The Influence of Liquid Coolant Flow Regimes On the Quality of Injection Molded Plastics Parts

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Abstract

The injection molding of plastics parts comprises sequential interconnected events, which include closing of the mold, injecting of molten plastics into the closed mold, forming of the molten plastics into a desired shape, cooling of the shaped molten plastics, and opening of the mold and ejecting the sufficiently cooled shaped plastics parts. Of these events, the cooling of the shaped molten plastics plays an important role in obtaining good and acceptable quality parts. For this reason, this study was undertaken to elucidate the cooling process and its impact on plastics molded parts. While there are many factors that affect molding cooling in injection molding, such as the layout of the cooling channels and the materials used in building the mold, the authors chose to study the influence of coolant flow regimes on molding cooling. The findings of this work suggest that coolant flow regimes and coolant temperatures affect the heat-transfer coefficient of the coolant and, consequently, the mold cooling efficiency. Furthermore, it was found that inefficient molding cooling can result in a rather large temperature difference between the coolant inlet and outlet temperatures, which in turn can result in substantial plastics part warpage. Based on the authors' findings, it is suggested that coolant flow rate for efficient mold cooling should be determined for individual plastics materials since it does not appear that one coolant flow rate is suitable for all plastics materials.

Introduction

The work presented in this paper was part of a senior capstone experience, which is a partial fulfillment of the Bachelor of Science' degree requirements in manufacturing engineering technology (MET) at Ball State University. The purpose of the capstone experience is to provide MET majors with opportunities to demonstrate the ability to resolve technical problems by utilizing skills acquired in the program. To achieve this goal, students are encouraged to understand the physical laws or the underlying technical principles governing a given problem, so that an appropriate solution can be formulated. It is for this reason that this paper seeks to understand the impact of liquid coolant flow regimes on the quality of injection molded plastics parts. For example, Rees [1] noted that "a product may become brittle or lack the required gloss when cooled too fast, or at too low a temperature, or it may show unwanted crystallization when cooled too slowly or not cold enough."

The injection molding of plastics parts consists of a sequence of interconnected events, and the time required to complete these events is known as the cycle time of the process. These events include closing the mold, injecting molten plastics into the closed mold, cooling the molten

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plastics, and opening the mold and ejecting the sufficiently cooled plastics parts. Among this series of events, the cooling process appears to play a crucial role in a successful injection molding process because it alone generally accounts for about 75% of the cycle time [2]. Furthermore, the cooling process has a large influence on plastics part quality [3].

Separately, the cooling process comprises three major components, (1) cooling of the molten plastics, (2) conduction of heat from the molten plastics to the cooling channels in the mold, and (3) convection cooling by liquid coolant in the cooling channels [4]. Of these three major components, the first two components are usually determined during the design stage of an injection molding project while the third component is implemented during the processing of plastics parts. Since the authors were interested in the effect of liquid coolant flow regimes on plastics parts quality, an existing injection machine and mold were used to examine the effects of convection cooling on physical properties and tensile properties of injection molded parts. To achieve these goals, the authors employed the relationship between the convection heat-transfer coefficient of the cooling process and the flow regimes of the liquid coolant. This relationship is captured by the Colburn [5] equation (equation 2), which shows how the coolant flow regime, described by its Reynolds number, N_{RE}

$$N_{RE} = \frac{DV\rho}{\mu} \qquad \text{(Eqn. 1)}$$

is related to the individual (inside of cooling channel) convection heat-transfer coefficient, h_i, for forced convection in turbulent flow (N_{RE} greater than 6,000) for Newtonian liquids.

