstract. The fabrication of conformal cooling channels (CCC's) has become easier and more affordable due to recent developments in additive manufacturing. The use of CCC's allows better cooling performance than the conventional (straight drilled) channels, in the injection molding process. The main reason for this is that the CCC's can follow the paths of the molded geometry, whereas the conventional channels made by conventional machining techniques are not able to do so. CCCs can help to reduce thermal strains and warpage by reducing cycle time and allowing for a more uniform temperature distribution. CCC, on the other hand, has a more complicated design procedure than traditional channels. Computer-Aided Engineering (CAE) simulations) are crucial to achieve an effective and cost-efficient design. This article focuses the comparison of two ANSYS modules, for results validation. The relative error between ANSYS Workbench and ANSYS Mechanical APDL varied from close to 0 to below 1 %, in the case of maximum temperature T_{max} , and between 1.5 to 5.5 approximately, for the average temperature T_{avg} . It can be concluded that, for the most refined mesh studied, the results are close by the two modules. Therefore, the ANSYS module to work on should be used based on the purpose of the work, as well as the complexity of the CAD geometry.

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

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1. Introduction

Much research has been done in the field of design and modeling of CCCs in injection molds. Various simulation packages have been used to analyze mold and channel designs. In 2005, Moldflow analysis was used in I-DEAS™ by Dimla et al. to find the best position of the channel [1]. ABM Saifullah and SH Masood analyzed the "part cooling time" using ANSYS thermal analysis modules [2]. In 2009, the same group of researchers used MPI simulation modules to analyze parts and compared the results for conventional and quadratic CCC profiles; they concluded that conformal channels have 38% shorter cooling time than conventional channels [3]. Gloinn et al. from Ireland conducted a FEM analysis to determine the mold temperature using ABS polymer as the molten material and cooling water inlet [4]. Another study was conducted in 2007 by [5] using Moldflow Plastic Insight 3.1 to investigate the thermal effects of cooling channel design on the injection molding process. The authors proposed a novel framework for the design of a uniform CC. Using the same simulation modules, Wang et al. verified the benefits of a cooling loop; they modeled only the part temperature [6]. In 2017, the comparative effect of conventional, serial, parallel, and additive-parallel cooling channels was studied by Khan et al. in terms of cooling time, total cycle time, volumetric shrinkage, and temperature variance using the modules AMI [7]. Even though there are numerous studies on CCC analysis, the number of studies focused on CCC design parameters for various types of designs is quite restricted. Most of the concepts were implemented based on the designers' prior experience. To the best of the author's knowledge. Any type of mixture, as well as the agreement between the design parameters, cross-section size, and the experimental results. Mayer [8] provides an example of a basic relationship between four factors for the design of CCC utilizing additive manufacturing. Previous research suggests that using cross-sections other than circular for channels could improve cooling efficiency. Cooling channels with variable spacing for tooling applications have been studied in some depth [9]. The authors conducted a study in which a full solution for conformal channel design was created for reconstructing the existing model, which was originally built with straight channels, with CCCs. The authors considered factors such as duct diameter, pitch spacing, and wall to duct separation.

This work compares the results of a 2D transient thermal analysis by two ANSYS packages: ANSYS Steady state/Transient Thermal, in Workbench, and ANSYS Mechanical APDL. The two modules' packages have different purposes: Workbench is more user-friendly, as well as CAD friendly. Mechanical APDL is fully integrated with ANSYS Parametric Design Language, which makes models built there fully compatible with any optimization procedures, by means of full parametrization capabilities. The aim of this work is to determine the optimal meshing parameters that can lead to optimal results. At the same time, results for both modules are validated with each other.

