International Journal of Integrated Engineering: Special issue 2018: Mechanical Engineering, Vol. 10 No. 5 (2018) p. 156-163
© Penerbit UTHM
DOI: https://doi.org/10.30880/ijie.2018.10.05.023

The Thermal Effect of Variate Cross-Sectional Profile on Conformal Cooling Channels in Plastic Injection Moulding

Md Saidin Wahab[1], Azli Amin Ahmad Raus[2], Irwan Amir[2], Aqeel Ahmed[3], Khairu Kamarudin[4,*]

[1]Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Batu Pahat, 86400, MALAYSIA.
[2]Centre for Instructor & Advanced Skill Training (CIAST), Jalan Petani 19/1 Seksyen 19, Shah Alam, 40900, MALAYSIA.
[3]Mehran UET SZAB Campus Khairpur Mir's, Pakistan.
[4]Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Pagoh EDU Hub, KM 1, Jalan Panchor, Panchor 84600, MALAYSIA.

Received 1 August 2018; Accepted 13 August 2018; Available online 30 October 2018

Abstract: Cooling system is an important role in designing a productive plastic injection moulding (PIM). The selection of geometry and layout for plastic injection moulding cooling channels strongly influences the cooling performance such as cooling time and thermal distribution that leads to shrinkage and warpage. This paper presents the study to determine the best cooling channel layout and cross-sectional profile which include circular straight drilled cooling channels, circular conformal cooling channels, square shape conformal cooling channels, elliptical conformal cooling channels and diamond conformal cooling channels. The cooling time and thermal distribution were simulated by Moldflow Insight (MFI) software. Results are presented based on ejection time and temperature variation by using transient analysis in MFI. The results found the best cross-sectional of cooling channels indicated by square shape conformal cooling channels, compare to others due to the shortest cooling time that recorded from simulation. The conformal cooling channel layout also resulted greater thermal distribution compared to straight drilled cooling channel design.

Keywords: Conformal cooling channels, temperature distribution, cooling time

1. Introduction

Conventionally straight drilled cooling channels is the most famous method to dissipate the heat from PIM process. The heat source from injected molten plastic was transferred by conduction process through mould insert and dissipated away by convection process through coolant flow in the cooling channels. The straight drilled cooling channels in simple shapes such round profile is fabricated by drilling straight line holes. These conventional cooling channel will lead to non-uniform mould cooling that will increase the cooling time and lead to the imperfection of the molded part such warpage, sink mark and differential shrinkage [1–3] The performance of cooling channels system, in term of heat dissipation rate was significantly affect by the design configuration of cooling system itself [4]. Time and cost are the most important relation in PIM process. The longer time to complete a PIM cycle will be intricate to higher cost. Thus, the ability of cooling system design to reduce the cooling time will radically increase the productivity, hence minimize the production cost. The performance of cooling systems was narrowed by the limitation of machining process that able to produce only circular shape. The cooling path also not able to be built closer to the mould surface due to drilling process limitations. Hence, more efficient cooling system such conformal cooling channels need to explore to employ any possible cooling channels geometry. The limitation of machining process also can be fix by additive manufacturing technology which able to construct special geometry such conformal cooling channel with various cross-sectional shapes. This paper will present the selection for the best cooling channels cross-sectional profile which include circular straight drilled cooling channels, circular conformal cooling channels, square shape conformal cooling channels, elliptical conformal cooling channels and diamond conformal cooling channels.

2. Mould and Cooling Channels

2.1 Part for Study Case

For the case study, the industrial mould was adopted from previous study by Shayfull et al. [5] which consisted of two plate mould with submerged gating system for the front panel housing with dimensions of 120 mm x 80 mm x 18.75 mm and 2.5 mm thickness with a volume of 27663.64 mm3 was carefully chosen as the case study part for analysis (shown in Fig. 1). The size of selected part was able to accommodate with Sumitomo SH100A plastic injection moulding machine that available in production laboratory at Institut Kemahiran Tinggi Belia

*Corresponding author: khairu@uthm.edu.my

Negara (IKTBN) Sepang, Selangor. Acrylonitrile Butadine Styrene (ABS) Toyolac 700-314 which manufactured by Toray Industries Incorporated was selected for the injected material for this study part.

