

Productivity Benefits of 3M™ Glass Bubbles in Injection Molded Thermoplastics via Increased Cooling Rates

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Introduction

Cooling of injection molded parts is a very important factor in the economics and operation of the molding process. Long cooling times incur additional manufacturing costs¹ and can limit production capacity.

The cooling time of molten plastic in the injection molding process can be estimated by calculating thermal diffusivity (α), as shown in Equation 1. This material property is the measure of a material's ability to transmit heat relative to its ability to store heat.² All process parameters kept constant, materials with higher thermal diffusivity require shorter cooling times.

Equation 1: Thermal Diffusivity

$$\alpha = \frac{k}{(\rho C_p)}$$

Where:

α : Thermal diffusivity ρ : Density
 k : Thermal conductivity C_p : Specific heat capacity

3M™ Glass Bubbles are low density, free-flowing powders consisting of thin-walled unicellular glass spheres. They offer several benefits in injection molded thermoplastic parts, including weight reduction and improvement of dimensional stability defects, such as warpage, sink and CTE.³ 3M glass bubbles can also reduce mold cycle times by causing the thermoplastic parts to cool faster in the mold. In this paper, we investigate experimentally to what degree 3M glass bubbles can increase cooling rates in the injection molding process.

Materials

The glass bubbles used for this study were 3M™ Glass Bubbles iM16K, which have a density of 0.46 g/cc and an isostatic crush strength of 16,000 psi. The resin material used for this study was a general purpose homopolymer PP (LyondellBasell Pro-fax™ 6523) with a melt flow rate of 4.0 g/10 min (230°C, 2.16 kg). A maleic anhydride grafted PP (MAPP) homopolymer (Polybond® 3200) was used as a compatibilizer and provided by Chemtura. Glass fibers used in this study were manufactured by PPG under the trade name ChopVantage® HP3299. Talc was provided by Imerys under the trade name Jetfine® 3CC.

Processing

Eight different PP based formulations were prepared by compounding glass bubbles, talc and glass fiber in a Thermo Scientific co-rotating, fully intermeshing, twin screw extruder system (PRISM TSE 24 mc- L/D 28:1) equipped with seven heating zones (Figure 1). Polymer resin was starve-fed in zone 1 via a resin feeder and passed through a set of kneading blocks to ensure its complete melting before the glass bubbles were side fed downstream in zone 4. At the point of glass bubble side feeding, as well as for the rest of the downstream processing, high channel depth conveying elements (OD/ID: 1.75) were used. Glass fibers (when used) were introduced in zone 6 via a volumetric feeder through top feeding ports. For talc-containing formulations, talc was always introduced through the feed throat using a separate powder feeder.

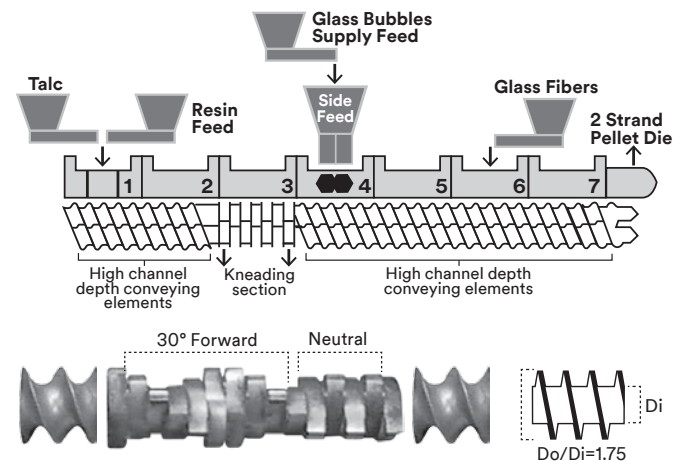


Figure 1. Compounding Setup

In order to assess the effect of glass bubbles in the injection molding cooling rate of unfilled PP, three formulations were prepared at 5, 10 and 20 wt%. For talc-filled PP, a 20 wt% talc-containing formulation was compared to a formula containing 10 wt% talc and 4 wt% glass bubbles. For glass fiber-filled PP, a 15 wt% glass fiber-containing formulation was compared to one

formulation with 15 wt% glass fiber and 5 wt% glass bubbles, and another with 18 wt% glass fiber and 7 wt% glass bubbles.

