Improvement in the Cooling Performance of Conformal Mold Cooling By Using Fin Concept

Manat Hearunyakij, Somchoke Sontikaew, and Dilok Sriprapai

Abstract**—**The Aim of this research work was to increase efficiency of conformal cooling system in plastic injection molding by using fin concept. Cooling channels of the new system were circular cross sections with fins. Effect of fin number on cooling time and cooling efficiency was investigated by using plastic flow analysis and simulation program, Moldex3D. The simulation results showed that cooling time reduced approximately by 6.5 second for the cooling channels with seven fins as compared with the cooling channels with circular cross section. The cooling efficiency in term of heat fluxincreased by 22.6 %. The addition of fins significantly increased a coolant velocity and a rate of heat transfer from molten plastic to coolant. The average temperature of cavity surface greatly reduced with increasing fin numbers in the cooling channels.

Keywords**—**Conformal cooling, Fin, Direct metal laser sintering, Plastic flow analysis

I. Introduction

PLASTIC injection molding process has been widely used in mass production of high quality plastic parts with various complex shapes. The process consists of three crucial stages which are filling stage, packing stage and cooling stage [1]. Among these three stages, the cooling stage takes about 65%-70% of each cycle time [2]. During cooling stage, heat of molten plastic was taken by cooling system until it reached ejection temperature [3]. Therefore, the cooling stage is very important to the production of plastic injection parts. Generally, the cooling system of a plastic injection mold required a straight drill hole to create coolant flow lines [4]. This kind of cooling system caused not only defects in molded parts such as warpage due to non-uniform shrinkage but also increased the cooling time [4], [5].

For cooling system design, main factors which affect cooling efficiency are:

- Diameter (Ø) and perimeter of Cooling channel
- Coolant velocity
- Distance between cavity surface to cooling channel
- Distance between cooling channels

Manat Hearunyakij is with The Department of Tool and Material Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, (manath@kmutnb.ac.th).

Somchoke Sontikaew is with The Department of Tool and Material Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, (somchoke.son@kmutt.ac.th).

Dilok Sriprapai is with The Department of Tool and Material Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, (dilok.sri@kmutt.ac.th).

From many studies, it was found that the conformal cooling can reduce cycle time by approximately 20% compared with conventional cooling [6], [7].However, method to create conformal cooling system is more complicated than that of conventional cooling system which consisted of straight drill holes [8]. For conformal cooling system, DMLS (Direct Metal Laser Sintering) technique is used to make injection mold inserts. The advantages of this technique were to create cooling channels with different cross sectional shapes such as circular, oval, rectangular, etc. Furthermore, DMLS can be used to create coolant flow line along with shape of plastic part [9].

The previous work concerning the effect of position and profile of cooling channel cross section on heat transfer rate and cooling efficiency in plastic injection mold was reported by Hamdy and Nicolas [10]. They compared cooling efficiency of circular, square and rectangular cooling channels. These cooling channels provided the same surface area but difference in perimeter. The result showed that cooling channel with the longest perimeter provided the shortest cooling time. According to research of Altaf in 2013 [11], he studied conformal cooling system by comparing circular cross section with profiled cross section. He used epoxy filled with aluminum for making injection mold. The result of this study showed that the change of cross sectional shape affected the cooling time because of the change in perimeter and hydraulic diameter. For conventional cooling system, the perimeter of cooling channel was increased by increasing diameter of the cooling channel. In this method, it was necessary to increase distance between cooling channel and cavity surface due to mold stiffness. Hence, efficiency of cooling system decreased because the distance of heat transfer from molten plastic to coolant in the cooling system increased. In order to increase heat convection efficiency, surface extension or fin has been used in electrical equipment, heat exchangers or radiators. The strategy of this technique is the increases of contact surface areas between object and fluid such as air or water.

For the heat transfer, fin concept is a technique to increase a rate of heat transfer to or from the environment by increasing heat convection. Fig. 1 and 2 illustrates typical external fins with rectangular and triangular cross section and Fig. 3 illustrates internal fins inside copper tube.

