Evaluation of heat management in injection mould tools

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The control and management of heat in injection mould tools is a vital requirement for obtaining optimum production processing conditions. This paper describes an investigation that compared conventional mould cooling methods with a relatively new technique called 'pulse cooling technology' (PCT). The principle of PCT is the use of an intermittent flow of the cooling medium in the mould tool with accurate control of the mould cavity surface temperature during the injection moulding cycle.

A mould tool instrumented for cavity pressure, cavity surface temperature and mould background temperature measurements was constructed for the study. Results showing the effectiveness of PCT compared with conventional cooling are presented for polypropylene (PP), polycarbonate and filled PP with talc and aluminium powders. A reduction of up to 22% of the conventionally cooled moulding cycle time for unfilled PP has been recorded when pulsed mould cooling was used.

Keywords: Injection moulding, Mould cooling, Pulsed cooling, Mould temperature control

Introduction

The objective of the temperature control system in an injection mould tool is to maintain a consistent cavity surface temperature cycle that is essential for part reproducibility in injection moulding. Changes in the cavity surface temperature cycle can result in a variation in properties, such as shrinkage, internal stress, warpage and the surface quality of mouldings.

The efficiency of the cooling system is a major factor that will affect the overall cycle time, as it is the time to cool the moulding from its injection temperature to a temperature at which it can be ejected from the mould tool that typically forms the largest portion of the moulding cycle time. The thermal properties of the mould material, the design of the cooling channels, the part section thickness, the properties of the processed material and the temperature of the cooling medium will all contribute to the efficiency of the tool.[1]

Numerous commercial products have been designed to improve the efficiency of the removal of the heat from a thermoplastics injection mould tool. Examples of some of these are as follows:

(i) alloys with high thermal conductivities based on beryllium and copper have been used for the production of mould inserts
(ii) conformal cooling channels have been used to achieve uniform heat removal from complex moulded sections
(iii) cooling probes and special designs to create turbulent flow in the cooling agent.

All of these features can offer significant benefits to the efficiency of the cooling of the mould tool, but they do not provide for the management of the heat extraction in the mould tool.

The conventional method of cooling that is used in the industry involves a temperature control unit that supplies a cooling fluid to the mould tool at a set temperature. The sensor used to control the temperature of the coolant can be situated in the mould tool or in the control unit. The main feature of this method of cooling is that the coolant is constantly flowing and that typically only one controlling sensor is used on a mould tool.

Over the last 15 years, a mould cooling process that claims to effectively manage the heat transfer in injection mould tools has been developed.[2,3] The process known as 'pulsed cooling technology' or 'PCT' operates with controlled pulses of the coolant to separate cooling zones in the mould tool. It also uses the heat supplied by the injected resin melt to maintain the temperature of the tool so that only the excess heat from that source is extracted from the mould.[2,3] A brief description of the operation of PCT is as follows:

(i) the mould is initially heated by the polymer that is moulded during the set-up procedure for the tool. Alternatively the tool can be initially primed by using an auxiliary heating system
(ii) when the mould reaches the set temperature the pulsed cooling control takes over. The mould surface temperature in each of the zones of the tool is used to control the demand for coolant
(iii) The PCT control is programmed to supply pulses of the cooling fluid only when the mould surface sensors demand it

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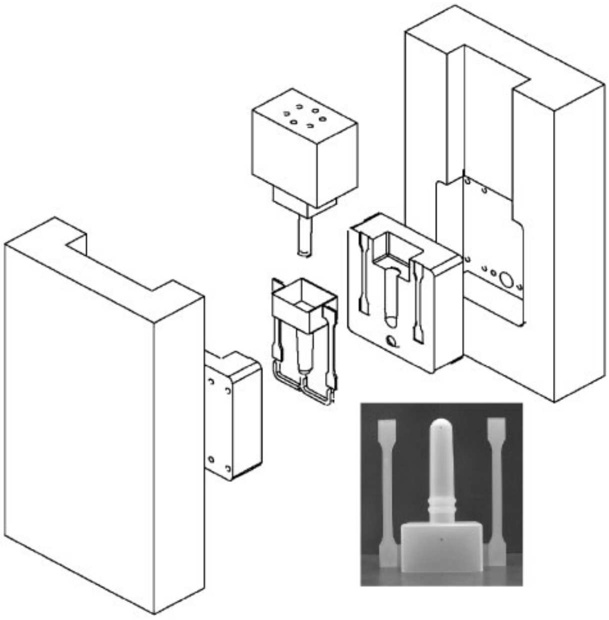