These formulations were chosen as they demonstrate comparable mechanical properties (Appendix A) to the original formula with reduced densities, a key benefit of glass bubbles.

For all samples, zone 1 was cooled with water. The temperatures in zones 2 to 7 were set to 180, 220, 220, 220, 220, and 220°C respectively. The die temperature was set to 220°C. The screw rotation speed was set to 250 rpm. The extrudate was cooled in a water bath and pelletized.

All samples were molded using a BOY 22D injection molding machine with a 28 mm general purpose barrel and screw manufactured by Boy Machines Inc. A standard ASTM mold with cavities for tensile, flex and impact bar was used for all molded parts. Barrel zones 1 to 4 were set to 430°F (220°C). The mold temperature was set to 135°F (57°C). The cooling time was set to 16 seconds.

Temperature Monitoring

Temperature images of the molded samples were taken using a FLIR Systems ThermoCAM™ P65 camera and analyzed by FLIR QuickReport software. Images were always taken at precisely 15 seconds; this interval included mold opening time, part ejection and placement of the ejected part in front of the camera in a marked location, as shown in Figure 2. This ensured that all parts experienced the same cooling history before their thermal images were taken.



Figure 2. Setup for taking thermal images after part ejection

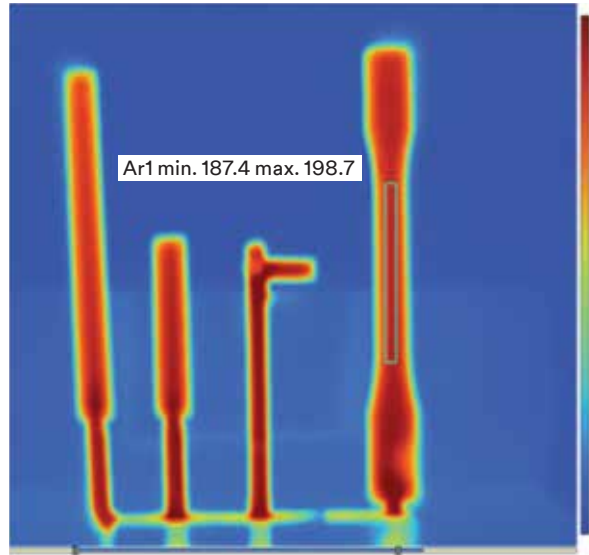
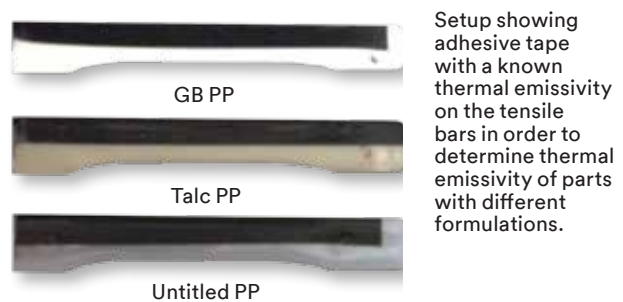


Figure 3. Area average temperature selection on the tensile bar

An area average temperature was determined on each tensile bar as shown in Figure 3. An average of 10 tensile bars was taken for each formulation. Since thermal imaging cameras work on the principal of thermal emissivity, it was necessary to take into account the thermal emissivity of molded parts for each formulation. This was done by adjusting the thermal emissivity parameter on the IR camera to match the temperature shown on a black material with a known thermal emissivity at 135°F. The black material was an adhesive tape which was placed on one side of the tensile bar with mirror symmetry as shown in Figure 4. Thermal emissivity results are shown in Table 1.