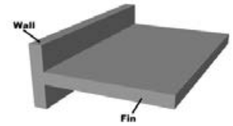


Fig.1 Typical Rectangular External Fin

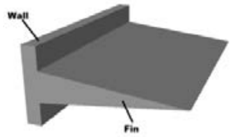


Fig.2 Typical Triangular External Fin

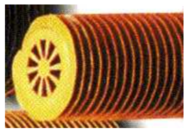


Fig. 3 Internal Fins for Copper Tube

The aim of this research was to increase cooling efficiency of conformal cooling by adding the fins in circular cross section. Cooling system design in this research was based on limitation of DMLS (Direct Metal Laser Sintering) process.

II. Theory

Energy conservation [12]

For the cooling stage of plastic injection molding, a three-dimensional, cyclic, transient heat conduction problem with convective boundary conditions on the cooling channel and mold base surfaces is involved. The heat transfer equation is governed by a three-dimensional Poisson equation,

$$\rho C_p \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \tag{1}$$

Where T is the temperature, t is the time, x, y, and z are the Cartesian coordinates, ρ is the density, C_p the specific heat, k is the thermal conductivity. Equation (1) holds for both mold base and plastic part with modification on thermal properties.

Initial condition

The initial mold temperature is assumed to be equal to the coolant temperature. The initial part temperature distribution is received from the analysis results at the end of filling (EOF) and packing (EOP) stages.

$$T(0,\bar{r}) = \begin{cases} T_c, & for\ \bar{r} \in \Omega_m \\ T_p(\bar{r}) & for\ \bar{r} \in \Omega_p \end{cases} \tag{2}$$

Boundary condition

Heat from the molten plastic part is released by the coolant flowing in cooling channel as well as the ambient air surrounding the exterior surfaces of the mold base through a heat convection mechanism. For this research, the effect of thermal radiation is disregarded. The conditions defined over the boundary surfaces and interfaces of the mold are specified as,

$$for\ t \ge 0, \quad -k_m \frac{\partial T}{\partial n} = h(T - T_0) \tag{3}$$

Where n is the normal direction of mold boundary. On the exterior surfaces of the mold base Γ_m :

$$h = h_{air}, T_0 = T_{air} \quad for\ \bar{r} \in \Gamma_m \tag{4}$$

On the cooling channel surfaces Γ_c :

$$h = h_c, T_0 = T_c \quad for\ \bar{r} \in \Gamma_c \tag{5}$$

when h_c and h_{air} are heat transfer coefficients of coolant and air

III. Methodology

Cooling system design

In this research, the study and the development of conformal cooling system focused on comparison of circular cross-sectional cooling channels with and without fins. The comparison of cooling efficiency is based on the same part model, injection condition and cooling flow lines. First, the part model was created in Rhinoceros 4.0. The part model was a square box with wall thickness of 5 mm and dimension of 100 mm × 100 mm × 25 mm as shown in Fig. 4. According to part thickness, the diameter (D) of cooling channel was 10 mm. Distance between cavity surface and cooling channel center was 10 mm. (1D) and distance between cooling channels was 15 mm. (1.5D). Sprue gate was used with 20 mm in length. The biggest and smallest diameters of the sprue gate were 4 mm and 2.5 mm.

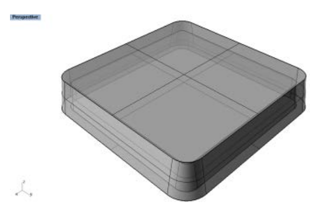


Fig. 4 Part Modeling

Pattern of cooling line was spiral as shown in Fig. 5. The spiral cooling line can be applied in injection molded parts with circular or rectangular shape as well as in the conformal cooling system.In spiral cooling system, the coolant flew from the center to the edge of the spiral pattern. The temperature of the coolant increased as it flows through the spiral channel, while the melt gradually cooled down to some degree due to heat transfer from the melt to the coolant.

