Automatic Design of Conformal Cooling Circuit for Rapid Tooling

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Abstract

This paper presents an automatic method for designing conformal cooling circuit, which is an essential component that directly affects the quality and timing for the products fabricated by rapid tooling. To reduce the time of cooling and control the uniformity of temperature and volumetric shrinkage, industry expects to have cooling channels that are conformal to the shape of products. We achieve the goal of automatically designing such conformal cooling circuit in twofold. First, the relationship between the conformal cooling and the geometry shape of cooling circuit is formulated. Based on that, we investigate a geometric modeling algorithm to design the cooling circuit approaching the conformal cooling. Simulations have been taken to verify the advantage of the cooling circuit generated by our algorithm.

***Keywords*:** conformal cooling, cooling circuit, generic shape, design automation, rapid tooling.

1 Introduction

Molds shape the hot and injected plastic into the desired product. The plastic part must be cooled to the temperature point where it can withstand the action of the ejectors and its shape is maintained after ejection. A substantial portion of the total molding cycle (e.g., as much as 80%) could be required for cooling. Therefore, for high production molds, it is imperative that the cooling time is reduced to a minimum. Besides, the design of a mold cooling system requires a number of considerations, such as composition of coolant, pressure drop of coolant and runner system. Among them, we focus on the aspect in 3D shapes of cooling channels, which should be conformal to the given plastic part.

Effective cooling achieved with the conformal cooling system has been developed in earlier studies and confirmed by experimental tests [1–6]. Tools with conformal cooling channels, which is fabricated by 3D printing, have demonstrated improvements in both the production rate and the part quality as compared with conventional production tools. Sachs et al. examined their conformal cooling tools in the industrial applications [1], which reduces the cycle time by 15% and the part distortion by 9%. The high efficiency of conformal channel in thermal control presents not only for cooling purpose, but also in mold heating [5]. However, it is unclear how to apply their approach to the products have more complicated shapes (e.g., the models tested in this paper).

Generally, a mold designer could face plastic parts with all kinds of shape. Thus, it is difficult to use the predefined shape of corresponding cooling channels but still make them conformal. An automatic design algorithm is needed to generate the cooling channels conformal to the plastic parts. Xu et al. [2] mathematically defined the conformal cooling condition with respect to the efficiency of heat exchange in a mold as: the cycle average temperature of the mold must reach its steady state value within one injection cycle. Based on this important condition and six design rules, the location and size of channel diameter were evaluated. However, we notice that their method can only be applied to parts in very simple shape. When applying their method to design cooling channels for parts with complex shape, the surface of a part must be decomposed into several so called *cooling zones* with simpler shape. After the decomposition, the cooling systems for each local zone are then generated one by one. The part partition was also conducted in another work [7] as a design prerequisite, where the concept of cooling feature was described instead of cooling zone. However, it is hard to apply the feature decomposition technique to the products with freeform surfaces, and a feature decomposition algorithm for generic shapes does not exist in the literature. Moreover, for complicated products, more than hundreds features could be presented. It is impractical to generate cooling systems for each of these features.

The objective of this study is to provide a generic methodology to directly build the complex conformal cooling channel in three-dimensional space. Different from prior methods, we automatically generate cooling channels in global manner (i.e., the decomposition step, which may violate the stability of an automatic design algorithm is not needed). The conformal surface that will be employed to locate the center of cooling channels is first computed by an offset surface generation method [8]. We then compute the *Centroidal Voronoi Diagram* (CVD) on the conformal surface, where the boundary of CVD will be used as the central lines of cooling channels. Figure 1 illustrates the steps of our algorithm to generate the conformal cooling circuit for a given product with freeform surfaces.

The major technical contribution of this paper is a new algorithm for designing the conformal cooling circuit and

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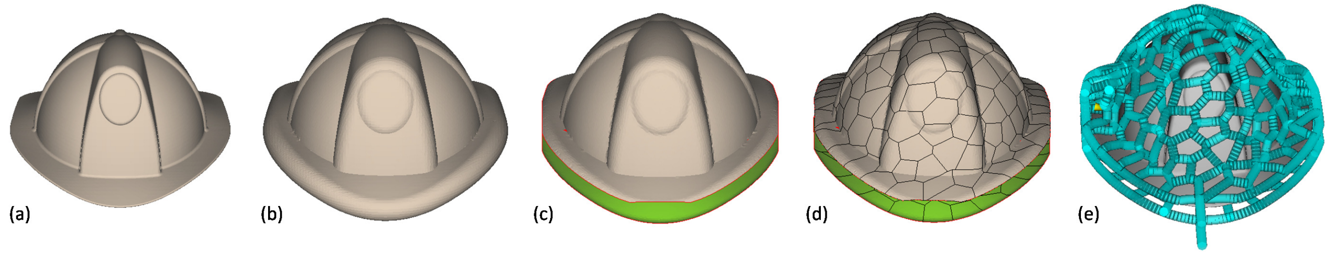


Figure 1: Overview of the cooling circuit generation algorithm: (a) a given model to be fabricated by rapid tooling, (b) the offset surface of given model, (c) the separated offset surface served as the conformal surface, (d) the refined discrete CVD, and (e) the resulting conformal cooling circuit.

the method to determine the input parameters for geometric computation according to the conformal cooling studies. As a result, our approach offers the following advantages to the cooling channel design in rapid tooling:

- **Conformability:** The circuit of cooling channels generated by our approach has the shape conformal to the surface of products to be fabricated. We do not have any assumption about the shape of products; therefore the circuit design algorithm is generic and can be applied to a variety of products (even for those having very complicated shape).
- **Automation:** The generation pipeline of the cooling channel can be performed automatically by only asking for several parameters from users. No tedious interactive modeling (or processing) is required, which greatly improves the efficiency of the cooling system design in rapid tooling.

To the best of our knowledge, there is no approach in literature that can provide the similar functionality as our method.

The rest of our paper is organized as follows. After reviewing the related work in Section 2, the algorithm for designing and generating conformal cooling circuit will be presented in Section 3. Section 4 formulates the physical equations to determine the input parameters for geometric modeling algorithms. The simulation results are shown in Section 5, and discussions for the limitation and the future work are given in Section 6. Finally, our paper ends with the conclusion section.

2 Related Work

In literature, there is now a substantial body of research on the design and analysis of conformal cooling channels for injection molding [1–7, 9–12]. Based on three-dimensional (3D) printing process, a number of studies developed design methodologies and fabrication techniques for conformal cooling, which provided significant advantages in controlling both the tool temperatures and the dimensions of molded parts. In a conformal cooling system (e.g., [1, 2]), the tool temperature become steady after a single injection. The conformal cooling condition was mathematically stated as requiring the time constant of a mold be less than one injection cycle. According to this condition, we approximate the typical dimensions of cooling channel in our design approaches.

Li [7] produced the final cooling system by synthesizing the sub-systems defined on each of the recognized features of plastic parts. However, as the feature decomposition step is hard to be automated, his approach may need the interactive input from users in general. Different from feature-based approach, cooling channels were also examined in divided regions of part surface in [6], but they decomposed regions according to the temperature distribution after the filling stage in molding simulation. Their design strategy was addressed as an optimization problem with defined objective function, the computation of which could be very slow as several simulation rounds are needed to obtain good cooling channels. As addressed in [5], not only for cooling, conformal channels were also applied in rapid thermal cycling process (i.e. rapid heating and cooling during filling and packing stage). Sun et al. [12] suggested U-shape milled groves for uniform cooling. Using finite element analysis and thermal heat transfer analysis, Saifullah et al. [3] demonstrated the advantage of conformal cooling system. All these prior methods do not provide an automatic method for generating the layout of conformal cooling channels on products with freeform shapes.