$$\frac{h_i}{c_p G}\left(\frac{c_p \mu}{k}\right)^{2/3}\left(\frac{\mu_w}{\mu}\right)^{0.14} = \frac{0.023}{\left(DG/\mu\right)^{0.2}} \qquad \text{(Eqn. 2)}$$

where, c_p = specific heat capacity at constant pressure, J/g-ºC or Btu/lb-ºF
D = diameter, m or ft
G = mass velocity, kg/m^2-s or lb/ft^2-s ($G = V\rho$)
h_i = individual heat-transfer coefficient, W/m^2-ºC or Btu/ft^2-h-ºF
k = thermal conductivity, W/m-ºC or Btu/ft-h-ºF
V = average velocity, m/s or ft/s
ρ = density, kg/m^3 or lb/ft^3
μ = viscosity, kg/m-s or lb/ft-s, μ_w = value at wall temperature

Equation 3 is used for laminar flows (N_{RE} less than 2,100), while a graphical solution [6] is used for transition flows (N_{RE} between 2,100 and 6,000).

$$\frac{h_i}{c_p G}\left(\frac{c_p \mu}{k}\right)^{2/3}\left(\frac{\mu_w}{\mu}\right)^{0.14} = 1.86\left(\frac{D}{L}\right)^{1/3}\left(\frac{DG}{\mu}\right)^{-2/3} \quad \text{(Eqn. 3)}$$

where, L = length of the cooling channels (tubes) in the mold, m or ft

The overall heat-transfer coefficient, U , for the cooling process is expressed by equation 4 [7], where K is the thermal conductivity of mold material and S is the conduction shape factor of the cooling channels. Values of h_i were estimated from equations 1, 2 and a graphical solution [6].

$$\frac{1}{U} = \frac{1}{K\,S} + \frac{1}{\pi\,D\,h_i} \qquad \text{(Eqn. 4)}$$

The ultimate goal of this work was to determine optimal coolant flow rates in gallons per minute (gpm) in the efficient production of good quality injection molded parts based on the coolant flow regimes and heat-transfer coefficients.

Experimental

Materials

Table I contains the plastics materials used in this study.

Table I. Plastics materials and some of their properties

Information	Polycarbonate (PC)	Polypropylene (PP)
Trade Name	Lexan® 940A	CP PRYME® PPH200-20M
Supplier	SABIC Innovative Plastics	Chase Plastics
Processing Grade	Injection Molding	Injection Molding
Melt Mass-Flow Rate	10g/10 min	12g/10 min
Nature of Solid	Amorphous	Semi-Crystalline

These materials were selected because they were readily available in house.

Equipment

A Sandretto 60-ton injection molding machine was used. A Conair Mold Temperature Controller (MTC), model TCI-DI, shown in Figure 1, was used to supply coolant to the mold and also control the mold temperature. The MTC displayed the coolant flow pressure, and the inlet and outlet temperature of the coolant.

Figure 1. Conair Mold Temperature Controller (MTC) and its control panel on the right.

A two-part cold mold made by Master Unit Die Products, Inc and shown in Figure 2a was used in the study to produce tensile and impact test specimens. The mold material was Stainless Steel 420 (420 SS). In Figure 2a, the blue tube represents the coolant inlet to the mold while the red tube was the coolant outlet from the mold. The coolant flow rate in each part of mold halves was controlled with two ball valves attached to two Omega flow meters, model FL-2300ABR shown in Figure 2b. Figure 3 shows a schematic diagram of the cooling channels of the two-part mold.

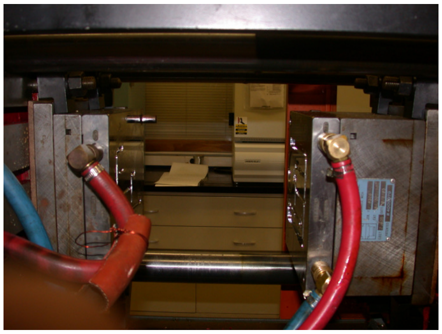

Figure 2a. A two-part injection mold.

Figure 2b. Omega flow meters & ball valves.