Table 1: Thermal emissivity (TE) of injection molded parts with different filler compositions

Formulation	TE
Unfilled PP	0.97
PP with 5 wt% Glass Bubbles	0.95
PP with 10 wt% Glass Bubbles	0.95
PP with 20 wt% Glass Bubbles	0.95
PP with 20 wt% Talc	0.91
PP with 10 wt% Talc, 4 wt% Glass Bubbles	0.94
PP with 15 wt% Glass Fiber	0.92
PP with 15 wt% Glass Fiber, 5 wt% Glass Bubbles	0.94
PP with 18 wt% Glass Fiber, 7 wt% Glass Bubbles	0.95



Setup showing adhesive tape with a known thermal emissivity on the tensile bars in order to determine thermal emissivity of parts with different formulations.

Figure 4. Adhesive Tape Setup for Thermal Emissivity Adjustment

Mechanical Properties

Though not the main focus of this study, mechanical properties were measured in order to demonstrate that formulations containing 3M glass bubbles show comparable, if not improved, mechanical properties at lower densities compared to their counterpart formulations without glass bubbles.

Mechanical properties of the injection molded composites were measured using ASTM standard test methods listed in Table 2, and are detailed in Appendix A. An MTS frame with a 5kN load cell and tensile and three point bending grips were used for tensile and flexural properties, respectively. A Tinius Olsen model IT503 impact tester and its specimen notcher were used to measure the Notched Izod impact strength of the molded parts at room temperature.

Table 2: Property Test Methods

Test (Units)	Abbr.	ASTM#
Tensile Modulus (MPa)	TM	D-638
Tensile Strength at Yield (MPa)	TS	D-638
Elongation at Break (%)	EL	D-638
Notched Izod Impact (J/m)	NI	D-256
Flexural Modulus (MPa)	FM	D-790
Flexural Strength at Yield (MPa) Bubbles	FS	D-790

Density of Injection Molded Parts: a Micromeritics AccuPyc™ 1330 Helium Gas Pycnometer was used to measure density for all samples.

Results

Thermal images of unfilled PP and glass bubble-filled PP molded parts are shown in Figure 5. The temperature of the ejected parts is reduced from 90°C to 68°C when the loading of 3M™ Glass Bubbles iM16K (0.46 g/cc) is increased from 0 to 20wt%, demonstrating that the parts cool faster with glass bubbles. Figure 6 shows that there is quite a linear relationship between the weight percent of glass bubble loading and the temperature of the ejected part. The reduction in temperature is roughly 1.1°C per each wt% of glass bubbles added into the formulation.

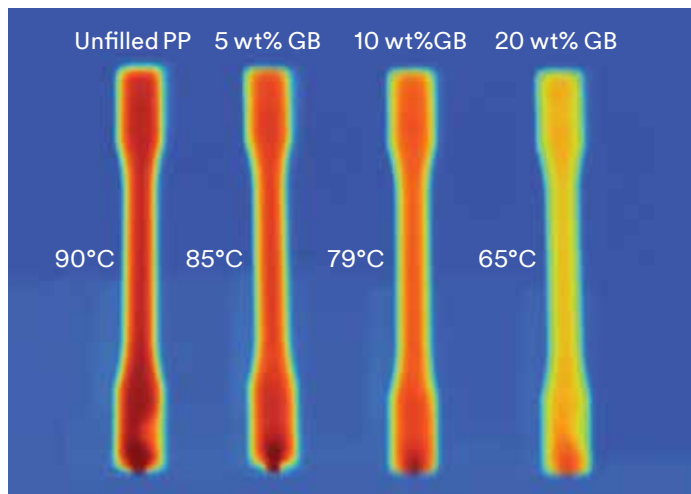


Figure 5. Thermal images and area average temperatures of molded parts: unfilled PP and glass bubble-filled PP at various loadings