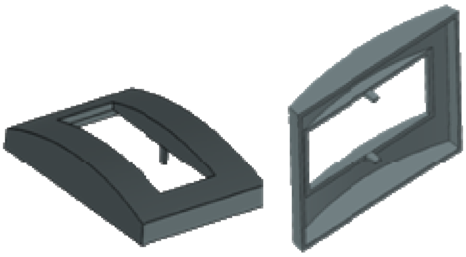


Fig. 1: Front panel housing part [2].

2.2 Design for Cross Section of Cooling Channels

Previously, researchers or mould makers were preferred to use circular cooling channels due to limitations of the drilling process. Nevertheless, other cooling channel's cross section profile such square shape also implemented in their study [2], [6–8]. Thus, the circular and square shape cooling channels resulted good performance of the cooling system depend on layout and the geometry of the cooling channel itself. Yet, else shape of cooling channel's cross section also can be considered since the ability of rapid manufacturing technology to reduce the limitation of machining process such drilling process.

In this study, four shapes have been evaluated to determine the best one for the cross-section of the cooling channels. A straight-drilled cooling channel with a circular cross-section was also included to enable performance-based comparisons between conformal cooling channels and straight-drilled ones. The aforementioned cross-sections were designed using the SolidWorks CAD software, after which the completed CAD file was imported to XT file for finite element method (FEM) analysis. The four shapes – circle, square, ellipse, and diamond (Fig. 2) – were designed to have an equivalent cross-sectional area with reference to the square cross-section. For this, the shape factor, S_c, which was defined as the ratio of the perimeter of the square cooling channel to that of another shape of cross-section, was employed. For example, the square-circle S_c was determined using equation (1) below:

$$S_c = \frac{4d}{\pi d} = \frac{4}{\pi} = 1.27 \qquad (1)$$

where;

$4d$ = perimeter of square (m)
πd = perimeter of circle (m)

Meanwhile, the square-ellipse S_c value is 1.38.

The diamond S_c was considered to be the same as that of the square.

The black-colored parts Fig. 3 denoted the area beyond the effective area of each shape. Thus, it could be deduced that a square cross-section had a 27% larger effective area as compared to its circular counterpart. Likewise, an elliptical cross-section had a 38% smaller effective area vis-a-vis its square counterpart. A larger effective area would translate into a greater area of contact with the surface, hence facilitating heat dissipation by the water (coolant) that flowed through the cooling channel. According to Altaf [9] as well as Au and Yu [10], a greater surface area of the cooling channels would increase the rate of heat dissipation and this, enable uniform heat distribution during PIM.

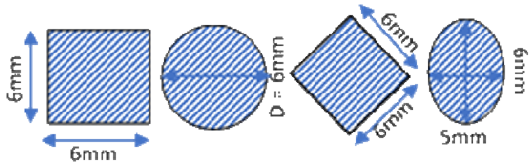


Fig. 2: Dimension for cooling channels cross-sectional profiles.

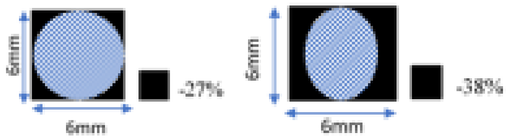


Fig. 3: Circular and elliptical cross-sectional area of shape of cooling channels.

3. Simulation Study

Further step after designing the various types of cooling channels cross-sectional profile is analyses the cooling time that conducted by Moldflow Insight (MFI) software. Different cross-sectional have been designed with SolidWorks CAD software and the completed CAD file was imported to XT file for finite element method (FEM) analysis. For the parameters setting, ABS Toyolac 700-314 that manufactured by Toray Industries Incorporated was selected as injected material. The processing parameter for this ABS Toyolac 700-314 was following the recommendation from the manufacturer which can be refer in MFI database are shown in Table 1. For this stage, the simulation was completed by two main steps only, that Fill Analysis and Cool (FEM) Transient Analysis. These two steps were adequate to determine the best cooling time that able to acquire amongst four type of cooling channels design.

This analysis purpose is to determine the shortest cooling time which figured by time to reach ejection temperature part that performed amongst presented cross-sectional profile. The shortest cooling time was selected as the best general cross-sectional profile. Moreover, the thermal analysis by using finite element analysis was carried out with MFI software to find out which cooling design configuration gives the best temperature distribution and ejection time. The acquired cooling time must comply with an accepted temperature distribution to make sure the best quality for the injected part. The centerline for cooling channel profile was benchmarked from previous study as shown Fig. 4.