An offset surface of a solid H is the set of points having the same offset distance r from the boundary of H. Basically, the offset surface being outside of H is called the grown offset surface, and the offset surface inside H is the shrunk offset surface. In our automatic design algorithm for conformal cooling circuit, the grown offset surface of a given product will be generated as the conformal surface to locate the central lines of cooling channels. Although the offsetting operation is mathematically well defined [13], offsetting a solid model exactly has proven to be difficult especially the freeform models. Simply shifting vertices by a distance r along the surface normals will lead to a self-intersected model, which does not correctly represent a solid. Recently, Liu and Wang present a new algorithm to generate intersection-free offset surfaces [8]. The basic spirit of their algorithm is to efficiently sample a narrow-band signed distance-field from the input model on a uniform grid by four filters, and then employs an intersection-free contouring algorithm to build the offset mesh surface from the signed distance-field. This algorithm is used in our approach to create the conformal surface.

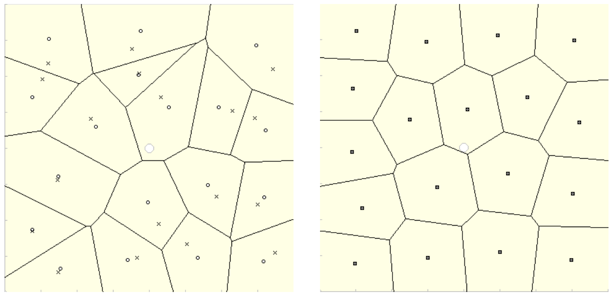


Figure 2: (Left) Voronoi Diagram, where the sites (the crosses) and the centroids (the dots) of Voronoi regions are located at different places. (Right) Centroidal Voronoi Diagram after 100 iteration of Lloyd's algorithm [14], where the centroid and the site in each Voronoi region are coincident.

A *Voronoi Diagram* (VD) on the plane is defined by a collection of n sites, by which the diagram divides the plane into n sub-regions such that the closest site of all the points within a sub-region S_i is the site $\mathbf{s}_i$ inside this region. Every sub-region can only hold one site, which is called Voronoi region. The boundary of these sub-regions are formed by points that are equidistant to more than one nearest sites. A *Centroidal Voronoi Diagram* (CVD) is a VD where each Voronoi site is also the mass-centre (centroid) of its Voronoi region. Figure 2 illustrates the difference of VD and CVD in a plane. A very useful property of CVDs is that they cover spaces fairly (i.e., a CVD will tile the space into Voronoi regions having the same area). Moreover, each Voronoi region of a CVD often approximates a regular hexagonal shape. In our approach, we will investigate the method to estimate the layout and the number of cooling channels based on these good properties of CVD. Two-dimensional CVDs are easily produced by using the Lloyd's algorithm [14]. However, since in our approach the CVDs should be computed on the conformal surface (which is piecewise linear), the algorithm for computing discrete CVD [15, 16] is used. But we noticed that, the boundaries of discrete CVD generated by their approach always pass through the edges of underlying mesh surface and thus are in zig-zag shape. The boundaries of discrete CVD must be modified before being used in the cooling circuit design.

3 Circuit Generation Algorithm

The input of our algorithm is a water-tight solid represented by a triangulated manifold mesh surface $M = (V, F)$, which is composed of a set of vertices V and triangles F. Each vertex is assigned with a position $\mathbf{x}_i \in \mathbb{R}^3$. Without loss of generality, such an input can be easily produced by many CAD/CAM software systems. The cooling circuit generation algorithm consists of the following major steps (see the illustration in Fig.1).

1. By an input diameter D of cooling channels, the conformal cooling condition is used to approximate the distance, l_m, between the central line of cooling channel to the mold surface (details can be found in Section 4.2).

2. Constructing an offset mesh surface $M^c = (V^c, F^c)$ over M with l_m as the offset distance by [8]. This offset mesh surface serves as the conformal surface in our approach, where the distance from every point $\mathbf{p} \in M^c$ to M is l_m. See the illustration shown in Fig.1(b).

3. Separating M^c into two parts M^c_{core} and M^c_{cavity} by the parting surfaces, and M^c_{core} and M^c_{cavity} serve as the conformal surfaces in the core and cavity sides of the mold. To avoid generating cooling channels near the parting surfaces, the regions on M^c_{core} and M^c_{cavity} with distances to the parting surfaces less than l_m will also be removed (as illustrated in Fig.1(c)).

4. According to the spacing analysis of cooling channels in Section 4.3, the number of CVD sites can be estimated for M^c_{core} and M^c_{cavity} respectively by the method presented in Section 4.4.

5. The discrete CVD of M^c_{core} and M^c_{cavity} are constructed by the method of Valette et al. [16], and the boundaries of Voronoi regions are smoothed by computing the approximate Geodesic curves [17] (see Fig.1(d)).

6. The final conformal cooling channels are generate by sweeping a sphere with diameter D along the smoothed boundary curves of the Voronoi regions (see Fig.1(e)). The resultant solid of the cooling channels is computed by a variation of the general sweeping method [18].

Our design approach starts with the construction of the conformal surface over the given plastic part model. The offset surface is treated as the conformal surface because it is a shape most conformal to the geometry of input part. To fast construct an offset surface without self-intersection, the work of Liu and Wang [8] is used.

After trimming the offset surface into two parts of the conformal surface in the core and cavity sides of mold, M^c_{core} and M^c_{cavity}, the discrete *Centroidal Voronoi Diagram* (CVD) is computed on the mesh surfaces by the algorithm of Valette et al. [16]. However, their algorithm constructs the discrete CVD by using triangles as basic components in the computation, which results to zigzag boundaries of the Voronoi regions (see the top row of Fig.3). If such zigzag boundaries are used to generate the cooling channels, the pipelines will have too many unnecessary turnings that slow down the flow of coolants and thus weaken the function of cooling. To overcome such drawback, we adopt the local Geodesic curve approximation method in [17] to refine the boundaries. The boundaries of Voronoi regions generated by [16] are divided into several piecewise linear boundary curves by the corner points that are adjacent to more than two Voronoi regions. The refinement of each boundary curve iteratively shortens the curve by moving its vertices onto the position approximating the Geodesic curve locally. Details can be found in [17] and the bottom row of Fig.3 shows the improved boundaries of CVD and the corresponding circuit of cooling channels.

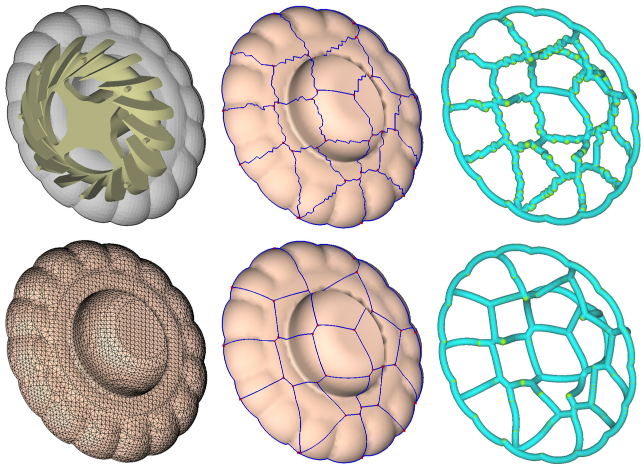


Figure 3: The boundary of discrete CVD must be refined to be used as the central lines of cooling channels: (Top row) the zigzag boundary of CVD generated by [16] (middle) and its corresponding cooling channels (right), and (Bottom row) the smooth boundary refined by [17] (middle) and the cooling channels (right).

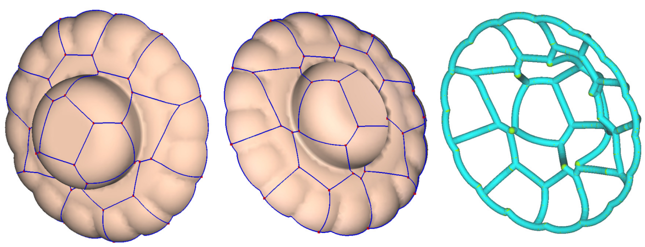


Figure 4: Using the farthest point sampling [19] to generate the initial positions of sites in the computation of discrete CVD can slightly improve its uniformity.