1 Schematic of five main elements of trial mould tool: moulded test piece is shown in centre of diagram; photograph of PP moulding from tool is shown in insert

(iv) The process works efficiently when the mould cavity surface temperature reaches the same value at the start of each moulding cycle.

The main feature of PCT is that the cavity surface temperature in the mould is used to control the supply of the coolant. All that the PCT control has to do, therefore, is to remove the excess heat supplied to the tool by the polymer and maintain an accurate mould surface temperature during the cycle. A significant feature of PCT is that with the use of the controlled pulses of the cooling medium lower coolant temperatures than those used in conventional cooling methods can be used.

As stated PCT has been available to the industry for about 15 years but in that time no detailed evaluation of the process has been carried out on the process. It was, therefore, the objective of this study to evaluate PCT and compare it with the conventional mould cooling method. In order to achieve this objective, an injection mould tool was constructed with provision for both conventional (direct) cooling and PCT. The paper describes the evaluation of both cooling methods and gives an assessment of them with respect to the moulding cycle time, consistency of cooling and ease of set-up and operation.

Experimental

Mould tool

The trial mould tool was designed to have both direct cooling (DC) that is widely practiced by the polymer processing industry and a commercial pulsed cooling technique as supplied by RE Promotion Services Limited, UK.

A schematic diagram of the mould tool is displayed in Fig. 1 and it shows the moulded component at the centre of the figure. A photograph of a polypropylene (PP) moulding is shown in the insert.

The moulded component comprises of three sections: a hollow box section 2 mm in thickness, a hollow tube section 2 mm in thickness and two ISO mechanical test bars. The cavity was gated at the three points shown in Fig. 2, and was designed so that they could be switched enabling cavity filling from any combination of one up to three gates. The cavity instrumentation (Fig. 2) included four Kistler type 6190A pressure–temperature sensors controlled by Kistler type 5049A Smart amplifiers. The cavity pressure was recorded from the transducers located opposite the gates.

Three separate temperature controlled zones were required on this mould tool: on the fixed plate, the moving cavity plate and the central core piece. Figure 3*a* and *b* shows the position of the three thermistor probes (REPS AP1/8 105/145) in each of the controlled temperature zones.

Figure 3*a* is a diagram of the cooling channels used in the conventional operation. In order to make a direct comparison between the PCT and conventional cooling, the conventional arrangement was set up to run with three water heater/coolers, one for each of the temperature controlled zones. It is to be noted that the conventional cooling included channels in the main bolster plates of the mould. The temperatures of the zones were monitored by the three probes and were adjusted by alterations to the coolant temperature on the individual temperature controllers.