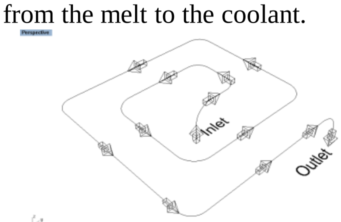


Fig. 5 Coolant flow line (Spiral Type)

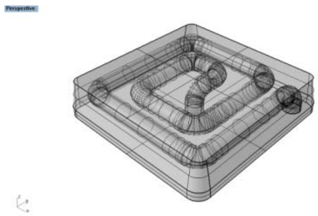


Fig. 6 Cooling system with circular cross section for mold insert core

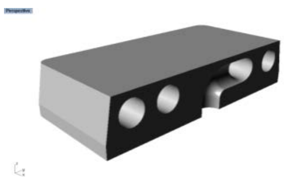


Fig. 7 Section view of mold insert core

Fin concept design

Fin concept design in this research was based on the limitation of DMLS technique. Factors to design fin were thickness [13], [14] and shape [15]. The basic shapes of the fin were triangle, trapezoid and rectangle as shown in Fig. 8.

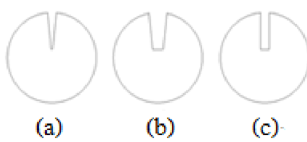


Fig. 8 Typical fin cross sections (a) Triangle, (b) Trapezoid, (c) Rectangle

The cooling channel with the triangular fins provided the largest surface areas but endpoints of the triangular fins were not strong enough to withstand a high pressure in the cooling channels. The Trapezoid fins were stronger than the triangular fins but the cooling channel with the trapezoid fins provided the least surface areas, especially when numbers of the fins increased. The rectangular fins provided more rigidity and more surface areas than those of the trapezoid fins. For these reason, the type of fin used in this research was the rectangular cross section. The thinnest wall in the vertical direction that can be created by DMLS technique was 0.5 mm [16]. In practical cooling conditions, the fins must resist a coolant pressure and a thermal stress due to the temperature changes during plastic injection. Therefore, the fin thickness used in this research was 1.0 mm. Fig. 9 shows the production of the cooling channel with the regular fins by using DMLS technique. In DMLS technique, the metal powder was melted by heat from laser beam to create a metal part layer by layer from bottom to top. Due to the laser sintering direction to produce the mold insert part, the minimum numbers of fins were three in the cooling channel.

Fig. 9 Support base creation for fins in cooling channel by DMLS

In this study, number of fins in the cooling channels increased from three to seven. Table 2 shows perimeter and cross-sectional area of the cooling channels with and without fin. When the number of fins increased, the perimeter of the cooling channels increased while the cross-sectional areas decreased.

TABLE I
PERIMETER AND CROSS SECTION AREA FOR COOLING CHANNELS

No. fins	Perimeter (mm)	Section area (mm$^{2)}$
Circular	31.41	78.53
3	56.34	63.93
4	61.48	58.68
5	67.1	54.75
6	72.66	50.88
7	76.16	46.76

Finite Element Model Preparation

The first step of finite element model preparation, 3D model of plastic part and injection mold system including cooling channels with different cross section are created in Rhinoceros 4.0 computer program. After that all of components are transformed into solid mesh model in Moldex3D R11.0. The flow chart of finite element model preparation in this research is shown in Fig. 10.

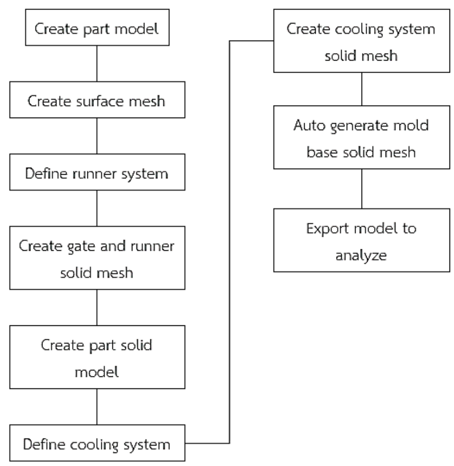


Fig. 10 Steps of model preparation

Plastic Feeding system of the part is the sprue gate. The gate position is at center of part according to schematic of part model in this research. The biggest Ø of the sprue gate is 4 mm. and the smallest Ø is 2 mm. the sprue length is 20 mm. as shown in Fig. 11 Solid mesh size of part model is approximately 0.8 mm. Type of solid mesh model is tetrahedral element.