Another interesting study is about the initial positions of sites in the computation of discrete CVD. Basically, there are two options: randomly selected or uniformly distributed sample points. When using the farthest point sampling method [19] to generate the initial sites, we can only find slight improvement on the uniformity of resulting CVD. For example, the results in Figs.3 and 4 are generated by the random point-selection and the farthest point sampling respectively. Therefore, in the rest part of this paper, all CVDs are computed by using randomly sampled initial sites.

4 Formulation of Cooling Design

4.1 Heat transfer model

The heat transfer model considered in this paper is based on some prior studies of conformal cooling system design [1,2]. The research of Xu et al. in [2] has derived a conformal cooling condition that significantly simplifies the heat transfer model of the injection mold, where the heat transfer is localized in a small region between two adjacent cooling channels and the surface of plastic parts. This leads to a number

Table 1: Notation

Items	Description
l_A	The shortest distance from cooling channel wall to mold surface
l_B	The distance from cooling channel wall to the middle of two adjacent channels
l_m	Distance between the central lines of cooling channels to the mold surface
l_p	Half the plastic part thickness
W	Pitch distance between central lines of channels
D	Cooling channel diameter
ρ_m, ρ_p	Density of the mold and the plastic part
c_m, c_p	Specific heat of the mold and the plastic part
K_m	Thermal conductivity of the mold
h	Heat transfer coefficient
T_{melt}	Plastic melt temperature
T_e^A, T_e^B	Plastic ejection temperature at points A and B respectively
t_{cycle}	Injection cycle time

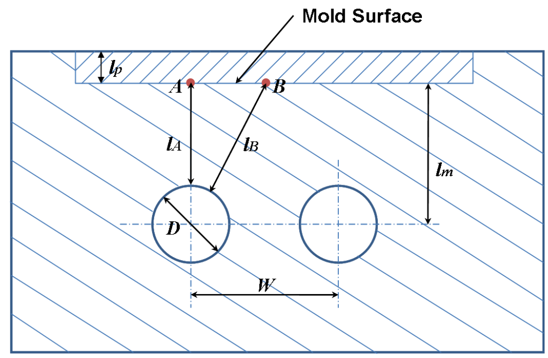


Figure 5: Typical dimensions of cooling channels in the heat transfer model, where D is the diameter of cooling channels and l_p is half thickness of a plastic part. Details of notation can be found in Table 1.

of studies (e.g., [4,5,9]) for the design methods of conformal cooling cells, where the 2D finite difference model and the 1D transient heat transfer simulation are employed to gain an accurate insight of thermal performance on molds.

Taking this on board, we express our design objective function subject to a local 2D cooling region in a cross-section of two adjacent cooling channels as illustrated in Fig.5. The notation details are listed in Table 1. A primary goal of cooling system design is to achieve a rapid, uniform and balanced cooling. If the cooling system is conformal, the global uniform cooling is guaranteed by keeping the coolant temperature uniform. Local cooling uniformity refers to the variation of the mold surface temperature on the mold surface right above the cooling channel and at the middle of two adjacent channels, i.e. points A and B in Fig.5. According to the equation of the steady state cycle average temperature of mold surface derived in [2], we can formulate the difference of mold surface temperature at points A and B as

$$\overline{T_m^B} - \overline{T_m^A} = \frac{\rho_p c_p l_p}{t_{cycle}} \{ \frac{2W\Delta t}{h\pi D} +$$

$$\frac{1}{K_m}[(l_B - l_A)T_{melt} - l_B T^B_{eject} + l_A T^A_{eject}]\} \quad (1)$$

where $\Delta t = T^B_{eject} - T^A_{eject}$ states the difference of plastic ejection temperatures at A and B. For a typical conformal cooling, the differences of mold wall temperatures must be controlled in a small range.

For the purpose of approximation, we assume heat transfer coefficient h goes to infinite. The term $\frac{2W\Delta t}{h\pi D}$ then becomes negligible. Our tests on various models also indicate that the contribution of term $\frac{2W\Delta t}{h\pi D}$ to the mold temperature deference is much less than other terms in curly braces in Eq.(1). Therefore, we can simplify the formula of temperature difference at mold surface into

$$\overline{T^B_m} - \overline{T^A_m} = \frac{\rho_p c_p l_p}{t_{cycle} K_m}[(T_{melt} - T^B_{eject})l_B - (T_{melt} - T^A_{eject})l_A]. \quad (2)$$

This simplified formula will be used to estimate the initial value of pitch distance, W, between cooling channels in the following computation.

4.2 Approximation of cooling channel depth

To build the conformal surface for an input mesh model, the depth distance from cooling channel to the mold surface, l_m, needs to be evaluated. Referring the design guide in injection mold design [20, 21], the wildly known appropriate range of l_m is about one to two times of cooling channel diameter D, i.e. $D < l_m < 2D$.

The conformal tool was also found to maintain a relative uniform temperature within the tool during an individual molding cycle [1]. Therefore, Xu et al. [2] stated the conformal cooling condition mathematically as the requirement that the time constant of mold should be less than one injection cycle, i.e. $\tau < t_{cycle}$. Our formulation of the time constant of the mold follows [2] as $\tau = \frac{\rho_m c_m l_m^2}{K_m}$. Again, a rough estimation of molding time constant can be applied with an assumption of extreme case, i.e. the infinite heat transfer coefficient. With the purpose to approximate the range of l_m, the simplified form is reliable enough. Thus we can write the range of l_m as

$$D < l_m < \sqrt{\frac{t_{cycle} K_m}{\rho_m c_m}}. \quad (3)$$

Putting the cooling channels too close to the mold surface may reduce the ability of a mold to withstand a high pressure. Based on this reason, we usually assign l_m with a value slightly smaller than its upper bound.

4.3 Spacing of cooling channels

To obtain a uniform cooling, we should control the mold temperature difference at point A and B, $\overline{T^B_m} - \overline{T^A_m}$, within a small amount. With the practical knowledge in cooling system design [21], the mold surface temperature difference should not exceed 10°C for part that require tight tolerance. Here, we further restrict it as $\overline{T^B_m} - \overline{T^A_m} \leq 5$°C. Given the expected mold temperature difference, from geometric point of view, we can seek the optimal length of l_A and l_B. Consequently, the optimum value of pitch distance W can be obtained. As illustrated in Fig.5, we can write l_A and l_B with respect to the typical dimensions for cooling channel configuration, i.e. the diameter D of cooling channel, the pitch distance between cooling lines W, and the depth of cooling lines l_m.

$$l_A = l_m - \frac{D}{2} \quad (4)$$

$$l_B = \frac{-D + \sqrt{4l_m^2 + W^2}}{2} \quad (5)$$

Substituting Eqs.(4) and (5) into Eq.(2) leads to an initial value of W. We then adopt this initial value of W in the non-linear equation – Eq.(1) to determine the final optimal value of W for the design of conformal cooling channels.

4.4 Estimating the number of Voronoi sites

Given a number of points as sites, a CVD with a uniform density function covers the space evenly with a hexagonal tilling. In our circuit generation algorithm, we also adopt the uniform density function for computing CVD. As a result, the idea layout of cooling channels will also approximate the regular hexagonal shape[1]. We estimate the number of sites by assuming that each Voronoi region approximates a regular hexagon. The number of Voronoi sites presents the density of our cooling channel lines and thus determines the sufficiency of cooling.