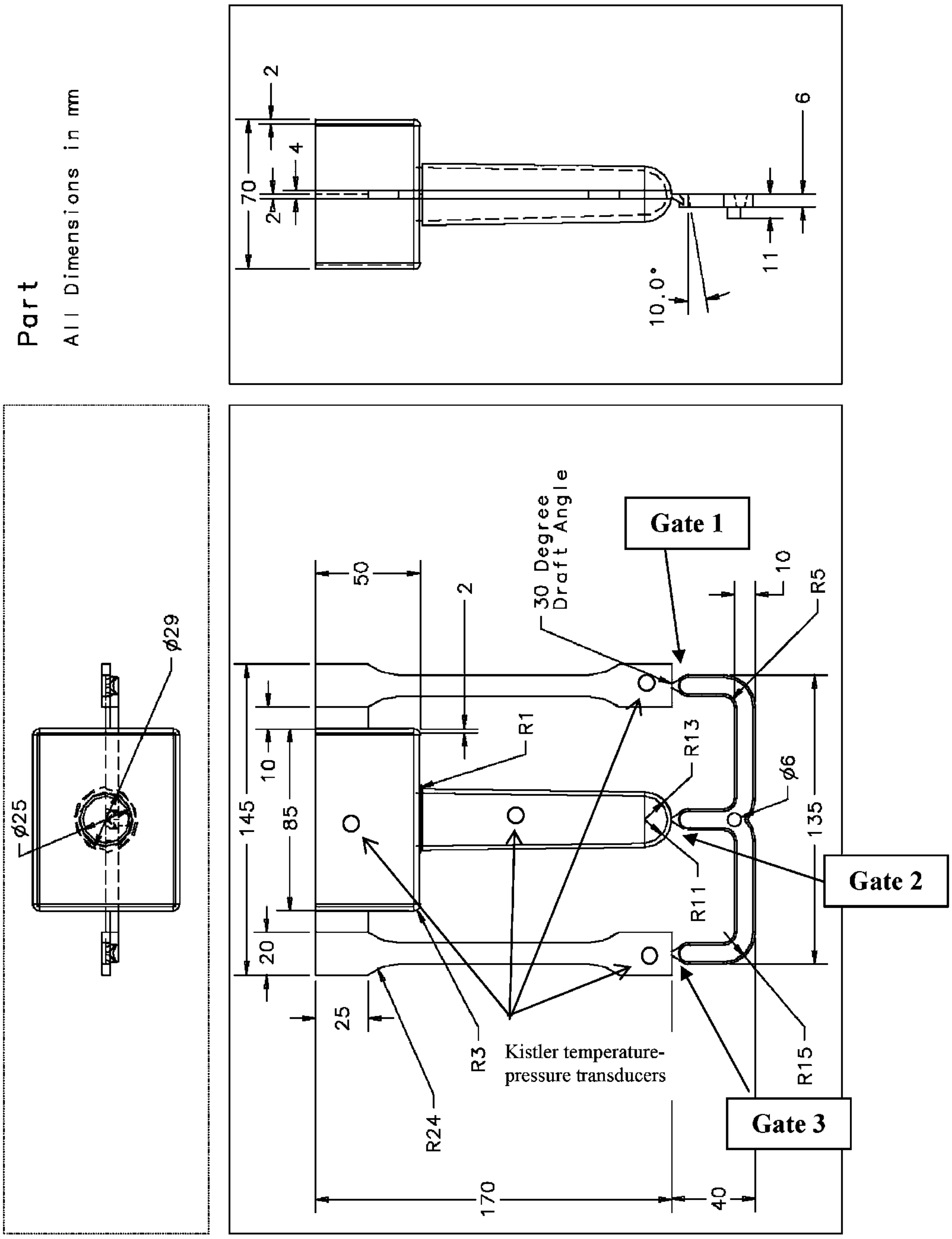
Figure 3*b* shows the arrangement for the PCT. It is to be noted that the channels labelled 'not used' could be brought into action to boost the initial heating of the tool before moulding. These channels were not used when the moulding commenced and the PCT control was switched on. The temperature of the three zones was maintained by closed loop control of the coolant pulses using the three temperature sensors connected to three channels on the PCT controller. The controller only supplied the pulses of coolant when the respective temperature probe indicated an increase over the set temperature.

All the pressure and temperatures sensors were connected to an Adept Strawberry Tree Data Shuttle Express (Adept Scientific, Letchworth, UK) and a computer running DASYLab for data acquisition and analysis.

Injection moulding

The mould was evaluated on a DEMAG 150 NCIII injection–moulding machine with the following resin compounds:

(i) polycarbonate, unfilled (GE Plastics LEXAN 141R)
(ii) polypropylene, unfilled (Moplen SM 6100 from Basell)
(iii) polypropylene (Moplen SM 6100 from Basell) talc (LUZENAC no. 2) filled 10, 20 and 30 vol.-%
(iv) polypropylene based conductive compounds. The base compound was a commercially available compound containing 44 vol.-% of a thermally conductive filler (mainly aluminium powder) (Konduit MT-210-14 supplied by LNP Engineering Plastics). This was used as supplied and also in compounds diluted with PP (Moplen SM 6100) to give 33, 23 and 11 vol.-% of the conductive filler.