2. Background

Injection molding is a widely used advanced manufacturing technology for the cost-effective and highly reliable production of engineered parts. The injection molding process involves several steps: (1) injection, (2) packaging, (3) cooling, and (4) ejection [10]. Injection molding has an important role on the plastics industry and consumes a large percentage of the total amount of plastics [11]. Plastic injection molding is a versatile process for producing various complex sizes and shapes of high-quality products from thermoplastic and thermoset materials by applying heat and pressure [12]. To obtain a high-quality plastic part, the design of the injection mold, especially the design of the mold core and cavity, is very important. It also plays an important role in the economic aspects of the business. Cooling channels must be used to ensure temperature control and cooling of the molded part. Traditionally, cooling channels were drilled straight using subtractive manufacturing methods. CCCs could be easily and economically fabricated using traditional methods. However, there are serious limitations to the geometry of CCCs that can limit the efficiency of the injection molding process. In fact, straight drilled channels are not able to induce optimal cooling because the shape of the cavity, to avoid interference between the cavity and the channel, and the drilling process limit their design. In the latter case, only straight holes can be drilled. Fig. 1 (left) shows a comparison between a straight cooling channel and a conformal cooling channel. Fig. 1 right shows inserts of CCCs.

Fig. 1 (a) straight-drilled and (b) conformal [13] (left); Comparison of straight-drilled cooling channels and CC channels: straight-drilled cooling channels in cavity insert (a) and in core insert (b), and CC channels in cavity insert (c) and in core insert (d) (Adapted from [14], in [15] with permission from the authors) (right)

The fabrication of CCC shapes is often not possible using traditional machining techniques. Therefore, additive manufacturing technologies are used in their fabrication [16-18] in [19]. Recent developments in the field of 3D printing technology have made the CCC fabrication process more affordable and commercial. A transient heat transfer process can describe injection molding. However, it can be assumed to stabilize after several cycles in the injection molding process (if the average mold temperature is considered constant). It is also assumed that heat transfer equilibrium occurs when the heat transfer rate (heat flux) from the molten polymer to the mold material, becomes equal to the heat transfer from the mold material to the coolant and ambient air. A simplified representation of the heat flows can be seen in Fig. 2.

Fig. 2 - Simplified representation of the heat flows [20].

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

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

Conduction, convection and radiation are three different heat transfer mechanisms in the process of injection molding. The heat transfer rate (heat flux) from the molten polymer to the mold material and the heat flux inside the mold material are determined by the conductive heat transfer mechanism. The heat flux from the mold material to the coolant is calculated as convective heat transfer. As the temperature of the mold material increases during the injection molding process, the surface

temperature of the mold material becomes higher than that of the ambient air. Therefore, the heat flow from the molding material to the ambient air occurs by both radiation and convection. Equations 2-4 analytically define the conductive, convective and radiative heat transfer rates, respectively [21,22].

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

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

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

Where λ and δ are the thermal conductivity and thickness, respectively, in Eq. 2, α is the heat transfer coefficient in Eq. 3, and σ_0 and ε are the constant Stefan-Boltzmann and emissivity in Eq. 4. The temperature and cross-sectional area are denoted by T and A , respectively.

In order to improve the cooling performance in CCC's, usually maximization is aimed during the cooling process. The maximum value of means the minimum value of, i.e., the heat loss through the molding material boundary. In some applications, the obtained loss is less than 5%. Thus, the is negligible and the molding material boundary is assumed to be adiabatic [23, 24] in [20]. When the $\dot{Q}_e$ is neglected, Eq. 1 can be rewritten as Eq. 5 [20]:

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

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 temperature and demolding temperature, c_p is the specific heat of the polymer, i_p is the latent heat, ρ_p is the density of the polymer melt, s is the molded part thickness, and x is the pitch difference between the cooling channels.

In addition, Eq. 7 [20] 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 shape factor of the cooling channel geometry, d is the cooling channel diameter, T_{mw} is the wall temperature of the tool material, and T_c is the supplied temperature of the coolant.