Since the conformal surface is assumed to be tiled into regular hexagons by CVD computation, the number of Voronoi sites can be estimated according to the area of surface and the dimension of a regular hexagon with $\frac{W}{2}$ as its apothem, where W is the pitch distance determined in the above subsection. Two CVDs are constructed on the conformal surfaces in core and cavity, i.e., M^c_{cavity} and M^c_{core} respectively. The number of sites can be calculated by

$$n = \frac{A_s}{A_h} \quad (6)$$

where A_s is the summed area of all triangles on a conformal surface (M^c_{cavity} or M^c_{core}) and

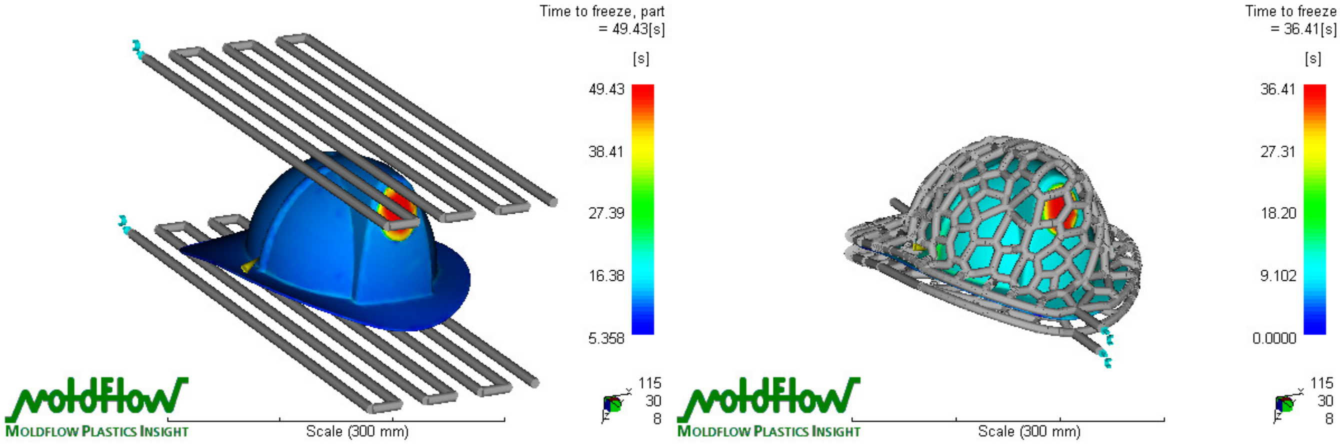
$$A_h = \frac{\sqrt{3}}{2} W^2 \quad (7)$$

is the area of a regular hexagon with $\frac{W}{2}$ as its apothem. By simulation tests which will be presented in the following section, such a simplification would not affect on the efficiency and uniformity of cooling.

5 Results

To present the easy usage of our technique and the cooling performance of channels generated by our method, we

[1] In practical computation, the resultant Voronoi regions by tilling may varied from regular hexagons. This is caused by factors including the initial positions of sites, the convergence speed of CVD computation, the 3D surface with high curvature in local regions, etc. Note that the hexagonal tilling in 3D polygonal surface is not a CVD in the strict sense.



(a) Conventional channel design

(b) Channels generated by our approach

Figure 7: Color maps for displaying the time of plastic part freezing to the ejection temperature.

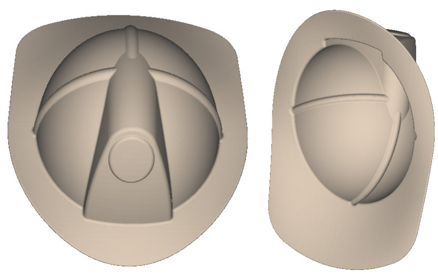


Figure 6: Case Study I: A helmet model shown in two views.

Table 2: Material Properties of Part and Mold

	P20	PP	ABS
Density $[kg/m^3]$	7800	900	1045
Specific heat $[J/(kg \cdot K)]$	460	1900	1950
Thermal conductivity $[W/(m \cdot K)]$	29	–	–
T_{melt} [°C]	–	220	230
T_{eject} [°C]	–	70	60

demonstrate it on two example models with complex shape in this section. As illustrated in the following two case studies, our method yields a global design solution without extra post-processing and all the conformal cooling channels are generated automatically.

Simulations in our tests are taken on the injection molding simulation software – MoldFlow Insight [22]. In our study, the melt of polymer is assumed to have a uniform initial temperature, namely the *melt temperature* that can be selected in the software for the cooling calculation. The ejection temperature of the molding must also be specified, which lies between the melt and mold surface temperatures. Polypropylene (PP) is employed as the part material and steel P20 is used for the part-forming components of molds. The material and geometric parameters applied in our tests are listed in Table 2 and 3. Water is selected as the coolant and its temperature is assigned as 25°C. In our simulations, the analysis sequence is set as filling, cooling and flowing. The last step, flowing, includes one additional filling phase and packing phase.

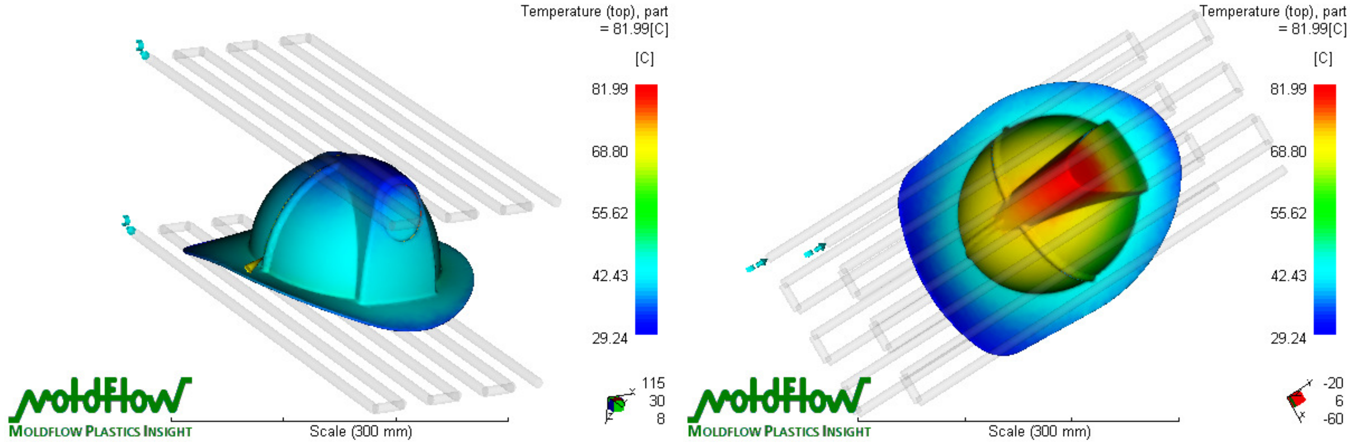
Table 3: Geometry Properties of Parts

	Helmet	Cell Phone
Dimension $[mm]$	$[229.8, 316.6, 157.0]$	$[219.4, 45.76, 69.68]$
Thickness $[mm]$	2.500	2.000
Volume $[mm^3]$	2.540×10^5	4.946×10^4
Area $[mm^2]$	2.008×10^5	5.723×10^4