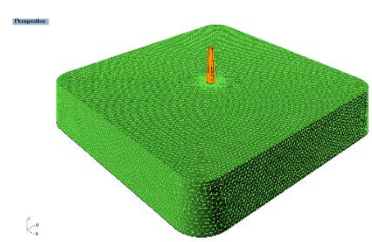


Fig. 11 Part solid mesh model and Sprue gate

For cooling system, coolant flow line was defined as spiral type as shown in Fig 5. The cross sections of cooling channel were shown in Table 2. Each of cooling channel cross sections were first created in the form of surface model and then were transformed into the form of surface mesh. Fig 13 from (a) to (e) shows solid mesh of cooling channels with fins from three to seven fins.Gaps inside the cooling channel were represented with mold base solid mesh after mold base solid mesh was created.

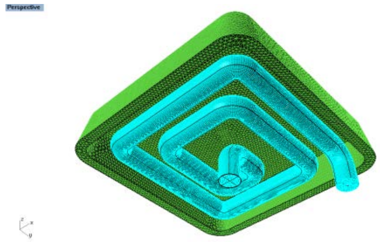
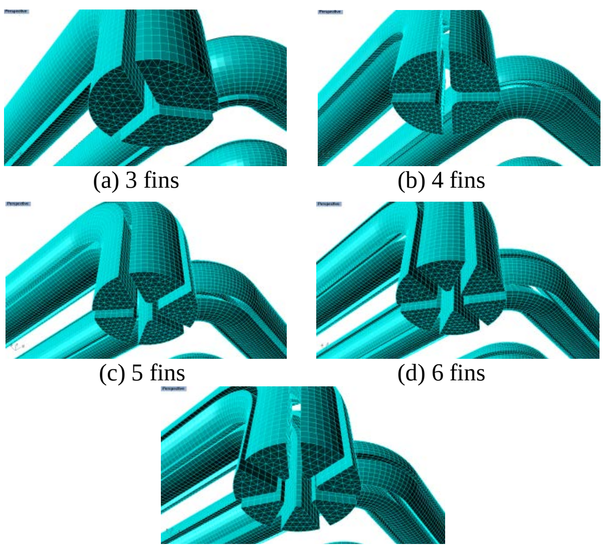


Fig. 12 Solid mesh of part model and cooling system



(a) 3 fins (b) 4 fins

(c) 5 fins (d) 6 fins

(e) 7 fins

Fig. 13 Cooling channel solid meshes

Injection Molding Condition

For injection condition setting in Moldex3D, plastic material used was Polypropylene (PP) grade C705-44 NAH of DOW Company. Properties of material are shown in Table 2. Size of plastic injection machine setting was 100 tons.

TABLE II.
MATERIAL PROPERTIES

Properties	Data setting
Density	0.9 g/cm^3
Melt flow index/ 230, 2.1	44 g/10 min
Melt temperature	210 °C
Ejection temperature	119 °C

For cooling stage condition setting, mold material in this research was mold steel grade P20 according to metal powder material option for DMLS. In order to estimate cooling time of part model, auto set cooling time command in Moldex3D was applied for cooling stage analysis. The injection mold setting conditions of cooling stage for this research are shown below.