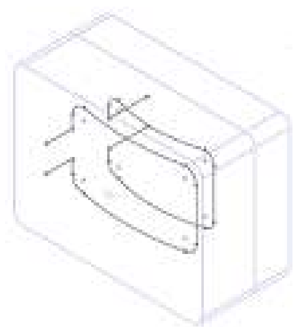


Fig. 4: Main path profile line for conformal cooling channel design

Table 1: Parameter setting for cooling time simulation for general cross-sectional profiles.

Processing parameters	**Values**
Mould surface temperature,	40°C
Melt temperature	240°C
Ejection temperature	85°C
Coolant temperature	25°C

4. Results and Discussions

4.1 Cooling Time Analysis

The ejection time was estimated time of the part to cooled down from melting temperature to the temperature that lower than the ejection temperature of plastic material. For this case, the ejection time significantly affect the cooling time for PIM process. The result of cooling time for all cross-sectional shape was shown in Table 2 which demonstrate the relationship between time to reach ejection temperature part (ejection time) to the different cross-sectional design of cooling channels. From Table 2, the circular straight drilled cooling channel recorded the highest value of ejection time. The value from circular straight drilled cooling channel was a benchmarked value to compare with others variate cross-section cooling channel profiles. For the percentage improvement, the square conformal cooling channels indicate the highest percentage of 61.03% with 9.12 s ejection time. Second lowest ejection time was recorded by circular conformal cooling channels of 9.34 s (61.03%), followed by elliptical conformal cooling channels with 10.40 s (55.56%) and lastly diamond conformal cooling channels of 11.97 s (48.85%).

Table 2: Percentage of improvement for time to ejection time compare to circular straight drilled cooling channels.

Variate cross-sectional shape	Time to reach ejection temperature part (sec)	Percentage improvement (%)
Circular straight drilled cooling	23.40	0.00
Circular conformal cooling	9.34	60.09
Square conformal cooling	9.12	61.03
Elliptical conformal cooling	10.40	55.56
Diamond conformal cooling	11.97	48.85

As mentioned, the shortest cooling time was observed in square conformal cooling channels, followed by circular conformal, elliptical conformal, diamond conformal, and circular straight-drilled cooling channels. Also, two main types of comparisons are discussed here: (1) layout comparison (i.e. straight versus conformal cooling channels) and (2), cross-sectional comparisons between the conformal cooling channels. As per the outcomes of the cooling analysis, conformal cooling channels enabled faster heat dissipation as compared to straight ones.

One aspect that could explain the better performance of the conformal cooling channels vis-a-vis the straight cooling channels is shown in Fig. 5 and Fig. 6. Fig. 5 shows the cross-sectional view of the mould insert, molten plastic, and straight cooling channels. During cooling, heat from the molten plastic would flow through the mould insert by conduction, and then get dissipated through the water in the cooling channel by convection. The layout of the cooling channels and their distance to the molten plastic had a significant effect on the rate of heat transfer, whereby a shorter distance resulted in a shorter cooling time. Also, a consistent distance would give rise to better thermal uniformity, which in turn had an influence on the quality of the injected part. On another note, the conformal cooling channels in Fig. 6 were closer and equidistant, hence resulting in a shorter cooling time and more uniform thermal distribution. These would subsequently improve the quality and productivity of the PIM process.