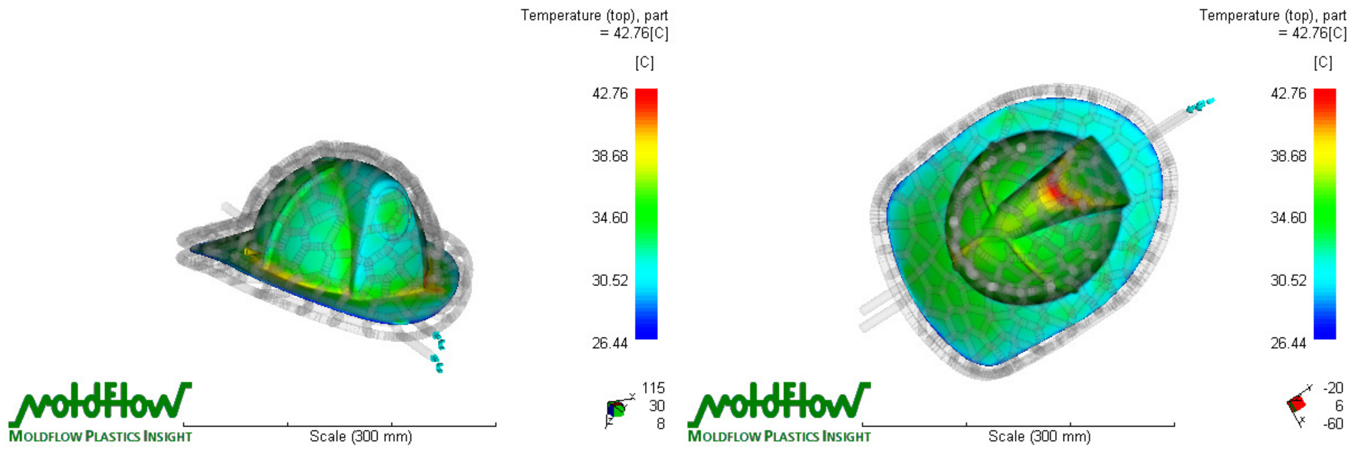
Three aspects of the physical properties are checked in the simulations. Cooling times are evaluated to show the time taken for a part freezing to the ejection temperature. The temperature distribution are computed on the mold surface to detect the localized hot or cold spots and the temperature variation. The average temperatures during the whole molding procedure are visualized by the color maps. The results of volumetric shrinkage simulation are also provided to predict the product quality, where the volumetric shrinkage is expected to be uniform across the whole part to reduce warpage. Moreover, sink marks and voids may also be resulted at the regions with high local shrinkage. The results of volumetric shrinkage are calculated at the end of packing phrase. From these three aspects of physical property analysis, the results demonstrate the advantage of our technique for generating conformal cooling channels, which shorten the cooling time and improve the part quality by providing a more uniform shrinkage.

5.1 Case study I: Helmet

In our first case study, the molding of a toy helmet made by ABS is simulated (see Fig.6 for the model), and the mold tool is machined from steel P20. According to industrial experiences, the cycle time $t_{cycle} = 20s$ and the channel diameter $D = 10mm$ are selected. After choosing $l_m = 12.7mm$

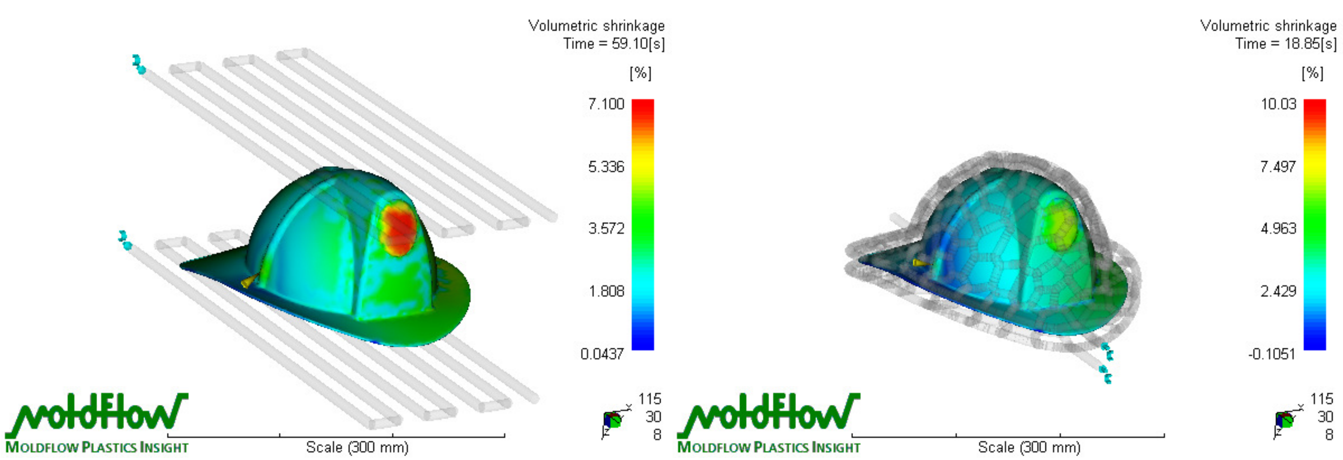


(a) Conventional channel design



(b) Channels generated by our approach

Figure 8: Color maps for displaying the average temperature on mold surfaces during the whole cooling cycle.



(a) Conventional channel design (b) Channels generated by our approach

Figure 9: Color maps for displaying volumetric shrinkages at the end of the simulation.

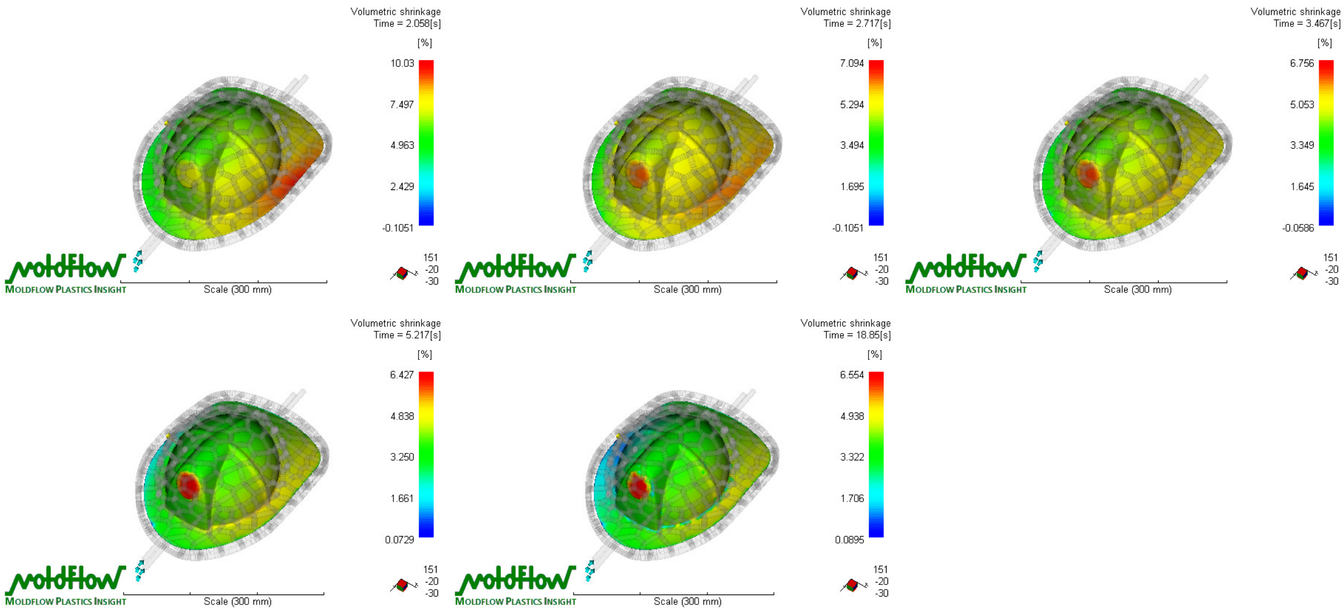


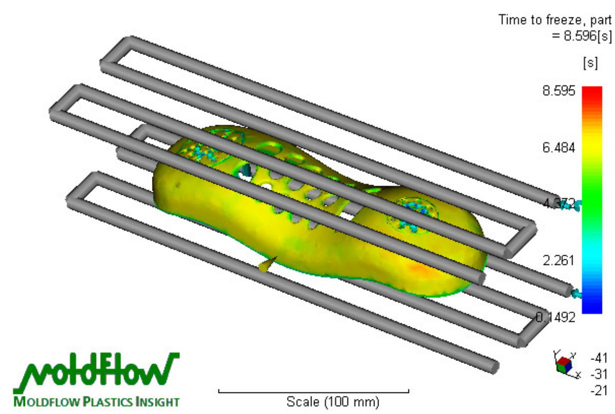
Figure 10: Volumetric shrinkage of plastic part at different time during the packing phase by using the cooling channels generated by our approach.