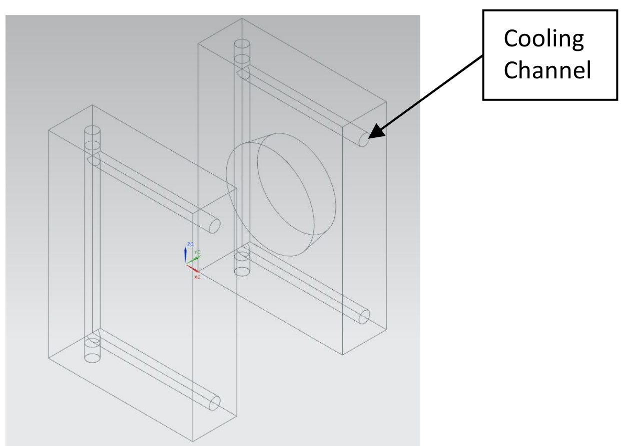

Figure 3. Schematic diagrams of the two-part cold mold.

Procedure

Before injection molding the plastics parts, PC and PP were dried for 3.5 hours at 250 ºF and for 1.5 hours at 190 ºF, respectively with a Conair CD30 dehumidifying dryer. During the injection molding process, samples were not collected until the difference between the coolant inlet and outlet temperatures had reached a steady state, that is, $\Delta T = (T_{\text{out}} - T_{in})$ = constant. After several trial runs, Table II shows the processing variables used to establish the baseline for this study. The baseline samples were regarded as the "perfect" plastics parts; the parts had no flash, short shot, sink marks, voids, or any visible defects.

Table II. Injection molding process variables

Processing Variable	Polycarbonate	Polypropylene
Melt Temperature	535 ºF	400 ºF
Mold Temperature	190 ºF	75 ºF
Injection Screw Speed	60 rpm	60 rpm
Back Pressure	100 psi	200 psi
Cooling Time	10 seconds	15 seconds
Coolant Flow rate	1.5 gpm	1.5 gpm

Having established the baseline processing variables, the effect of coolant flow regimes on the parts quality was examined by varying the coolant flow rates while keeping other variables constant. For any given coolant flow rate, 10 samples were collected after the system had attained a steady state condition, that is, ΔT (=$T_{\text{out}} - T_{\text{in}}$) of coolant = constant. The coolant flow rates were randomly changed to prevent any systematic errors in the data collecting process. After a 40-hour wait period following the injection molding of the parts, five samples were randomly selected for testing for each coolant flow rate and material. The following tests were performed on the samples.

- Gloss test with a Horiba Gloss Checker IG-320
- Warpage test with a bench steel block from Smith Tool and Engineering Company
- Tensile strength at yield and tensile strain at yield test using Instron® Universal Testing Instrument, Model 1011

Results and Discussion

Figure 4 shows the effect of the coolant temperature on coolant flow regimes as indicated by its Reynolds Number, N_{RE}. With regard to the mold, all processing variables were the same except for the coolant inlet temperature (T_{in}), which was 75 ºF for PP and 190 ºF for PC. From equation 1, it appears that coolant viscosity and density were highly impacted by the "average" coolant temperature $\left[T_{average} = \frac{T_{out} - T_{in}}{2}\right]$; the effect of temperature of these fluid properties explains the large difference between the N_{RE} for PP and PC. This is so because the higher the average coolant temperature, the lower the coolant viscosity and density. Since the viscosity of water seems to be more sensitive to temperature changes than the density of water, the increase in coolant temperatures resulted in substantial increases in N_{RE} according to equation (1) with other variables held constant. The data showed that the coolant attained turbulent flow, $N_{RE} > 6000$, at 0.3 gpm for PC and 0.7 gpm for PP.