All parameters in equations 6 and 7 are known or assumed during the process, except for the parameters t_k and T_{mw} [20]. The energy equation, neglecting the effect of axial conduction, can be expressed by [26]:

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

The phenomenon of heat transfer at the interface between mold cavity and molten polymer is complex. It depends on several factors, such as surface roughness, geometry, mold coating, and polymer composition.

The condition usually considered for the contact heat transfer rate is the one that considers 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 determined experimentally [27].

After the temperature and velocity profiles are determined at any z -axis location, the average melt temperature can be calculated using the concept of mixing cup temperature [28]. The corresponding equation is shown below:

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

In injection molding, the theoretical aspects related to heat transfer are very important.

One important equation is the energy balance. Let us consider the active part of the mold. An energy balance can be written as in equation 11 [29]:

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

The active part of the tool is considered as the zone between the surface and the cooling lines. The first term of equation (18) represents the thermal mass of the tool and the build-up of heat as the tool temperature increases. The second term in equation (18) represents heat transfer by conduction through the tool and then by convection into the coolant. The right-hand side of equation (18) represents the heat source. The heat source is the cooling of the plastic. The first order ordinary differential equation represented by equation (11) has a solution in the form of equation (12) [29]:

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

where T_{ms} is the cycle-averaged tool temperature in the steady state and τ is the time constant of the system.

Equations (13) and (14) give the expressions for the cycle-averaged tool temperature and the time constant, respectively. The definition of conformal cooling (CC) can now be written formally by requiring it to be less than or equal to an injection cycle time [29]:

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

$$\tau = \frac{\rho_m C_m l_m (h\pi D l_m + 2K_m W)}{h\pi DK_m} \quad (14)$$

When heat transfer is considered to be lossless, the expression for the time constant represented by equation (14) reduces to the form shown in equation (15) [29]:

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

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

3. Procedure

3.1 CAD Models (Computer Aided-Design)

The CAD model used in this work was built in both ANSYS Workbench and ANSYS Mechanical APDL 2020 R2. The geometry was built in 3D and is composed by 8 cooling channels, represented by circles, a mold cavity, represented by a rectangle and the part, represented by a bent plate. The assembly is shown in Fig. 3.

Fig. 3- Assembly drawing of the mold, showing dimensions, in millimeter and components ID.

The components of the geometry are explained in Table 1:

Table 1 –Components of the geometry used in the simulations and in the optimizations.

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

3.2 Materials

A detailed description of the materials used in the simulation in "Steady/ Transient Thermal" and their properties can be found in the simulation report of the present project [14]. The materials used in the simulations were water, for the cooling channels, polypropylene for the injected part. And p20 steel for the mold. Of these materials, only water is assumed to be in a liquid state, i.e., PP and steel are assumed to be in a solid state. The properties of the used materials are shown in Table 2,

Table 2– Properties of the materials used in this work

Material	Water in liquid state	Polypropylene, with 10% mineral	P20 steel
Density [(kg/m ³)]	998.2	1050	7861 [11]
Specific heat [J / (kg.K)]	4182	1800, Considered constant	502,48 [12]
Thermal conductivity [W/ (mK)]	0.6	0.2 Considered constant	41,5

For the cooling channels, represented by circles, water in liquid phase was used. The injected part is made of Polypropylene (PP) and the mold cavity is assumed to be of p20 steel. Of these materials, only the steel is assumed to be in solid state, the other two behaving as liquids.

3.3 Numerical procedure

The meshing parameters are shown in Table 3.

Table 3 - Meshing parameters

	Esize [mm]	Mesh type
Cooling channels and mold	1	Quadrilateral free mesh
Part	0.0625	

Although the same mesh parameters were used in both modules, there is a significant divergence in the total number of elements of the mesh: 82871 for Workbench and 151885 for Mechanical APDL. The mesh, built in Mechanical APDL and in Workbench, is shown in Fig 4 a) and b), respectively.