Figure 11: Case Study II: A cell phone model shown in two views.

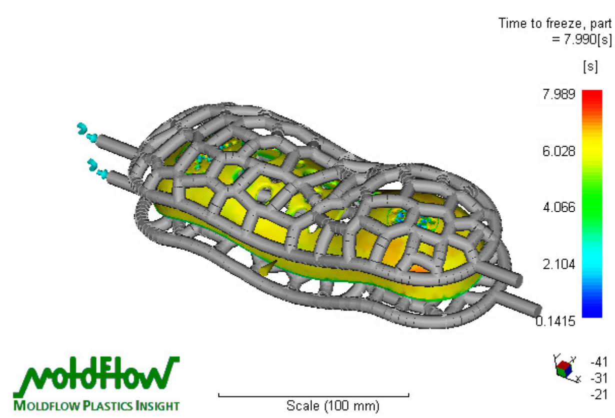
by Eq.(3), we first estimate the value of W from Eq.(2) as $W = 30.5mm$ and then refine its value to $W = 29.8mm$ by Eq.(1). Lastly, the conformal cooling channels can generated by the algorithm presented in Section 3.

The cooling efficiency of this new type of cooling circuit is compared with the conventional straight channels which use the same pitch distance W and the same diameter D. Both simulations adopts the same coolant – water at 25°C and with Reynold number $Re = 10^5$. From Figs.7 and 8, it is not difficult to find that the heat is removed from the plastic material much faster and more uniformly when using the cooling channels generated by our method. First, the cooling time (time to freeze) has been shortened by more than 26%. Next, the average temperature distribution of the plastic/mold interface demonstrates a more uniform distribution than the conventional cooling channel design. In particular, with the aid of the conformal CVD channles, a fairly little temperature difference is shown, i.e. within the range from 26.44°C to 42.76°C. On the contrary, a great temperature variation, from 29.24°C to 81.99°C, takes place in the case with conventional design. Moreover, we notice that the highest temperature in the whole analysis sequence is reduced more than 47%.

A noticeable instance shown in Fig.9 is that a slightly

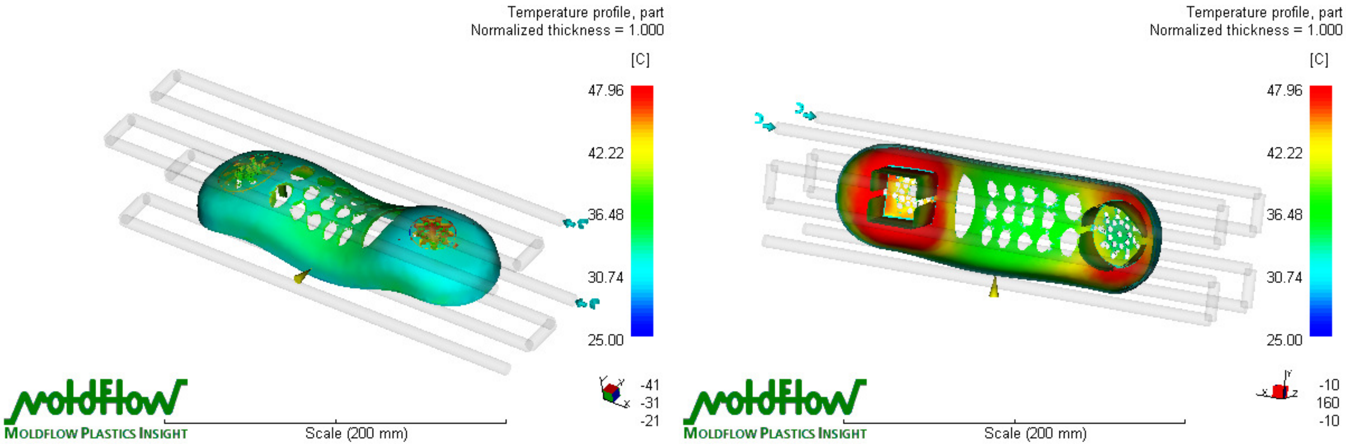


(a) Conventional channel design: 8.596 sec.

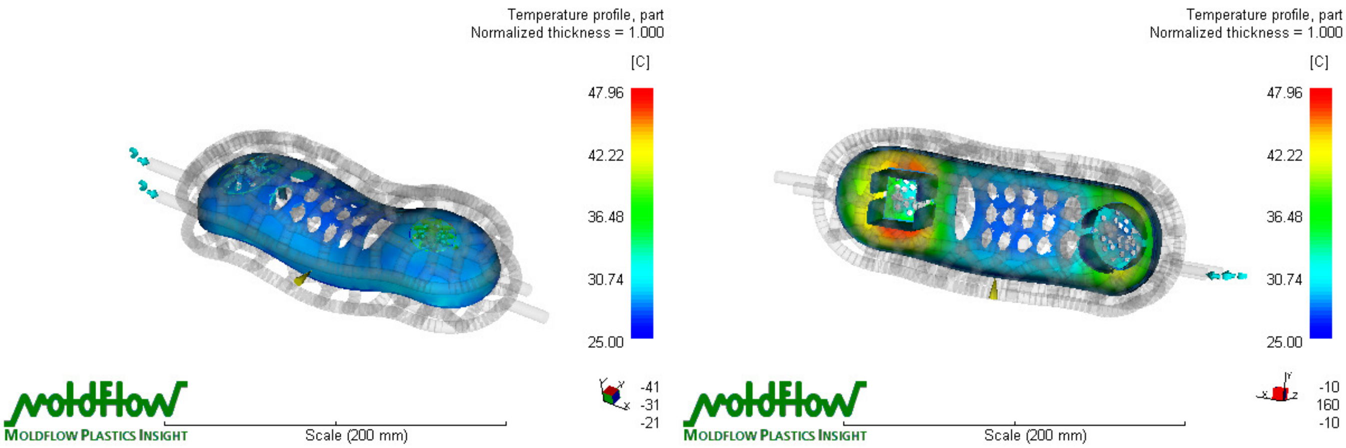


(b) Channels generated by our approach: 7.989 sec.

Figure 12: Color maps for displaying the time of plastic part freezing to the ejection temperature.



(a) Conventional channel design: the temperatures are distributed in the range between 25.00°C and 55.04°C



(b) Channels generated by our approach: the temperatures are distributed in the range between 25.00°C and 47.96°C

Figure 13: Compare temperature profiles in the same range: [25.00°C, 47.96°C].

higher percentage of volumetric shrinkage is given by the conformal cooling channels generated by our approach. This however cannot be explained as that the conventional design solves the part distortion problem better. As a result of the rapid conformal cooling, a high shrinkage happens at the very beginning of packing phase, i.e. the first 2.058 seconds of a 18.85 seconds period as described in Fig.10. After that, the volumetric shrinkage quickly tends to lower and uniform. Moreover, the volumetric shrinkages shown on the simulation using conformal cooling channels are distributed more uniformly (see Fig.9). From these aspects, the mold using conformal cooling channels produces plastic parts with better quality.

5.2 Case study II: Cell-phone

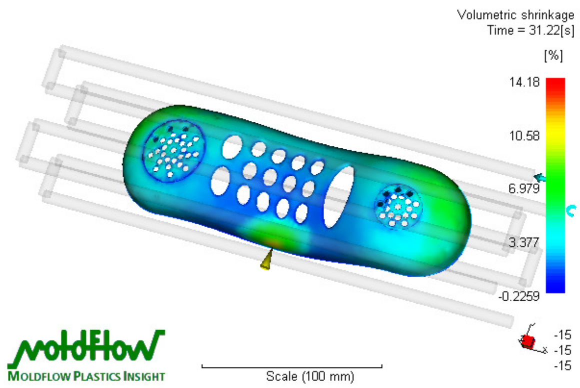
In the second example, a cell phone model as shown in Fig.11 is studied. When setting the cycle time t_{cycle} to $15s$ and the channel diameter D to $8mm$, we can approximate $l_m = 11.0mm$ and $W = 21.4mm$ (obtained by iterating from an initial value $W = 22.2mm$). Accordingly, Fig.12(b) gives the conformal cooling channels generated by our method, which shortens the cooling time comparing to the conventional channels shown in Fig.12(a). With the help of our design method, the mold surface temperature is fairly uniform across the part, with an average temperature about 36°C. To demonstrate the temperature uniformity, the color map of temperature distribution on the mold surface is normalized into the same range between 25.00°C and 47.96°C in Fig.13. This provides a clear evidence that conformal channels give better temperature uniformity on the both sides of a model even if it have very complex geometry (e.g., the bottom of cell-phone). Fig.14 claims the volumetric shrinkage results of two types of cooling channels. The part with channels generated by our method gains slightly less shrinkage than the conventional cooling channels.