2 Component drawing showing runner, gates and locations of four cavity pressure–temperature transducers

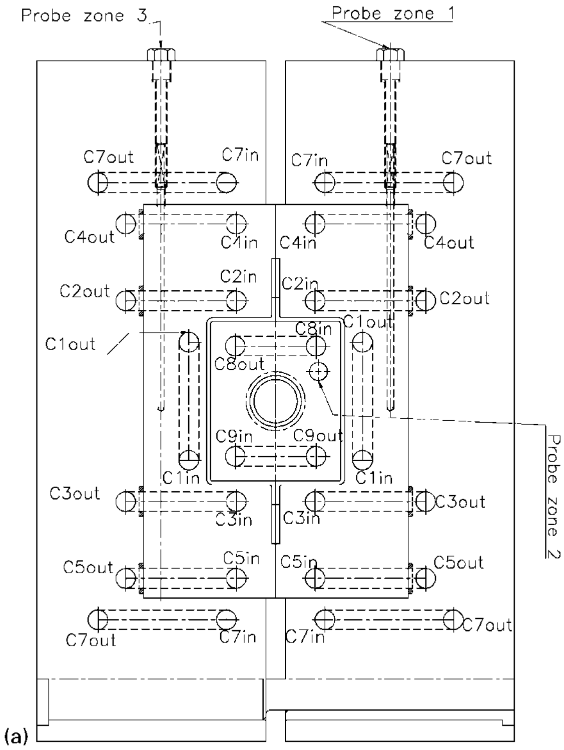
The talc filled PP compounds were made by blending PP powder (ground from pellets), with the dried talc powder in a V-blender and then compounding the mix in a corotating twin screw extruder (a Betol TS40).

The moulding trials for both conventional cooling and pulsed cooling were carried out with injection gates 1 and 3 on the ends of the tensile bar cavities (Fig. 2). When the basic moulding conditions had been established for a moulding run, the cycle was finally optimised by the use of cavity pressure monitoring to set the stroke position at which injection pressure was switched to holding pressure.

The injection–moulding machine was set to operate in the fully automatic mode and was allowed to stabilise before any readings were recorded on the data acquisition system. After the moulding conditions had been set for a particular resin compound, the same conditions were used for both conventional cooling and PCT. This meant that any difference in the cycle time between the two sets of mouldings could be directly related to the mould cooling method used.

Typical mould cavity pressure and temperature traces are shown in Fig. 4*a* and *b* respectively. The mould cooling time is taken from the point when the cavity is volumetrically full, (at the change over from injection pressure to holding pressure) to the point when the cavity pressure dropped to atmospheric. The cycle time was established from the temperature sensor profiles, as indicated in Fig. 4*b*. The mouldings were produced using both direct cooling and pulsed cooling at various set mould temperatures.

For the pulsed cooling experiments, the coolant temperature was set at 11°C. The mould for the trials was set up according to the principles of pulsed cooling[3]



3 **Piping of mould tool for *a* conventional cooling and *b* pulsed cooling: in Fig. 3*a* all of channels were installed in line with typical moulding practice. It is to be noted that cooling in zones 1 and 3 is active in whole of cavity plates; in Fig. 3*b* channels marked 'Not used' could be used for initial heating but they were not used with PCT during moulding**