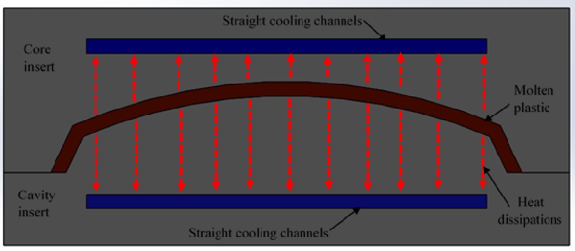


Fig. 5: Heat dissipation in straight cooling channels

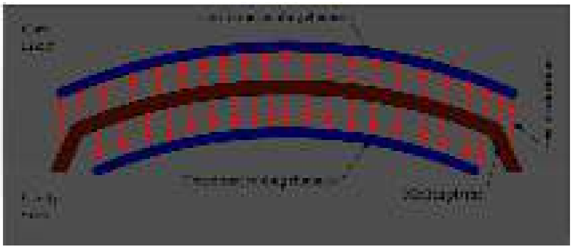
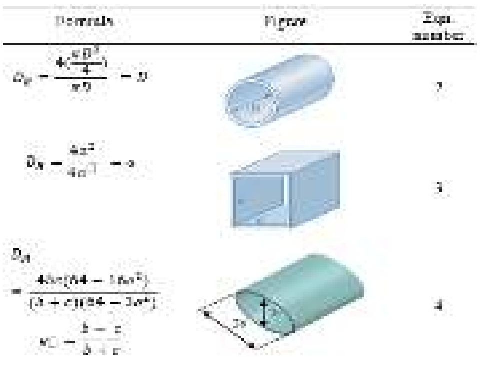


Fig. 6: Heat dissipation in conformal cooling channels

In addition, the geometries of the profiles had an influence on the cooling time as well. The former variable comprised the perimeter and total area of each cooling profile. Table 3 shows the perimeters and total areas of the cross-sections of the profiles which have been calculated using equations (2) to (4). The square and diamond cooling chambers had the highest aforementioned values, which were 24 mm and 36 mm^2 respectively. This was followed by circular (18.85 mm and 28.27 mm^2 respectively) and elliptical cooling chambers (17.36 mm and 23.70 mm^2 respectively).

Table 3: Formulae for hydraulic diameters of each cross-section shape of conformal cooling channels



With reference to Table 4, the square, circular, and diamond profiles had the same D_H, although the perimeters and total areas of the square and diamond profiles were different from those of the circular and elliptical profiles. Thus, a larger surface area resulted in an increase in heat extraction from the molten plastic. Even though a square and diamond had the same perimeter and area, the geometry of the latter provided better surface uniformity vis-a-vis the latter and hence, better thermal dissipation from the molten plastic to the coolant in the cooling channels. Evidently, the ability of the circular conformal cooling channels to build closer to the part resulted in better thermal dissipation in the mould, hence making them superior to circular straight cooling channels. These outcomes were in agreement with those of Hassan et al. [11], whereby the shortest cooling time was seen in the cooling channels with the longest perimeters. Likewise, Altaf et al. [12] reported that the cooling time was affected by the D_H and perimeters of the cooling channels.

Table 4: Hydraulic diameters, DH of each general cross-section of cooling channel

Cross-sectional shape	**Total area (mm^2)**	**Perimeter (mm)**	**D_H (mm)**
Square	36.00	24.00	6.00
Circular (conformal)	28.27	18.85	6.00
Circular (straight drilled)	28.27	18.85	6.00
Diamond	36.00	24.00	6.00
Elliptical	23.70	17.36	5.44

The performance of the cooling channels is shown Fig. 7. Four types (shapes) of cross-sectional profiles were arranged so that the centers of the profiles were in a line since the conformal cooling channels were built with respect to the same reference center (Fig. 7). Owing to the fact that the square cooling channels followed the contour of the surface of the mould, the depth of heat conducted through the mould insert was shorter and more uniform. On the contrary, curved shapes like circles and ellipses were of varying distances from the surface of the mould, thereby making the heat conduction process slower and less uniform. Hence, the quicker heat flow in the square cooling channels inevitably led to a more rapid cooling of the part.

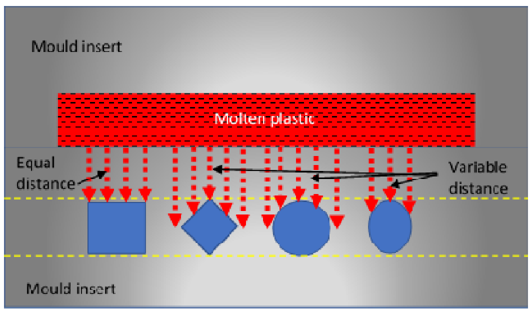
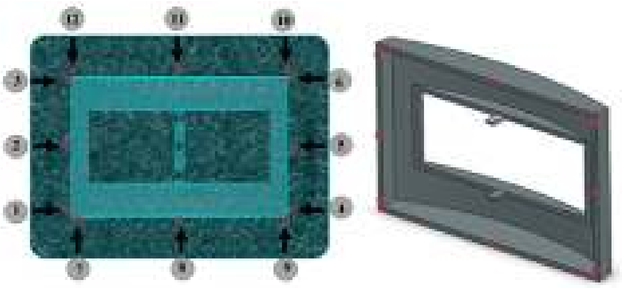