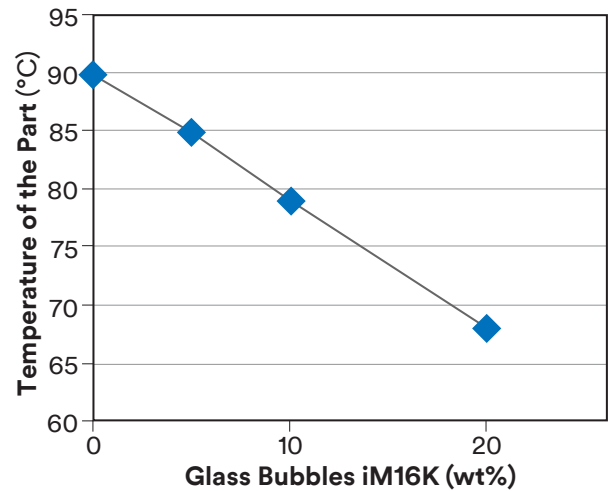


Figure 6. Area average temperatures of the PP molded parts after ejection as a function of glass bubble loading

Likewise, the temperature of the ejected molded part decreases from 88°C to 79°C with 5 wt% glass bubbles in a 15 wt% glass fiber formulation, as shown in Figure 7. The temperature further reduces to 74°C when the part is reformulated to contain 18 wt% glass fiber and 7 wt% glass bubbles.

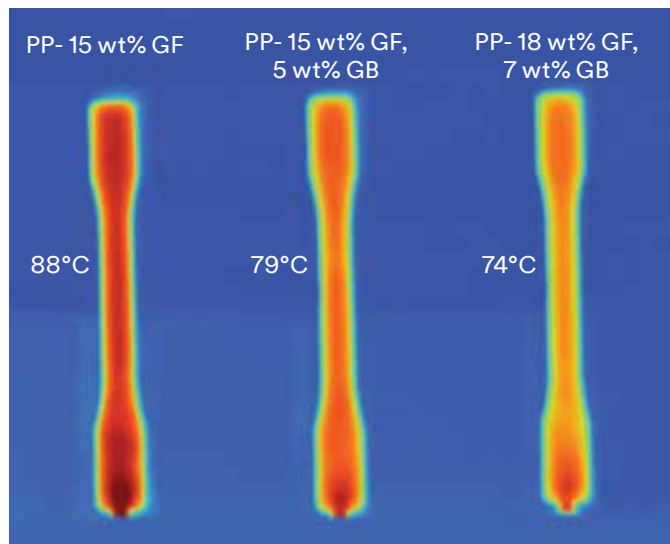


Figure 7. Thermal images and area average temperatures of glass fiber-filled PP molded parts at various loadings of glass bubbles.

Similar observations are true for PP-talc compositions, though with a lesser effect on cooling. When a polypropylene part containing 20 wt% talc is reformulated to 10 wt% talc and 4 wt% glass bubbles, the temperature of the part is reduced from 83.3 to 80°C (see Figure 8).

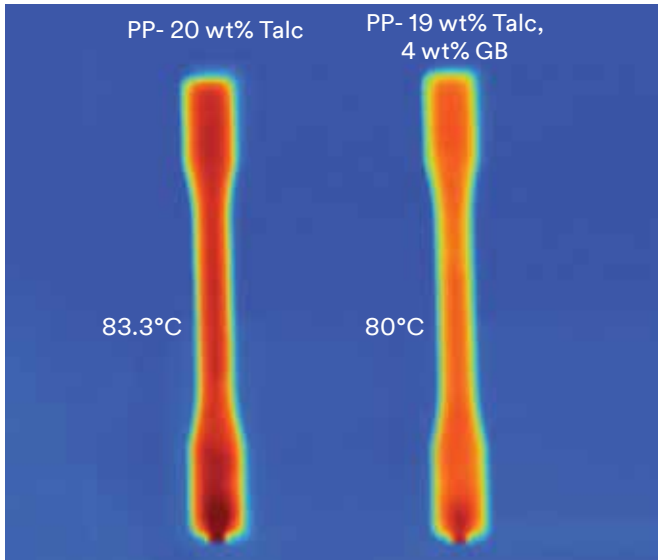


Figure 8: Thermal images and area average temperatures of talc-filled PP molded parts, with and without glass bubbles