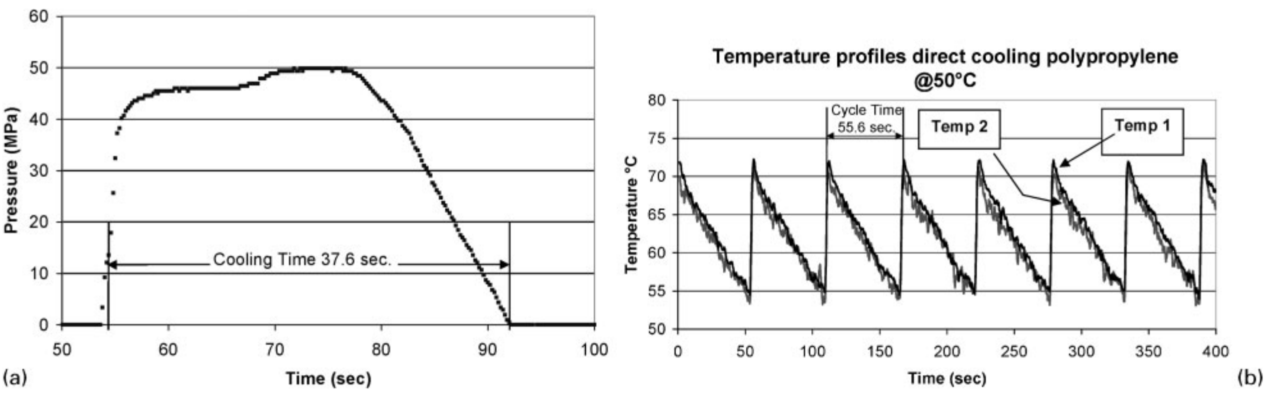
given in the introduction involving the following procedure:

(i) the required mould temperature was set on the PCT controller and the moulding run started
(ii) the tool began to heat up as the moulding progressed and when the temperature of the mould exceeded the set temperature, the controller initiated pulses of coolant to the mould
(iii) as moulding continued, the PCT controller was able to control the mould temperature so that the temperature of the mould cavity surface was constant and at the set temperature at the start of each moulding cycle.

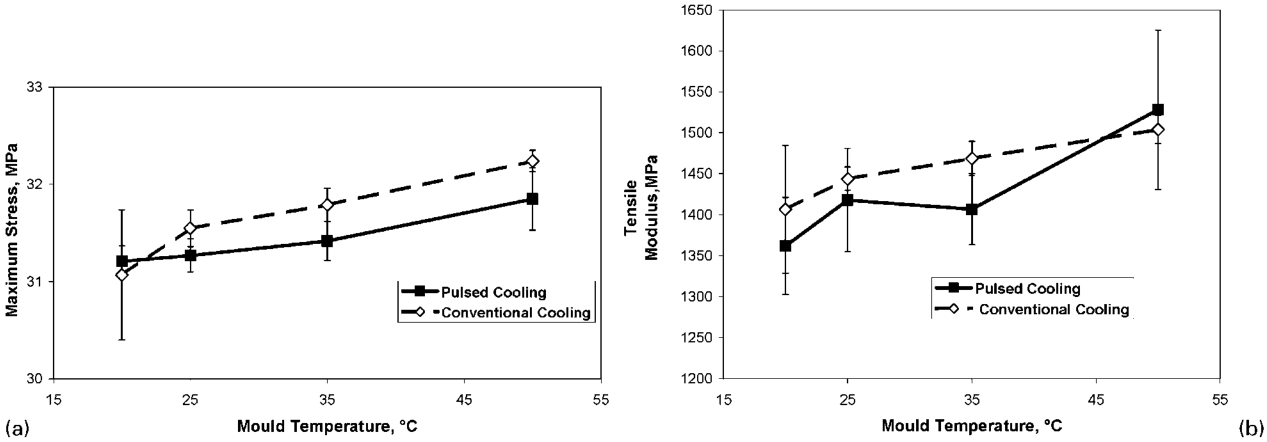
In the direct (conventional) cooling experiments with three water heaters, the set mould temperature was achieved by individually controlling the temperature of the water heaters until the required mould temperature was reached as indicated by the three sensors in the cavity. It should be noted however, that these sensors would not be installed in normal industrial practice. Ten mouldings were collected at each set mould cooling temperature and the temperatures and pressures within the mould cavity were recorded by the data acquisition system.