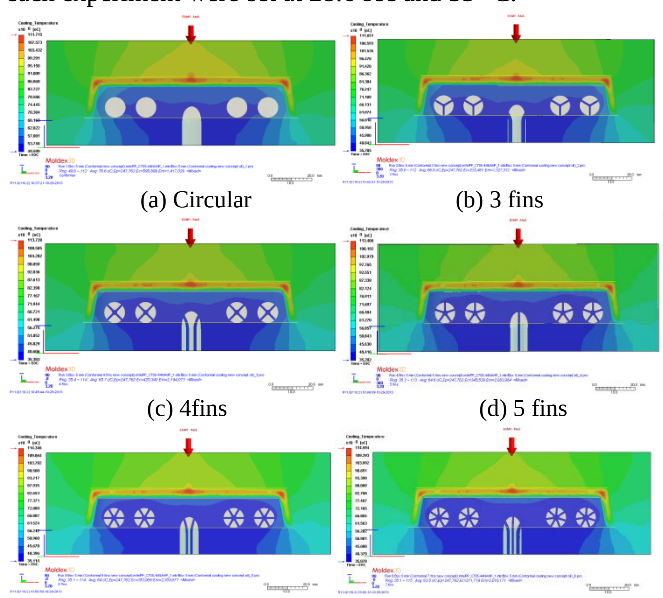
- Initial mold temperature = 35 °C
- Initial coolant temperature = 35 °C
- Coolant velocity = 60 cm^3/sec
- Coolant type = Oil

For the cooling time and cooling efficiency analysis, the same injection conditions of plastic injection mold with different cooling channel cross sections were applied in all simulation cases.

IV. RESULT

The results of temperature distribution in plastic injection mold are shown in Fig 14. For the cooling channel without fin, mold temperature distribution was in the range of 45.9°C to 66.1°C. It was different by approximately 20°C. Cavity surface temperature was approximately 57.88 °C as shown in Fig 14. For the cooling channel with three fins, the mold temperature distribution was narrower than that of the cooling channel without fin. The mold temperature distribution was in the range of 35.3°C to 51.0°C. The difference in the mold temperature distribution decreased from 20°C to 15.7°C. The temperature at the cavity surface was approximately 45.8°C, lower than that of circular cross section by 12.08°C. When the fin numbers increased from four to seven fins, the ranges of the temperature distribution were in the range of 35.3°C to 50.0°C, closed to that of three fins. However, the cavity surface temperature decreased as the fin numbers increased. For seven fins, the temperature around the cooling channels was approximate 35.0°C that was close to the desired mold temperature.

In Fig. 14, the simulation results show the relationship between cavity-surface temperature and injection time. Each injection molding simulation was consisted of filling, packing and cooling phases. The cycle time and mold temperature of each experiment were set at 28.6 sec and 35 °C.



(a) Circular (b) 3 fins

(c) 4fins (d) 5 fins

(e) 6 fins (f) 7 fins

Fig. 14 Mold temperature distribution

The mold surface temperature increased from 35 °C and remained constant after the first injection molding simulation. The cavity-surface temperature was about 64.71 °C for the cooling system without fin. The cavity-surface temperature was 58 °C for the cooling channel with three fins, decreased by 6.71 °C as compared to that of the cooling system without fin. The cavity-surface temperature decreased with increasing fin numbers. The cooling channel with seven fins provided the lowest cavity-surface temperature of 47°C which lowered than that of the circular cross section by 17.71 °C.

Fig 15 illustrates the relationship between the part average temperature and the fin number in the cooling channel. The part average temperature of the circular cross section was 61.01 °C. For cooling channel with three fins, the part temperature was 52.56 °C. It was lower than that of the circular cross section by approximately 8.45 °C. The temperature gradually decreased as fin number increased. The lowest part average temperature was 46.7 °C for cooling channel with seven fins.