The increased cooling observed in formulations containing 3M glass bubbles can be explained by the effect of glass bubbles on the thermal diffusivity of the part (Equation 1). An increased glass bubble weight fraction decreases composite density and composite specific heat capacity, which in turn increases thermal diffusivity and hence cooling rates. Composite density decreases because glass bubbles are lower in density than polymers. Composite specific heat capacity decreases because the specific heat capacity of glass (~750 J/kg K) is lower than that of most thermoplastic materials (1500 to 3500 J/kg K).

Glass bubbles also influence thermal conductivity, which has a proportional effect on thermal diffusivity. Fillers with high thermal conductivity increase composite thermal conductivity and hence the thermal diffusivity of the parts. Glass bubbles of very low densities (0.12 to 0.38) decrease thermal conductivity of PP, which has a thermal conductivity of about 0.21 W/mK. However, due to strength requirements, glass bubbles with densities between 0.46 and 0.6 g/cc are typically used in injection molding processes. At this density range, glass bubbles have a neutral to minimal effect on the thermal conductivity of PP.

Transfer of heat between the plastic and the mold is typically governed by the transient heat conduction (Equation 2) where t is time, T is temperature and z is the thickness of the part.

Equation 2: Transient Heat Conduction

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2}$$

This equation can be solved analytically for simple geometries such as plates and rods to provide cooling time as a function of melt, coolant (mold) and ejection temperatures. For plates, the theoretical minimum cooling time is as shown in Equation 3.

Equation 3: Theoretical Cooling Time for an Injection Molded Plate

$$t_c = \frac{h^2}{\pi^2 \alpha} \ln \left(\frac{4}{\pi} \frac{T_{melt} - T_{mold}}{T_{eject} - T_{mold}} \right)$$

Where

h : thickness of the part

α : Thermal diffusivity of the part

T : Temperature

Using the temperature of the melt (220°C) and the mold (57°C), ejection temperatures of the parts (90, 85, 79, and 68°C for 0, 5, 10 and 20 wt% glass bubbles, respectively), part thickness (3.13 mm) and cooling time (16 sec), thermal diffusivity was calculated from Equation 3, as shown in Table 3.

Table 3: Thermal Diffusivity of Glass Bubble-Filled PP Composites in mm²/s at RT calculated from Equation 3

	No GB	5 wt% GB	10 wt% GB	20 wt% GB
Thermal Diffusivity from Equation 3	0.114	0.124	0.139	0.182

In order to determine the minimum cooling time necessary to reach the same ejection temperature of 90°C, Equation 3 was used with experimental thermal diffusivity values for each formulation, i.e. 5, 10 and 20 wt%.

Table 4: Calculated cooling time to reach an eject temperature of 90°C as a function of glass bubble loading

	No GB	5 wt% GB	10 wt% GB	20 wt% GB
Cooling time (seconds)	16	14.7	13.1	10
% Reduction	0	8.2	18	37

We can see in Table 4 that cooling times could be reduced up to 37% by the addition of glass bubbles.

Similarly, glass bubbles increase thermal diffusivity in glass fiber-filled and talc-filled PP formulations, as calculated with Equation 3 using experimentally determined “eject temperatures” of molded parts.