Mechanical Testing

Samples of the ISO standard tensile bar forms in the mouldings from all of the trials were tested in tension with a crosshead speed of 50 mm min^{-1}. Figure 5 shows results of the maximum tensile stress (Fig. 5*a*) and the tensile modulus (Fig. 5*b*) plotted against the set mould temperature. It can be seen from the results that there was little difference in the tensile modulus properties between the mouldings made with the pulsed mould



4 ***a* typical cavity pressure profile for PP using direct mould cooling with mould temperature of 50°C and *b* typical sequence of mould cavity surface temperature profiles taken from positions close to gates 1 and 3 (Fig. 2) in moulding run of PP with direct cooling and mould temperature of 50°C**



5 *a* maximum tensile stress and *b* tensile modulus of PP mouldings made with pulsed and conventional mould cooling for mould temperatures ranging from 20 to 50°C

cooling compared with those made with conventional mould cooling. Generally both the modulus and the maximum stress values from the pulsed–cooled mouldings were slightly lower than those from the conventional mouldings. This is consistent with the reduced cooling time recorded for the mouldings made with pulsed cooling compared with the conventional mouldings.

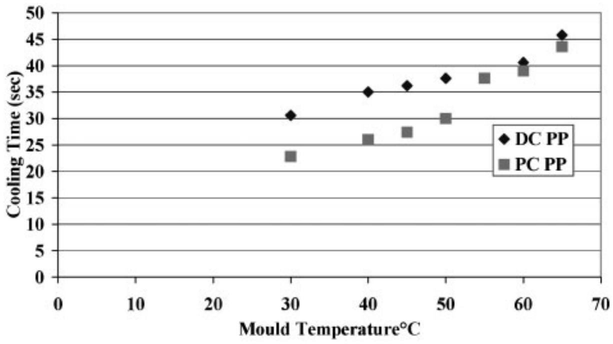
Results and discussion

Polypropylene

The variation in cooling times with mould cooling temperatures for PP is compared in Table 1 and displayed graphically in Fig. 6.

It should be noted that in the direct cooling experiments the coolant temperatures were set lower than the required mould temperature in order to achieve this value. The coolant temperatures were set during the moulding run in response to the recorded zone temperatures, a practice that would not be normal in industry. This procedure did, however, allow a direct comparison to be made between direct cooling and PCT at the set mould temperatures.

The recorded cooling times clearly demonstrate the greater efficiency of pulsed cooling over direct cooling in these moulding trials. The main reason for this observation is that the PCT operates with a lower coolant temperature than the direct cooling method. The greater efficiency of the PCT is, therefore, due to the greater temperature difference between the coolant and the mould cavity (ΔT) than that of the direct cooling.[4–6]



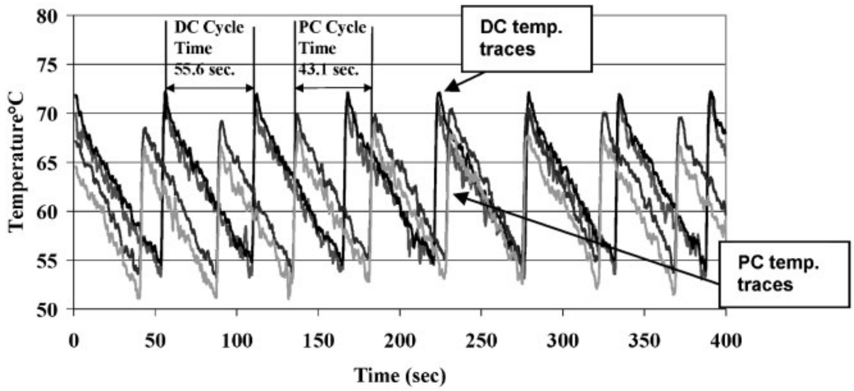
6 Cooling time versus mould temperature for pulsed and direct cooling of PP

Figure 7 shows the temperature plots from the sensors opposite the gates in the tool. These traces give an accurate measure of cycle time and show that PCT reduced the conventional moulding cycle time by 22% for the trial mould run with PP at a cavity temperature of 50°C.