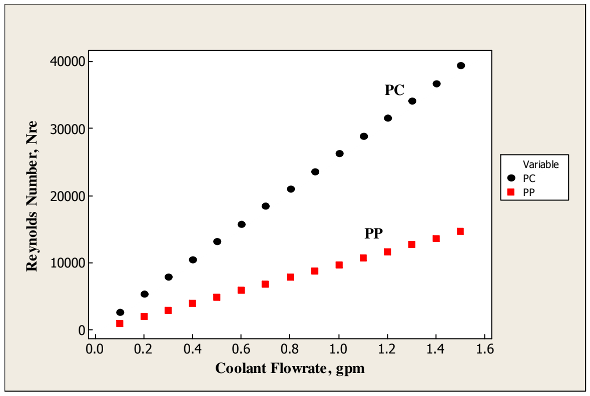

Figure 4. Coolant Reynolds Number for PC and PP

Figure 5 shows the influence of the coolant flow regimes on the individual (inside of the tube) heat transfer coefficient of the coolant for PC and PP. The breaks in the plots show the effect of transitioning from laminar and transition flows to turbulent flow on the heat-transfer coefficient of the coolant for PC and PP. Combining the results of Figures 4 and 5, it is apparent that coolant regimes contributed to the differences in the heat-transfer coefficient of the coolant for PC and PP.

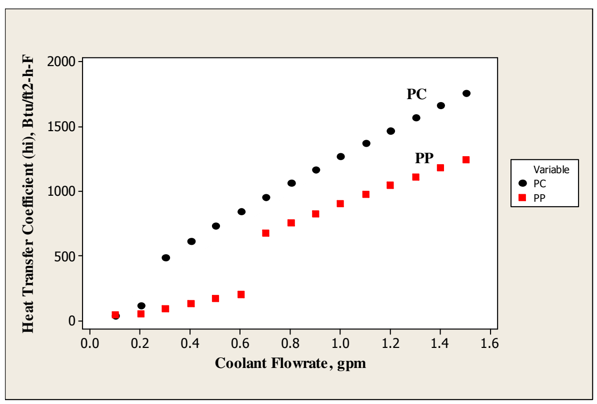

Figure 5. Heat Transfer Coefficient of Coolant for PC and PP

Figure 6 shows the temperature difference (ΔT) between the coolant inlet and outlet temperatures. The temperature readings were read off the mold temperature controller with a unit digit resolution. The low resolution in temperature readouts may be responsible for the shape of the plots in the figure. Despite this drawback, the figure shows a larger ΔT for PP than for PC at all coolant flow rates. Also, the difference appeared larger at lower flow rates (laminar and transitions flow) than at higher flow rates (turbulent flow). The significance of ΔT on part quality was noted by Rees [8] and Dym [9]. Rees [8] suggested that large ΔT could result in "uneven molding cooling and longer molding cycles." He suggested that for some molding applications ΔT should be between 1 – 2 ºC (2 – 4 ºF) while Dym [9] suggested a ΔT of 10 ºF for simple moldings and 5 ºF for complex moldings. Choosing a ΔT of 5 ºF for this study resulted in a recommendation that a coolant flow rate greater than 0.4 gpm will suffice for PC while a coolant flow rate greater than 1.4 gpm will work for PP. These coolant flow rates correspond to N_{RE} of 10,500 and 13,500 for PC and PP, respectively.