Fig. 7: Distances of heat dissipation in different cross-sections of cooling channels

The acquired data from this simulation analysis shows the conformal cooling channels influenced very significant improvement to the conventional straight cooling channels in terms of productivity and quality. However, at this stage, this simulation analysis is not considering the quality of injected part in term of warpage and shrinkage. The simulations were focused on "scanning" stage to determine which cross-sectional perform the best ejection time before proceeding with next design stage that not discussed in this paper.

4.2 Temperature Analysis

The ability to achieve uniform temperature distribution in the PIM also a compulsory feature for a mould's cooling system. It arises together with ability to reduce the cooling time to minimize the undesirable defect. Fig. 8 shows the selected points that faced the thin wall region for the front panel part to demonstrate the temperature variations which potential to lead the shrinkage and warpage. Each coordinate of the nodes was positioned almost same for all models to maximize the accuracy of temperature distribution plots.



(a) (b)

Fig 8-(a): The nodes position on the surface of core insert; (b) The position of nodes that faced the edge of thin wall at the front panel part

On the other hand, Fig. 9 to Fig. 12 was plotted to show the comparison of temperature different between each cooling channels type by selected nodes. The data for temperature different was gather from the MFI transient simulation which use to plot the different temperature between maximum and minimum value against the time. Overall trend indicated the highest temperature different was resulted from the circular straight cooling channels. At the same time the circular straight cooling channels shows the longest time compare to others. On the contrary, the lowest temperature different shows by circular conformal cooling channels, however, the shortest time was performed by square conformal cooling channels. From this result, the circular straight cooling channels show the lowest performance due higher temperature variations and longest cooling time which potential to lead quality issue. On other hand, almost all conformal cooling channels show better temperature variations compare to straight cooling channels. Since only small different shown in temperature different for all conformal cooling channels profiles, the square conformal cooling channels can be selected as the best profile due to shortest cooling time and acceptable temperature different.