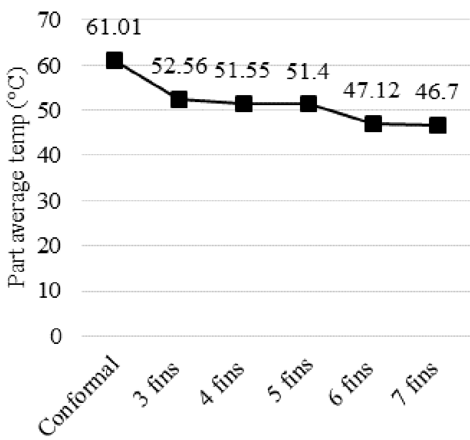


Fig. 15 Part average temperature and cross section

Fig. 16 illustrates the relationship between cooling time and fin number. The cooling time was the estimated time of the part cooled down from melting temperature to the temperature lower than the ejection temperature of plastic material (PP). The cooling time for the circular cross section was 30.5 sec and reduced to 27.98 sec for three fins. The cooling time for the cooling channels with five fins slightly decreased to 27.1 sec. It significantly reduced to 24.31 sec for 6 fins. The shortest cooling time was 24.0 sec for cooling channel with seven fins. Fig 16 illustrates the relationship between cooling heat flux and fin number. The cooling heat flux was the amount of heat that was removed from the molten plastic to outside by cooling system. Hence, high rate of heat flux indicated high efficiency of cooling system. The highest cooling heat flux was 1.95 J/sec*cm2 for seven fins which was more than that (1.59 J/sec*cm2) of the circular cross section.

Fig. 18 shows the relationship between cooling time and coolant velocity for each cooling channel cross section. The result showed that increasing fin number had an influence on the coolant velocity and the cooling time. The coolant velocity became faster when the fin number increased in the cooling channel. It therefore provide the improvement in the efficiency of heat convection in the cooling system due to fast heat removal from the molten plastic.

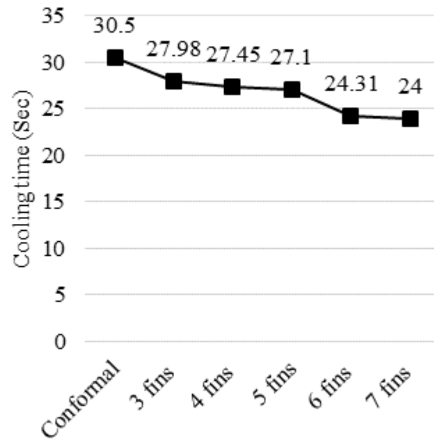


Fig 16. Cooling time and cross section

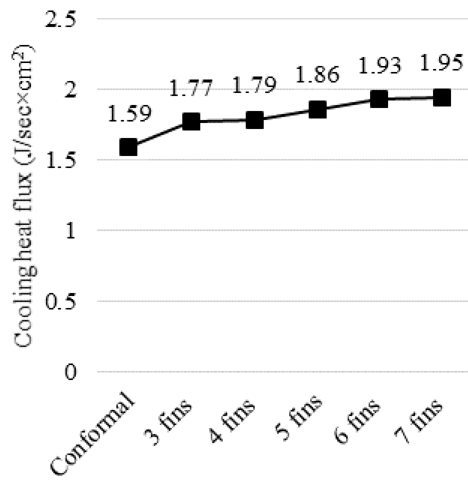


Fig. 17 Cooling heat flux and cross section

According to cooling time, it became lower when coolant velocity increased. Coolant velocity of circular cross section was 74.17 cm/sec. The fastest coolant velocity was 632.05 cm/sec for seven fins. The reason of the increase in the coolant velocity was the change of proportion between cross section area and perimeter of cooling channel.

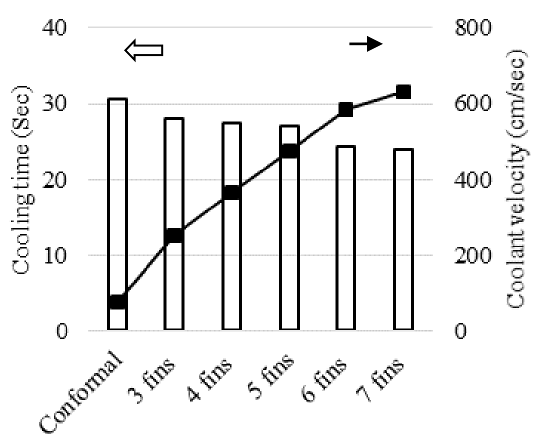


Fig. 18 Cooling time and coolant velocity

V. CONCLUSION

The aim of the adding fins was to increase cooling channel perimeter. The fin had an effect on cooling efficiency of a plastic injection mold. From the simulation result, cooling time decreased when fin number increased in the cooling channel. When considering the other effect on cooling efficiency such as coolant velocity, the cooling channel with fins provided faster coolant velocity than that of the circular cross section. Hence, the cooling channel with fins was able to release the heat from molten plastic to injection mold better than the circular cross section due to the heat convection principle. The change of hydraulic diameter that was proportion between peripheral and cross section area resulted in the increase of the coolant velocity and the cooling heat flux.