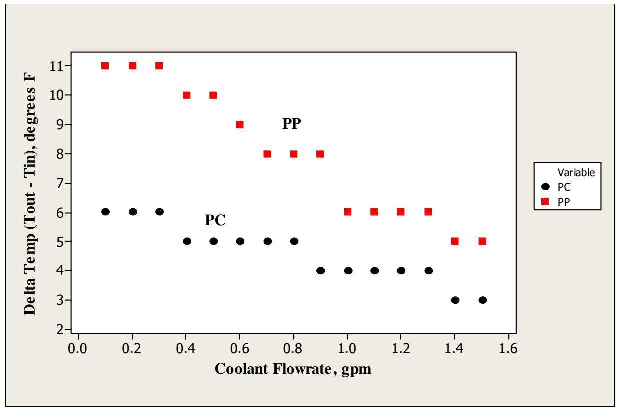

Figure 6. Difference, ΔT, in the coolant inlet and outlet temperatures

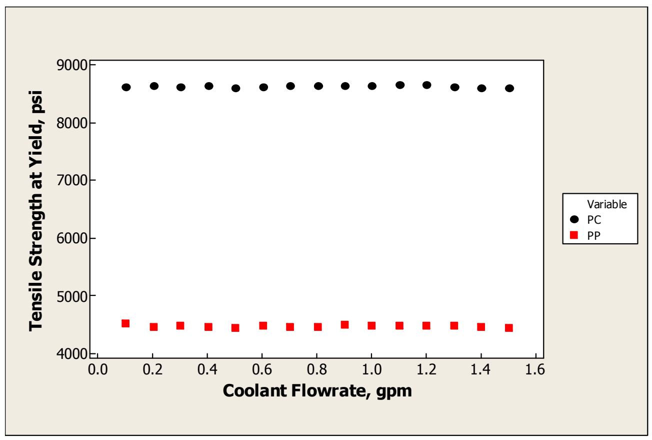

Figure 7. Tensile strength at yield of PC and PP

In Figure 7, the authors examined the influence of the coolant flow regimes on the tensile strength at yield of PC and PP, and it did not seem that coolant flow regimes had any significant on this property. Likewise, Figure 8 showed that coolant flow regimes had no effect on tensile strain at yield of PC and PP, thus indicating negligible or no occurrence of brittleness due to thermal degradation, particularly in PP.

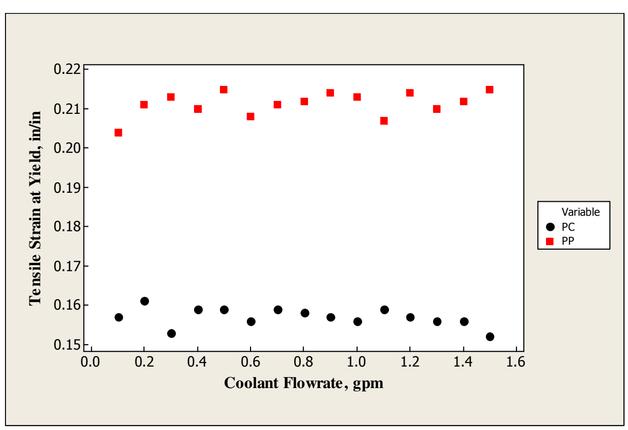

Figure 8. Tensile strain at yield of PC and PP

As noted earlier, Rees [1] suggested that gloss of molded products could be a problem if the mold was cooled too fast. In this study, the authors did not observe any effect of the coolant flow regimes on the gloss of PC and PP. Perhaps the authors did not use very high coolant flow rates, hence the absence of any measureable effect of the coolant flow regimes on the gloss of PC and PP.