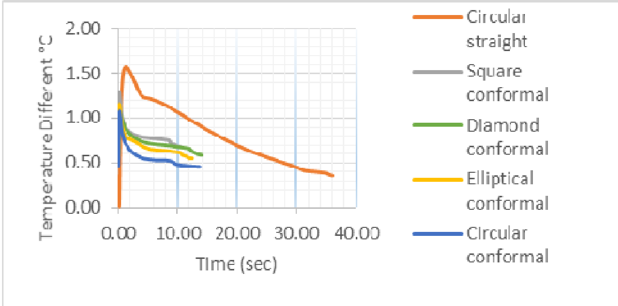


Fig. 9: Temperature different for variate cross-sectional profile for nodes 123

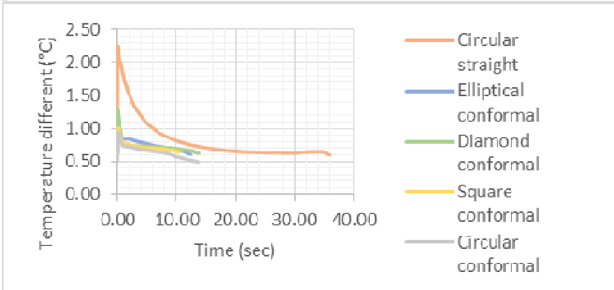


Fig. 10: Temperature different for variate cross-sectional profile for nodes 456

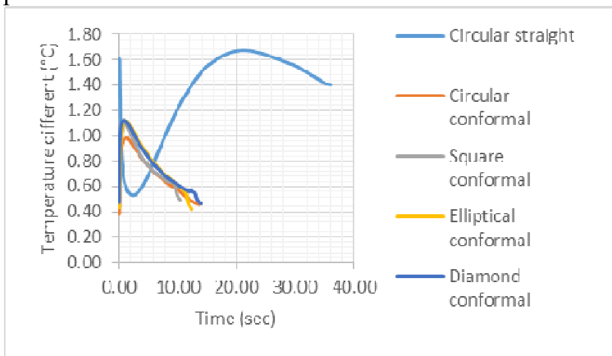


Fig. 11: Temperature different for variate cross-sectional profile for nodes 789

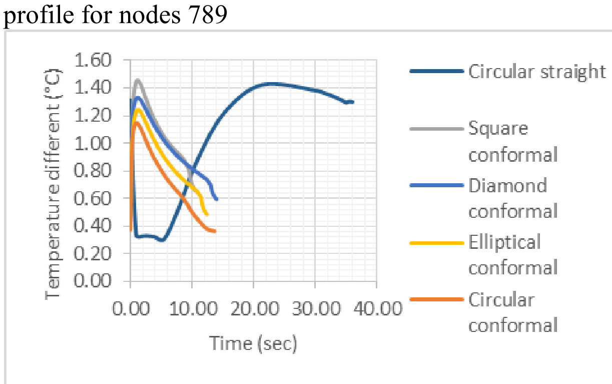


Fig. 12: Temperature different for variate cross-sectional profile for nodes 10 11 12

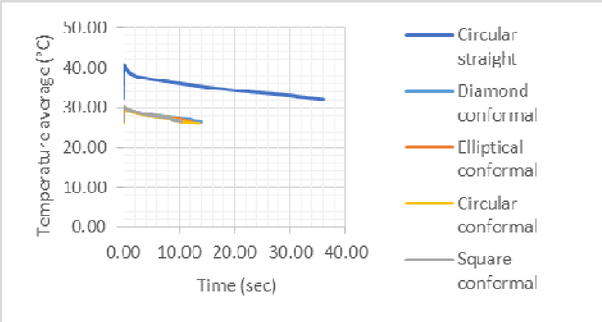


Fig. 13: Temperature average for variate cross-sectional profile for nodes 123

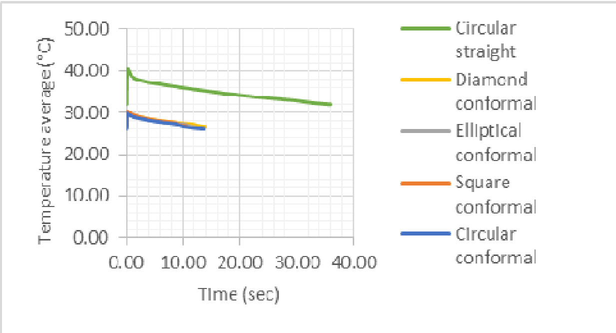


Fig. 14: Temperature average for variate cross-sectional profile for nodes 456

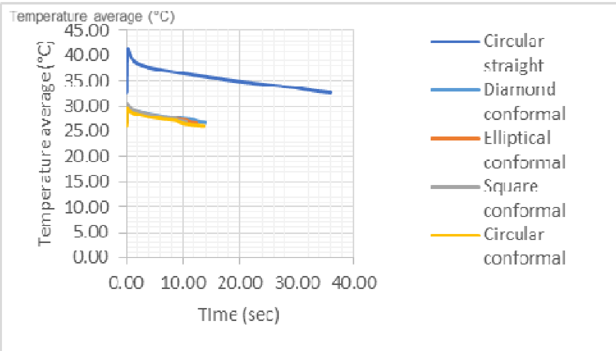


Fig. 15: Temperature average for variate cross-sectional profile for nodes 789

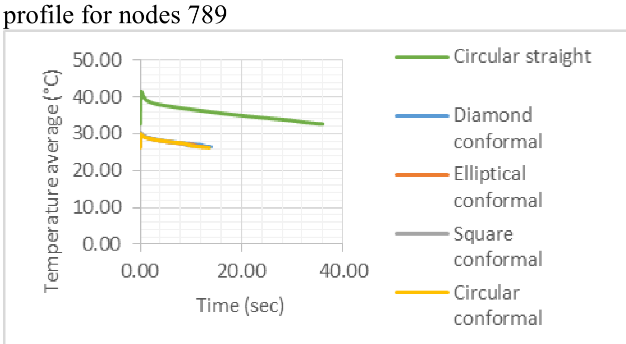


Fig. 16: Temperature average for variate cross-sectional profile for nodes 10 11 12

The average temperature against time also plotted in Fig. 13 to Fig. 16. The circular straight cooling channels shows different about 10°C compare to others conformal cooling channel profiles. This shows the heat dissipation in the mould with straight cooling channel is lower compare to the conformal cooling channels. Thus, the distance of cooling channels to the heat source (mould surface) significantly contribute to the cooling time. While, the shortest cooling time also indicate by square conformal cooling channels.