Fig.4 – Mesh in ANSYS Mechanical APDL (a) and in ANSYS Workbench (b)

In order to be able to implement the boundary conditions in "Steady/ Transient Thermal", selections were defined in ANSYS Workbench. These are shown in Table 4.

3.3.3 Boundary Conditions

Table 4 – Thermal conditions applied

Condition	Value [C]	Application
Tini	210	Part, 1 area
Tini	40	Cooling channels, 8 areas
T	40	Mold, 1 area
T	23	Boundary, 4 lines

The temperature of 210 [C] is the temperature melt approximation previously determined in experimental work within the Tooling4G project [rel2]. With respect to the cooling channels, the water is assumed to have a constant temperature of 40 C.

The methodology followed in this work aimed the comparison and validation of numerical results with two software modules of the same suite, in this case, ANSYS. Fig. 5 shows a flowchart with the followed methodology, which aimed to cross-validate results from two ANSYS software packages: Mechanical APDL and Workbench.

Fig. 5 -Methodology developed for the validation of the numerical results.

The steps taken are those that are typical in a Finite Element analysis: Geometry building, meshing, defining initial and boundary conditions, and solving. However, there are two significant differences between the two approaches: the geometry was built natively, in both modules, which implies that the geometry environment is different. Another difference is inherent to the meshing. The same mesh conditions originate different meshing with significant differences between the number of elements. This may be due to the meshing in Workbench having many more meshing options that Mechanical APDL. The default value was kept in all the options that are present in Workbench and are absent in Mechanical APDL.

4. Results and Discussion

4.1 Mesh Sensitivity Analysis

A convergence analysis was performed to ensure that the mesh is refined enough to obtain results with high accuracy. The mesh sensitivity was done in both Mechanical APDL and Workbench, to ensure that, despite the differences between the meshing modules, the results between the two modules are close to each other. Fig. 6 shows the

results of the sensitivity analysis for the maximum value of the temperature T_{max} , for different element sizes and for both ANSYS Mechanical APDL and Workbench.

Fig. 6- T_{max} for different mesh refinement levels

It can be seen in Fig. 6 that the maximum temperature is significantly higher in Mechanical APDL in comparison with Workbench. The only exception is for mesh size of 0.0625 mm, in which the values of temperature obtained in workbench are slightly higher. Fig. 7 shows the results of the sensitivity analysis for the average value of the temperature T_{avg} .

Fig. 7– Tavg for different mesh refinement levels

In figure 7, similarly to Fig. 6, the results of temperature are significantly higher for ANSYS Mechanical APDL when comparing to ANSYS Workbench. However, that difference is almost insignificant for refined mesh, with mean element size of 0.0625 mm. Fig. 8 shows the discretization error in Mechanical APDL and in Workbench, in term of maximum temperature. The results shown in Fig. 8 were built from those of Fig. 6, using Equation 23

$$Error_{T_{max_n}}[\%] = \frac{T_n - T_{(n-1)}}{T_{(n-1)}} * 100\% \quad (23)$$

Where n is the refinement level, whose relationship with element sizes is shown in Table 5

Table 5- Relationship between Element sizes and refinement levels

Esize, first n-1	Esize, second, n	Refinement level
0.0005	0.00025	1
0.00025	0.000125	2
0.000125	0.0000625	3

Fig. 8– Mesh Error in Mechanical APDL and in Workbench, in term of maximum temperature, for different mesh refinement levels

Fig. 9 shows the discretization error in Mechanical APDL and in Workbench, in term of average temperature. The results shown in Fig. 9 were built from those of Fig. 7, using Equation 24

$$Error_{T_{avg}}[\%] = \frac{T_n - T_{(n-1)}}{T_{(n-1)}} * 100\% \quad (24)$$

Fig. 9– Mesh Error in Mechanical APDL and in Workbench, in term of average temperature, for different mesh refinement levels

When comparing errors of the mesh in comparison with coarser mesh, with double mean element size, one can see that error are significantly higher for Mechanical APDL in the last level of refinement, while errors for workbench decrease over refinement levels. This is valid for both maximum temperature (Fig. 8) and Average temperature (Fig. 9)

This suggests that ANSYS Mechanical APDL only gives good approximation for the last used refinement level, while Workbench is able to obtain much better approximations that Mechanical APDL for refinement levels of 1 and 2. This can be due to the mesh in ANSYS Workbench being more regular/uniform, both in shape and size, than that of APDL, although same setting for meshing were used in both modules.