It is evident from Fig. 6 that over the temperature range investigated, the benefits in terms of cycle time reduction from the PCT are the greatest at the lower mould temperatures and decrease significantly when mould temperatures exceed ~55°C. The reason for this is that as the mould temperature is increased, there will be an increase in the proportion of the heat lost by the mould to the surroundings by convective, radiant and conductive processes. Consequently a greater proportion of the heat supplied to the mould by the moulding resin is lost to the surroundings than at the lower mould

Table 1 Mould/zones set temperatures and cooling times for both pulsed and direct cooling

	Coolant temperatures for the three zones (direct cooling only), °C			Cooling time, s	
Mould cavity temperature for all three zones (Conv. and PCT), °C	Fixed	Moving	Core	Conventional/direct	Pulse cooling (coolant at 11°C)
30	20	26	28	30·6	22·8
40	30	36	38	35	26
45	35	41	42	36·2	27·8
50	41	46	48	37·6	30
55					37·6
60	52	58	57	40·6	39
65	58	62	61	45·8	43·6



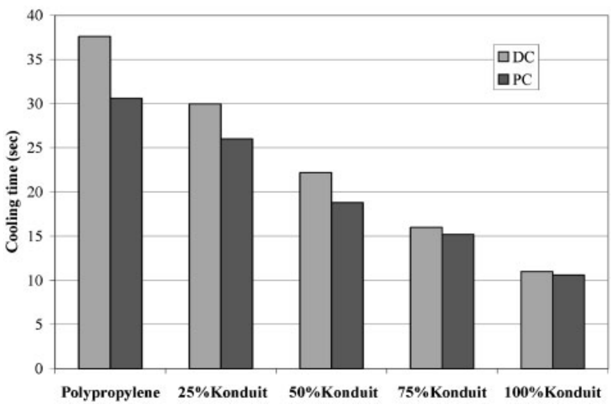
7 Comparison of cycle time between pulsed and direct mould cooling of PP shown by recorded traces of mould surface temperature: set mould temperature was 50°C

temperatures. The demand on the PCT will, therefore, reduce as the mould temperature is increased. There will eventually be a mould temperature at which the heat supplied by the moulded resin will equal the heat lost by the mould to the surroundings. From Fig. 6 this temperature was ~60°C for the mould and PP combination used in this study.

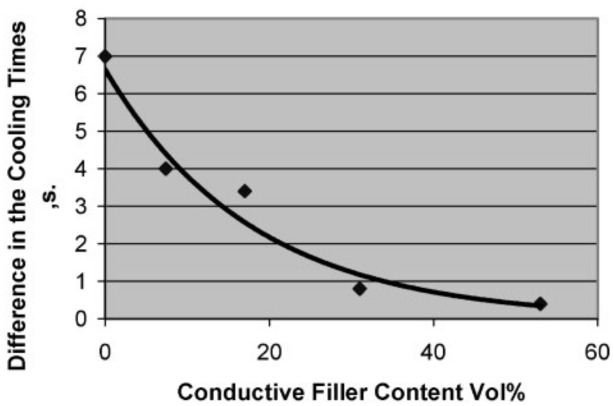
It is also expected that the benefits of PCT will decrease as the set mould temperature decreases provided that the PCT coolant is kept at 11°C. The reason for this is that the coolant temperature of the direct cooling method will approach that of the PCT and thus the advantage of the lower coolant temperature used by PCT over the conventional method will be lost. It should be possible to restore the advantage of the PCT at low mould temperatures if the coolant temperature was further reduced. This may, however, be accompanied with problems of condensation on the cooling equipment.