These results concurred with those of previous researchers whereby non-circular cooling channels had a better cooling performance [1], [2], [5], [13–15]. As per the data of this simulative analysis, conformal cooling channels showed highly significant improvements as compared to conventional straight ones in terms of productivity and quality. However, at this stage, the quality (i.e. warpage and shrinkage) of the injected part has not been evaluated; rather, the aim of this ‘scanning’ stage was to identify the type of cross-section that had the best ejection time. Since the square conformal cooling channels were the best-performing ones, it was selected for the enhancement of its design.

As mentioned, mould inserts with conformal cooling channel dissipated heat better than those with straight-drilled cooling channels. The ability of the conformal cooling channel to be placed closer to the surface of the moulds (which was considered to be the heat source) significantly contributed to the increase in rate of heat transfer, which translated into shorter cooling times and better quality of the injected parts.

On the contrary, the straight-drilled cooling channels could not be placed closer to the surface of the moulds owing to the limitations of subtractive machining. Thus, the performance of the moulds with straight drilled cooling channels was relatively inferior, and this had a potential effect on the quality as well as productivity of the injected parts.

As per the outcomes of both types of cooling channel layouts (i.e. conformal and straight-drilled cooling channels) this parameter had a significantly influence on the cooling time. As a side note, the performance of the cooling channels in the same path layout could be improved by increasing the area of their cross-sections (i.e. area of contact with the surface). These results agreed with those of Shayfull et al. [5], Kuo et al. [16] and Saifullah et al. [17], whereby conformal cooling channels had 40% to 65% shorter cooling times in view of their special geometries that enabled them to be placed as close as possible to the heat source. Also, the superior performance of square cooling channels was proven by Shayfull et al. [5] and Hassan et al. [11].

Overall, there were only small differences in the temperature distributions of the conformal cooling channels. Again, this finding indicated that the ability of the conformal cooling channels to (1) conform to the surface of the mould and (2) be placed closer to the heat source (i.e. the injected molten plastic) significantly increased the rate of heat dissipation. The heat from the injected molten plastic was transferred via conduction through the mould insert and dissipated via convection through the coolant which flowed in the conformal cooling channels.

5. Conclusions

This paper was discussed on the selection for the best cooling channels cross-sectional profile which include circular straight drilled cooling channels, circular conformal cooling channels, square shape conformal cooling channels and diamond conformal cooling channels. From the MFI simulation study, the best cooling channels in term of temperature performance shows by circular conformal cooling channels, follow by square conformal cooling channels, elliptical conformal cooling channels, diamond conformal cooling channels and lastly by circular straight cooling channels. However, the shortest cooling time was achieved by square conformal cooling channels. The value of temperature different and temperature average for conformal cooling channel indicate big different compare to the straight cooling channel. At the same time, variate cross-sectional profile for the conformal cooling channel not shows the obvious different in temperature variations. This verified that the layout of cooling channels for PIM could contributed major improvement for quality and productivity of PIM process. Thus, the square shape conformal cooling channels was appropriately significance selection and acceptable for the next design stage that will discussed on another paper. Even though the circular and elliptical cooling channels shows slight different performance compared to square cooling channels, the manufacturability for build both cooling channels to build by additive manufacturing method need to be consider. The manufacturability of cooling channels design was discussed on another paper. For the further design process, the square shape conformal cooling channels will be enhanced by including adds on for the geometry of cooling channels profile that able to increase the performance of PIM process.

Acknowledgments

The authors would like to express the deepest appreciation to the UTHM's Registrar Office for the funding of this paper publication.

References

[1] Y. F. Sun, K. S. Lee, and A. Y. C. Nee. Design and FEM Analysis of The Milled Groove Insert Method for Cooling of Plastic Injection Moulds, *Int. J. Adv. Manuf. Technology*, Volume 24, (2004), pp. 715–726.

[2] Z. Shayfull, S. Sharif, A. M. Zain, S. M. Nasir, and R. Mohd Saad. Improving the Quality and Productivity of Molded Parts with a New Design of Conformal Cooling Channels for the Injection Molding Process, *Advance Polymer Technology*, Volume 35, (2016), pp.1.