Fig. 10 shows the error in Maximum and Average temperature, for Mechanical APDL in comparison with Workbench. The results shown in Fig. 10 were built from those of Fig. 8 and 9, using Equation (25):

$$Error_{AWb} = \frac{\frac{T_{nAPDL} - T_{(n-1)APDL}}{T_{(n-1)APDL}} - \frac{T_{Wb} - T_{Wb}}{T_{Wb}}}{\frac{T_{nWb} - T_{(n-1)Wb}}{T_{(n-1)Wb}}} * 100 \quad (25)$$

where T is either the Maximum or Average temperature

Fig. 10– Error between Mechanical APDL and Workbench, in term of maximum and average temperature, for different mesh refinement levels

Fig. 10 suggests that errors are significant for all Element sizes/Refinement levels, except for the element size of 0.0625 mm. This suggests that, in either case of using ANSYS Workbench or ANSYS Mechanical, the only suitable mesh size for obtaining low-error approximations, is 0.0625 mm.

4.2 Comparison

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

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

It can be seen in Figs. 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. The errors regarding the results shown in Fig. 11 (T_{max}) and in Fig. 12 (T_{avg}) are shown in Fig. 13. The errors were calculated using (26)

$$|Error|_{[\%]} = \frac{|T_{wb} - T_{APDL}|}{T_{wb}} * 100\% \quad (26)$$

Fig. 13- Error between Mechanical APDL and Workbench, in function of time, for both maximum and average temperature

As it is shown in Fig. 13, the error in function of time fits an exponential function, in the case of the average temperature Tavg and a 3rd degree polynomial function, in the case of the maximum temperature Tmax. The value of the quadratic correlation is very close to 1, as is shown in Fig. 13.

4.2 Contours

Figs. 14-16 show temperature contours taken from both Mechanical APDL and Workbench, for $t=6$ s and for refined mesh, with mean element size of 0.0625 [mm].

Fig. 14 -Temperature distribution for 2 [s], Mechanical APDL (a) and Workbench (b)

Fig. 15-Temperature distribution for 4 [s], Mechanical APDL (a) and Workbench (b)

Fig. 16-Temperature distribution for 6 [s], Mechanical APDL (a) and Workbench (b)

The temperature distribution shows some differences in the two software modules for all the studied substeps, shown in Fig 14-16. 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 $t=6$ 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 can be concluded that, for the situation studied, a mesh with 0.0625 mm is needed to achieve results with acceptable accuracy. It was possible to fit the errors between the two software packages in two different equations. Those equations can be used to predict if further mesh refinement may be worth the increase in computational time. - Analytical models, 4 in total, were possible to obtain, in the form of 2nd degree quadratic equations, for the prediction of temperature over time, as shown in Fig. 11 and 12. Some differences in modules options are present between the two programs used which limits the aim of reproducing exact simulation conditions, particularly regarding the characteristics of meshing, despite the best efforts. In fact, the most significant differences were associated to element type and mesh details. The divergence between the two modules for coarse meshes may happen for that reason, while a good agreement is obtained for the most refined mesh. Therefore, the differences between the elements and mesh are the main explanation for the observed differences in numerical results. It is possible to conclude that it was easy to obtain solution for this particular problem. This is due to the sparse direct solver being used in both modules, for several substeps.

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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 analyzed 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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