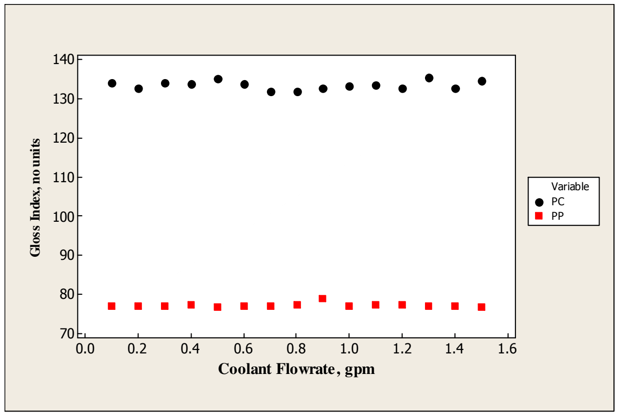

Figure 9. Gloss Index for PC and PP

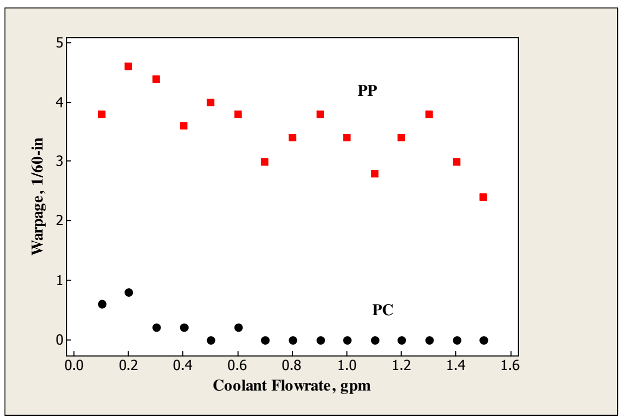

Figure 10. Warpage of PC and PP

Figure 10 shows that significant warpage was not found in PP parts when the coolant flow rate was greater than 0.8 gpm while it was present in the PP parts for all coolant flow rates used in the study. However, the plot of PP showed a slight negative (slope = -0.0957) trend with increasing coolant flow rate. The results further suggest that coolant flow regimes and mold temperature can significantly affect part quality. Figure 11a shows the ASTM test specimens (i.e., plastics parts) produced in this study. Figures 11b and 11c show how part warpage was estimated using the bench steel block from Smith Tool and Engineering Company.

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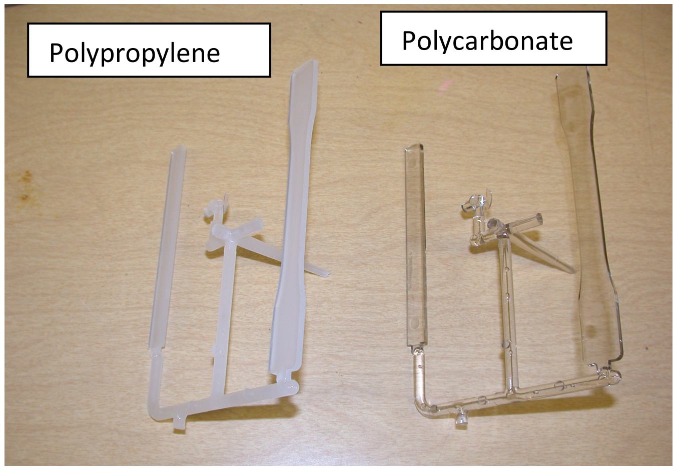

Figure 11a. Injection Molded Polypropylene and Polycarbonate ASTM test specimens

Figure 11b. Warpage absent in sample

Figure 11c. Warpage present in sample

Conclusion

This study has shown that coolant flow regimes do influence the cooling process of injection molding through the individual heat-transfer coefficient, h_i, of the cooling channels: a higher value of h_i results in a better cooling process. This was evidenced by the occurrence of warpage in PP plastics at coolant flow rates less than 1.4 gpm. Given the processing conditions used in this study, it is suggested that for the materials studied, for efficient cooling process to take place a minimum coolant flow rate of 1.4 gpm and 0.8 gpm had to be attained for PP and PC, respectively. Furthermore, this article reveals that each plastics material is unique and may require a minimum coolant flowrate for efficient mold cooling; in other words, one minimum coolant flow rate may not "fit" all plastics materials [10]. The authors did not find any effect of coolant flow regimes on the tensile strength at yield or the tensile strain at yield of PC and PP suggesting that the parts did not become brittle because of inefficient cooling, particularly for the PP parts. Similarly, no effect of coolant flow regimes on gloss of PC and PP were found.

Future Work

Educational activities

This study has been incorporated into the plastics curriculum by two methods. The first approach is the continuation of this study by other students to find out if the same effects would be observed with other plastics materials. These exercises will be carried out in the upper level plastics course titled "ITMFG 325 – Plastics Product Design." Presently, a polyblend consisting of acrylonitrile-butadiene-styrene (ABS) and polycarbonate (PC) is being studied. The second method is by sharing the findings with students through lectures and discussions in plastics courses offered in the program.

Other Plastics Materials and Temperature Effects

In this study, the authors found that the temperature of the coolant had significant effects on cooling efficiency. Based of this finding, other studies are in the works to examine the coolant temperature range for which cooling is efficient for selected plastics materials. Plans are to study both semi-crystalline and amorphous thermoplastics materials.

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Biography

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