REFERENCES

[1] Lin, J. C. "Optimum cooling system design of a free-form injection mold using an Adductive network". *Journal of Materials Processing Technology*, Volume 120, 15 Jan 2002, Issues 1-3, pp. 226−236.

[2] H. S. PARK and N. H. PHAM. "Design of conformal cooling channels for an automotive part", *International Journal of Automotive Technology*, Volume 10, No. 1, pp. 87−93.

[3] S.H. Tang, Y.M. Kong, S.M. Sapuan, R. Samin, S. Sulaiman, "Design and thermal analysis of plastic injection mould", *Journal of MaterialsProcessing Technology*, Volume 171, 20 Jan 2006, pp. 259–267

[4] R. Sánchez, J. Aisa, A. Martinez, D. Mercado, (2012), "On the relationship between cooling setup and warpage in injection molding", *Measurement*, Volume 45, June 2012, pp. 1051–1056

[5] J.G. Kovács, B. Sikló, "Investigation of cooling effect at corners in injection molding", *International Communications in Heat and Mass Transfer*, Volume 38, Dec 2011, Issues 10, pp. 1330–1334

[6] DIMLA, D.E.; CAMILOTTO, M.; MIANI, F. "Design and optimisation of conformal cooling channels in injection moulding tools". *Journal of Materials Processing Technology*, Volume 164–165, 15 May 2005, pp. 1294–1300

[7] L-E. Rannar, A. Glad, C-G. Gustafson, "Efficient cooling with tool inserts manufactured by electron beam melting", *Rapid Prototyping Journal*, 2007, pp. 128–135

[8] K. Altaf, V.R. Raghavan, A.M.A Rani, "Comparative thermal analysis of circular and profiled cooling channels for injection mold tools", *Journal of applied science*, Volume 11, Issues 11, 2011, pp. 2068-2071

[9] Mayer, S.,"*Optimised mould temperature control procedure using DMLS*." EOS GmbH Electro Optical Systems, www.eos.info.

[10] Hamdy Hassan, Nicolas Regnier, Ce´dric Le Bot, Guy Defaye, "3D study of cooling system effect on the heat transfer during polymer injection molding."*International Journal of Thermal Sciences*,Volume 49, Issues 1, Jan 2010 pp. 161–169

[11] Khurram Altaf, Ahmad Majdi, Abdul Rani, Vijay R. Raghavan, "Prototype production and experimental analysis for circular and profiled conformal cooling channels in aluminium filled epoxy injection mould tools." *Rapid prototyping journal*, 2013, pp. 220-229

[12] Yan-Chen Chiou, Ya-Yuen Chou, Hsien-Sen Chiu,,Chau-Kai Yu, Chia-Hsiang Hsu, "*Integrated true 3D simulation of rapid heat cycle molding process*."CoreTech System Co., Ltd., www.moldex3d.com

[13] William S. Janna, Engineering heat transfer, CRC Press Publishers, 3rd ed, 2009

[14] Dong-Kwon Kim, Jaehoon Jung, Sung Jin Kim, "Thermal optimization of plate-fin heat sinks with variable fin thickness." *International Journal of Heat and Mass Transfer*, Volume 53, 2010, pp. 5988–5995

[15] Mohsen Torabi a., Abdul Aziz b, Kaili Zhang, "Comparative study of longitudinal fins of rectangular, trapezoidal and concave parabolic profiles with multiple nonlinearities."*Energy*,Volume 51, 2013, pp. 243-256

[16] *Design rules for DMLS*, EOS GmbH Electro Optical Systems, www.eos.info.