6 Discussion

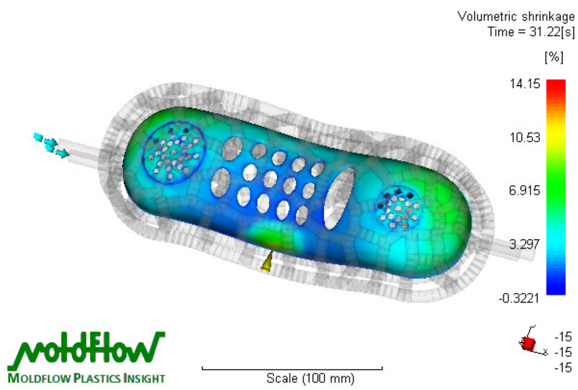
Several practical issues about using the conformal cooling circuit in rapid tooling are discussed in this section.

6.1 Injection cycle

The method proposed in this paper can generate the conformal cooling channels automatically after selecting the type of coolants (e.g., water), the diameter of channels D and the in-

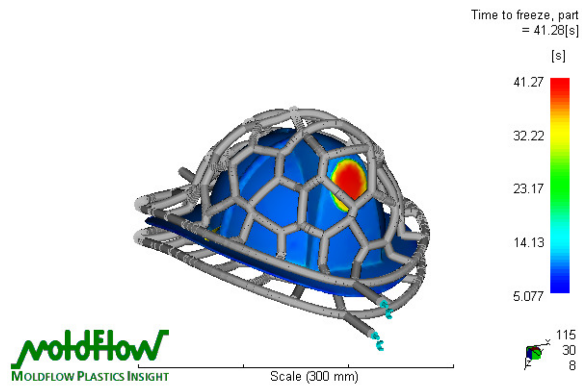


(a) Conventional channel design: 14.18%

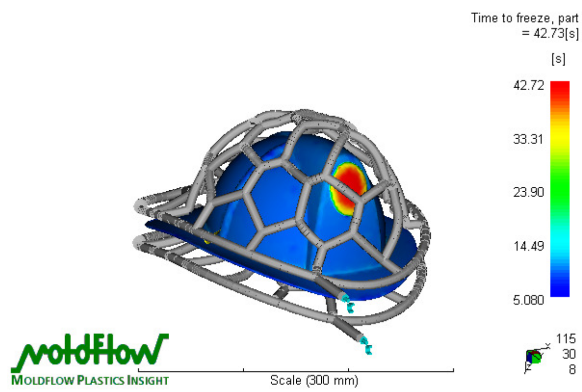


(b) Channels generated by our approach: 14.15%

Figure 14: Volumetric shrinkage



(a) Freezing time 41.28s when using $t_{cycle} = 40s$



(b) Freezing time 42.73s when using $t_{cycle} = 50s$

Figure 15: Fine-tuning the cooling channels by adjusting the input injection cycle time of our algorithm.

jection cycle time t_{cycle}. Ideally, the freezing time of a plastic part is expected to be less than the injection cycle time, which however cannot be guaranteed when users set the value of t_{cycle} at the beginning of channel design. Therefore, an iterative optimization procedure is needed to fine-tune the cooling channels by adjusting the value of t_{cycle}.

Using the toy helmet model shown in case study I as an example, the freezing time resulting from the simulation is 36.41s (see Fig.7(b)). It is longer than the estimated injection cycle time $t_{cycle} = 20s$ that is used to generate the conformal cooling channels. Therefore, we choose a larger t_{cycle} – e.g., 40s to generate a new set of cooling channels (as shown in Fig.15(a)), which shows 41.28s to freeze in the simulation. This time is still slightly greater than t_{cycle}. We further enlarge t_{cycle} to 50s. As a result, the newly generated conformal cooling channels give the freezing time, 42.73s, less than t_{cycle} (see Fig.15(a)). The cooling system will present better performance after this fine-tuning.

6.2 Coolant

Another problem of the current pattern of conformal cooling channels has many branches for the flow of coolants inside, which slow down the transmission of coolants. When using an input coolant with the Reynold number $Re = 10^5$ (i.e., a turbulent flow), the simulations give very small value of Re in the channel of cooling circuit. For example, as shown in Fig.16, the Reynold number for the Helmet example is $Re = 110.9$, which is laminar flow. In order to let the cooling channel fully filled with coolant even if they have 'U'-shape or 'S'-shape, a check-valve needs to be installed on the exit of a cooling circuit.

The speed of coolant at the entry of the cooling system is supplied by a pump, the size of which can be determined by the required supplying speed of coolant. The flow rate at the entrance can be easily calculated if the Reynold number Re, the viscosity of fluid and the dimension of the channel have been selected by user as design parameters (ref. [23]). Thus, the pump can be selected. Usually there are several other practical issues need to be considered for the selection of pump, which however is beyond the scope of this paper.

In the other aspect, the slow transmission of coolants actually provides a slow heat transfer. Although it has a relative slower heat transfer, the cooling circuit generated by our algorithm still outperforms the conventional cooling circuit. On the contrary, the performance of the cooling channels can be further enhanced if we can change the pattern of cooling circuit to speed up the flow of coolants inside. This is a near future work of our research.

6.3 Pressure resistance

During the injection procedure, clamp force should applied (see Fig.17 for an analysis – with 164.628 at the peak). "*The Clamp force result is a time series result generated from a midplane, fusion, and 3D flow analysis, and shows the force of the mold-clamp over time.*" (by the explanation from MoldFlow [22]). The conformal cooling channels developed in this approach are usually fabricated by the 3D additive manufacturing method (e.g., *Laser Metal Sintering* (LMS) or rapid soft tooling [24, 25]). However, when very huge clamp forces are applied, whether the stiffness of the mold fabricated by LMS (or rapid soft tooling) is strong enough needs to be further studied. We consider this as another possible research of our work.

The stiffness of mold with conformal cooling channels can be enhanced by using a 'sandwich' like design. As illustrated by Fig.18, it is possible to make the mold have stronger stiffness by putting the relative soft core containing conformal channels into a hard crust (e.g., steel). The performance of such design is another work that will be conducted in our future research.

7 Conclusion

Given a model of plastic part to be fabricated by rapid tooling, we present an automatic method for designing conformal cooling circuits. The technical contribution of our approach is a new algorithm for designing the conformal cooling circuit and the method to determine the input parameters for geometric computation according to the conformal cooling studies. Comparing to prior methods, our approach offers the advantages in automatic generation and producing the cooling channels conformal to the shape of products. The results from simulations are quite encouraging, in which the cooling circuits constructed by our method can effectively reduce the time of cooling and control the uniformity of temperature and volumetric shrinkage.