Table 5: Thermal Diffusivity and calculated cooling time to reach an eject temperature of 88°C as a function of glass bubble loading in glass fiber-filled PP formulations

	PP-15 wt% GF	PP-15 wt% GF/5 wt% GB	PP-18 wt% GF/7 wt% GB
Thermal diffusivity (mm ² /s)	0.118	0.139	0.155
Cooling time (seconds)	16	13.5	12.15
% Reduction	0	15.3	24

Table 6: Thermal Diffusivity and calculated cooling time to reach an eject temperature of 83.3°C as a function of glass bubble loading in talc-filled PP formulations

	PP-20 wt% GF	PP-10 wt% Talc/4 wt% GB
Thermal diffusivity (mm ² /s)	0.18	0.136
Cooling time (seconds)	16	15
% Reduction	0	6

Conclusions

As demonstrated by thermal imaging experiments, 3M™ Glass Bubbles improve cooling rates of injection molded polypropylene parts as well as glass fiber and talc based PP composites.

These experimental results show that glass bubbles could reduce cooling times by as much as 37% in unfilled polypropylene at 20 wt% loading.

In glass fiber-filled formulations, cooling time reductions as high as 25% were observed when glass fiber and glass bubble loadings were increased. The smallest cooling time reduction was seen in formulations containing talc; this is possibly due to talc's high thermal conductivity, which increases the thermal diffusivity and cooling efficiency of the parts.

All formulations were shown to have comparable, if not improved, mechanical properties in addition to reductions in density.

References

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Appendix A. Mechanical Properties

Table A1: Properties of general purpose homopolymer PP-Glass Bubble composite (Figure 5 samples)

	Formula 1		Formula 2		Formula 3	
	PP		PP-GB10-M		PP-GB20-M	
	wt%	vol%	wt %	vol%	wt%	vol%
PP-General Purpose	100	100	87	80.6	76	65.8
Glass Bubbles iM16K	-	-	10	16.65	20	30.8
MAPP	-	-	3	2.75	4	3.4
Density (g/cc)	0.9		0.835		0.785	
TS @ RT	30		29.8		28.7	
TS @ 90°C	10.1		11.6		13.5	
TM @RT	1195		1513		1830	
TM @ 90°C	162		230		300	
FS @RT	37.9		44.3		49.2	
FM @1% secant	1063		1486		1740	
NI @ RT	38.5		34.8		30.3	
MI	5.8		0.835		2.6	

Table A2: Properties of general purpose homopolymer PP-Glass Fiber-Glass Bubble composite (Figure 7 samples)

	Formula 1		Formula 2		Formula 3	
	wt%	vol%	wt %	vol%	wt%	vol%
PP-General Purpose	85	94	77	80.9	72	75.7
GF-3299	15	6	15	5.6	18	6.7
Glass Bubbles iM16K	-	-	5	10.4	7	14.5
MAPP	-	-	3	3.1	3	3.1
Density (g/cc)	1.001		0.953		0.956	
TS @ RT	53.7		50		56	
TS @ 90°C	23.5		22.5		24.4	
TM @RT	2565		2500		2700	
TM @ 90°C	703		645		723	
FS @ RT	70		65		74	
FM @1% secant	1750		1890		2170	
NI @ RT	52		51		59	
MI	4.7		3.6		2.7	

Table A3: Properties of general purpose homopolymer PP-Talc-Glass Bubble composite (Figure 8 samples)

	Formula 1		Formula 2	
	PP-T20		PP-T10 GB4 -M	
	wt%	vol%	wt %	vol%
PP-General Purpose	80	92.5	83	85.5
Glass Bubbles iM16K			4	8
Talc	20	7.5	10	3.4
MAPP			3	3.1
Density (g/cc)	1.046		0.943	
TS @ RT	31.7		32.7	
TS @ 90°C	12.5		13.5	
EL (%)	10		12	
TM @RT	2110		1835	
TM @ 90°C	270		250	
FS @RT	49		50	
FM @1% secant	1650		1620	
NI @ RT	32		39	

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