[3] Nasir, S. M., Ismail, K. A., Shayfull, Z., & Shuaib, N. A. Comparison Between Single and Multi Gates for Minimization of Warpage Using Taguchi Method in Injection Molding Process for ABS Material, *Trans Tech Publications*, Volume 594, (2014), pp. 842-851.

[4] A. Saifullah and S. H. Masood. Optimum Cooling Channels Design and Thermal Analysis of an Injection Moulded Plastic Part Mould, *Materials Science Forum*, Volume 561, (2007), pp. 1999–2002.

[5] Z. Shayfull, S. Sharif, A. MohdZain, R. MohdSaad, and M. A. Fairuz. Milled Groove Square Shape Conformal Cooling Channels in Injection Moulding Process, *Material Manufacturing Process*, Volume 28, (2013), pp. 884–891.

[6] X. P. Dang and H. S. Park. Design of U-Shape Milled Groove Conformal Cooling Channels for Plastic Injection Mold, *International Journal of Precision Engineering and Manufacturing*, Volume 12, (2011), pp. 73–84.

[7] Ab Kadir, M. I., Mustapa, M. S., Rosli, N. L., Yahya, M. S., Mohamad, M. A. H., & Rahim, A. K. A. The Effect of Microstructures and Hardness Characteristics of Recycling Aluminium Chip AA6061/Al Powder On Various Sintering Temperatures, *International Journal of Integrated Engineering*, Volume 10, (2018), no. 3.

[8] Ikhmal, M., Ahmad, S., Taib, H., & Chen, T. C. Effect of Sintering Temperature and AR Glass Addition towards Physical Properties of Porcelain Ceramic for Sewer Pipes Application, *International Journal of Integrated Engineering*, Volume 10, (2018), no. 3.

[9] K. Altaf, Novel Techniques for Reducing Cooling Time in Polymer Injection Moulds using Rapid Tooling Technologies, *Universiti Teknologi Petronas,* (2011).

[10] K. M. Au and K. M. Yu. A Scaffolding Architecture for Conformal Cooling Design in Rapid Plastic Injection Moulding, *International Journal of Advanced Manufacturing Technology*, Volume 34, (2007), pp. 496–515.

[11] Hassan, H., Regnier, N., Le Bot, C., & Defaye, G. 3D Study of Cooling System Effect on The Heat Transfer During Polymer Injection Molding. *International Journal of Thermal Sciences*, Volume 49, (2010), pp.161-169.

[12] K. Altaf, A. Majdi Abdul Rani, and V. R. Raghavan. Prototype Production and Experimental Analysis for Circular and Profiled Conformal Cooling Channels in Aluminium Filled Epoxy Injection Mould Tools, *Rapid Prototyping Journal*, Volume 19, (2013),pp. 220–229.

[13] X.-P. Dang and H.-S. Park. Design of U-Shape Milled Groove Conformal Cooling Channels for Plastic Injection Mold, *International Journal of Precision Engineering and Manufacturing*, Volume 12, (2011), pp. 73–84.

[14] K. Altaf, A. M. A. Rani, and V. R. Raghavan. Fabrication of circular and Profiled Conformal Cooling Channels in Aluminum Filled Epoxy Injection Mould Tools, *2011 National Postgraduate Conference - Energy and Sustainability: Exploring the Innovative Minds, NPC 2011*, Volume 1, (2011), pp. 1–4.

[15] A. B. M. Saifullah. An Investigation on Conformal Cooling in Plastic Injection Moulding, *Swinburne University of Technology*, (2011).

[16] Kuo, Chil-Chyuan, Wei-Hua Chen, Jia-Wei Zhang, Dong-An Tsai, Yu-Liang Cao, and Bo-Yu Juang. A New Method of Manufacturing a Rapid Tooling with Different Cross-Sectional Cooling Channels, *The International Journal of Advanced Manufacturing Technology*, Volume 92, (2017), pp. 3481-3487.

[17] A. B. M. Saifullah, S. H. Masood, and I. Sbarski. Thermal–Structural Analysis of Bi-Metallic Conformal Cooling for Injection Moulds, *The International Journal of Advanced Manufacturing Technology*, Volume 62, (2012), pp. 123–133.