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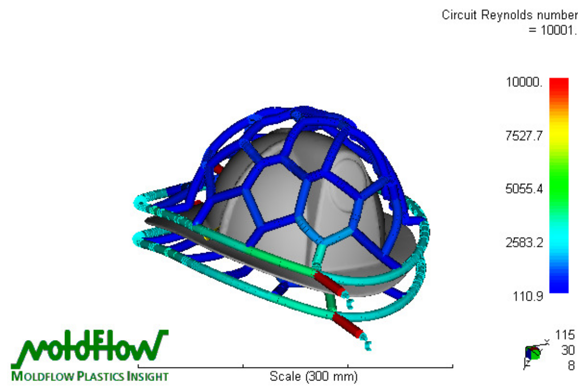
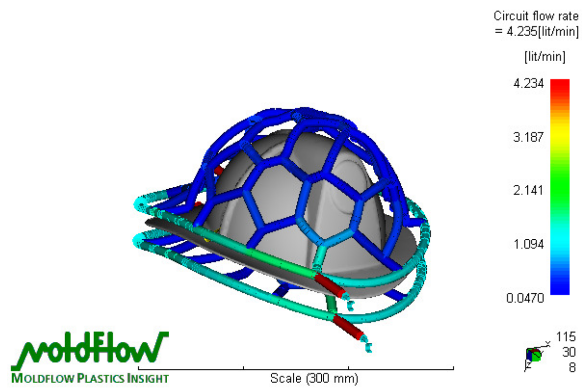


(a) Distribution of Reynold number *Re*



(b) Distribution of flow rate

Figure 16: Study about the flow in the cooling channel, where the input is turbulent flow ($Re = 10^5$) and the flow become laminar in the cooling channel.

References

[1] E. Sachs, E. Wylonis, S. Allen, M. Cima, H. Guo, Production of injection molding tooling with conformal cooling channels using the three dimensional printing process, Polymer Engineering and Science 40 (5) (2000) 1232–1247.

[2] X. Xu, E. Sachs, S. Allen, The design of conformal cooling channels in injection molding tooling, Polymer Engineering and Science 41 (7) (2001) 1265–1279.

[3] A. B. M. Saifullah, S. H. Masood, Finite element thermal analysis of conformal cooling channels in injection moulding, in: Australasian Congress on Applied Mechanics, Brisbane, Australia, 2007.

[4] K. M. Au, K. M. Yu, A scaffolding architecture for conformal cooling design in rapid plastic injection moulding, The International Journal of Advanced Manufacturing Technology 34 (2007) 496–515.

[5] X. Xu, E. Sachs, Rapid thermal cycling with low thermal inertia tools, Polymer Engineering and Science 49 (2) (2009) 305–316.

[6] H. S. Park, N. H. Pham, Design of conformal cooling channels for an automotive part, International Journal of Automotive Technology 10 (1) (2009) 87–93.

[7] C. L. Li, A feature-based approach to injection mould cooling system design, Computer-Aided Design 33 (14) (2001) 1073–1090.

[8] S. Liu, C. C. L. Wang, Fast intersection-free offset surface generation from freeform models with triangular meshes, IEEE Transactions on Automation Science and Engineering 8 (2011) to appear.

[9] S. Yoo, D. F. Walczyk, A preliminary study of sealing and heat transfer performance of conformal channels and cooling fins

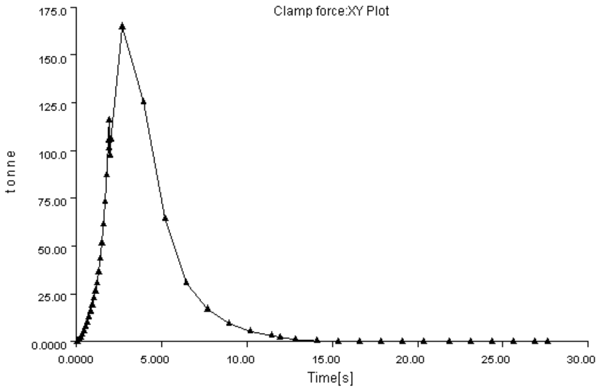


Figure 17: Plot of clamp force for the Helmet example shown in Fig.15(b).

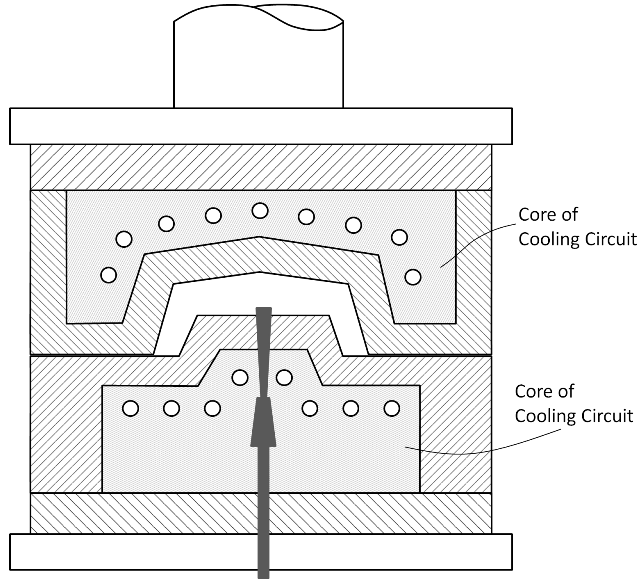


Figure 18: Conceptual design of mold by using the cores with conformal cooling channels, where the conformal channels fabricated by LMS are surrounded by steel shells to enhance the stiffness.

in laminated tooling, Journal of Manufacturing Science and Engineering 129 (2) (2007) 388 (12 pages).

[10] D. E. Dimla, M. Camilotto, F. Miani, Design and optimization of conformal cooling channels in injection moulding tools, Journal of Material Processing Technology 164-165 (2005) 1294–1300.

[11] J. C. Ferreira, A. Mateus, Studies of rapid soft tooling with conformal cooling channels for plastic injection moulding, Journal of Material Processing Technology 142 (2003) 508–516.

[12] Y. F. Sun, K. S. Lee, A. Y. C. Nee, The application of u-shape milled grooves for cooling of injection moulds, IMechE Proceedings Part B, Journal of Engineering Manufacture 216 (2002) 1561–1573.

[13] J. R. Rossignac, A. A. G. Requicha, Offsetting operations in solid modelling, Comput. Aided Geom. Des. 3 (2) (1986) 129–148.

[14] S. Lloyd, Least squares quantization in PCM, IEEE Transactions on Information Theory 28 (2) (1982) 129 – 137.

[15] S. Valette, J. M. Chassery, Approximated centroidal voronoi diagrams for uniform polygonal mesh coarsening, Computer Graphics Forum 23 (3) (2004) 381–389.

[16] S. Valette, J. M. Chassery, R. Prost, Generic remeshing of 3d triangular meshes with metric-dependent discrete voronoi diagrams, IEEE Transactions on Visualization and Computer Graphics 14 (2) (2008) 369–381.

[17] C. C. L. Wang, CyberTape: an interactive measurement tool on polyhedral surface, Computers & Graphics 28 (5) (2004) 731–745.

[18] X. Zhang, Y. J. Kim, D. Manocha, Reliable sweeps, in: Proceedings of 2009 SIAM/ACM Joint Conference on Geometric and Physical Modeling, 2009, pp. 373–378.

[19] C. Moenning, N. A. Dodgson, Fast marching farthest point sampling for point clouds and implicit surfaces, Tech. rep., University of Cambridge (UCAM-CL-TR-565).

[20] H. Rees, Mold Engineering, 2nd Edition, Hanser Gardner Publications, 2002.

[21] J. Shoemaker, Moldflow Design Guide: a Rresource for Plastic Engineers, Hanser Gardner Publications, 2006.

[22] Autodesk, Mold Flow Insight.

[23] P. K. Kundu, I. M. Cohen, Fluid Mechanics (Fourth Edition), Elsevier, 2008.

[24] T. Yoneyama, H. Kagawa, Fabrication of cooling channels in the injection molding by laser metal sintering, International Journal of Automation Technology 2 (3) (2008) 162–167.

[25] J. C. Ferreira, A. Mateus, Studies of rapid soft tooling with conformal cooling channels for plastic injection moulding, Journal of Materials Processing Technology 142 (2) (2003) 508–516.