Thermally conductive polypropylene compound

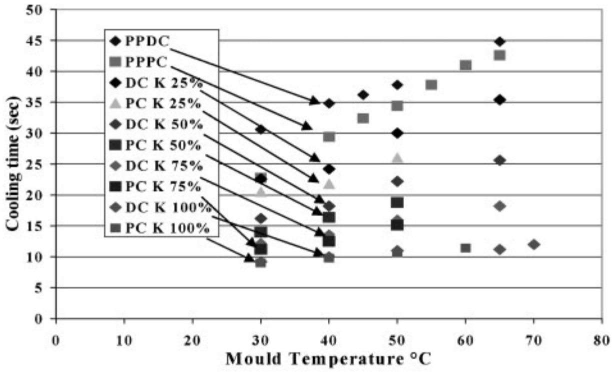
Results for the thermally conductive compound of polypropylene (Konduit MT210-14) are displayed in Figs. 8 and 9. Figure 8 shows that undiluted Konduit reduced the cooling time by 60% compared with the pure PP at a mould temperature of 50°C. The results from the diluted compounds of Konduit are presented in Fig. 9 and show that the difference between cooling times of the mouldings made with direct and pulsed cooling decreases as the thermal conductivity (and content of Konduit) increase. In fact the cooling time for the undiluted Konduit shows very little change over the whole mould temperature range and identical values were obtained from mouldings made using PCT and conventional cooling. This result implies that as the thermal conductivity of the moulding material increases, the temperature difference between the coolant and the mould becomes a less important factor in influencing the cooling time.[5] In order to explain this further the heat capacities of the mouldings were calculated from the specific heats of PP and aluminium (this was the main additive in the Konduit compound). The results from this showed that the heat content of the pure PP moulding was ~8% greater than the heat capacity of the undiluted Konduit compound. More significantly, the thermal conductivity of the undiluted Konduit was ~5·5 times that of the pure PP. Both of these results indicate that the heat from the Konduit compound will, as expected, be removed significantly faster (~5 times) than the heat from the pure PP. The results from the moulding trials show that the cooling time for the undiluted Konduit is ~4 times less than that for the pure PP (Fig. 8). Figure 9 shows the effect of the volume content of the conductive filler (Al powder) in the PP on the difference recorded between the cooling times for the pulsed cooling and the conventional mouldings of the compounds with a mould temperature of 50°C. It is believed, therefore, that as the content of the conductive filler increases the rate of extraction of the heat from the mouldings increases and eventually becomes too fast for the pulsed cooling controller to react effectively. This



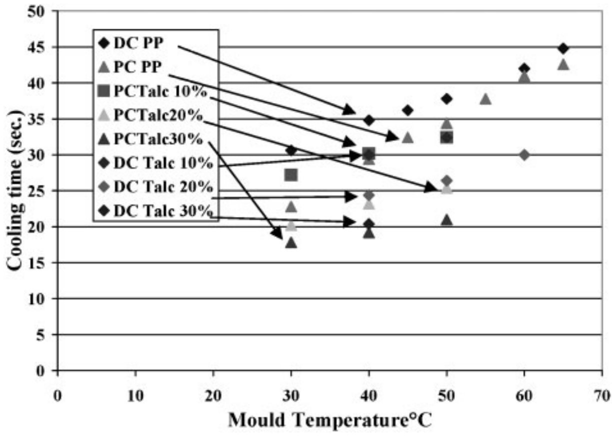
8 Cooling times for direct and pulsed mould cooling for Konduit–PP compounds at mould temperature of 50°C



9 Difference in cooling time between PCT and DC mouldings related to content of conductive filler (Al) in PP with mould temperature of 50°C



10 Cooling time versus mould temperature for Konduit–PP compounds: difference between pulsed cooling and direct cooling times can be seen to reduce to almost nothing for undiluted Konduit



12 Cooling time versus mould temperature for talc filled PP

result is further illustrated in Fig. 10 that gives the results obtained from the other mould temperatures used in the experiments. In fact the cooling time for the undiluted Konduit shows very little change over the whole mould temperature range and identical values were obtained from mouldings made using PCT and conventional cooling.

The conclusion is that for the PP mouldings the pulsed cooling controller would have had time to be more effective in removing the heat from the moulding than the conventional cooling process but the rate of heat extraction from the Konduit moulding was too fast for the pulsed cooling to provide an advantage.

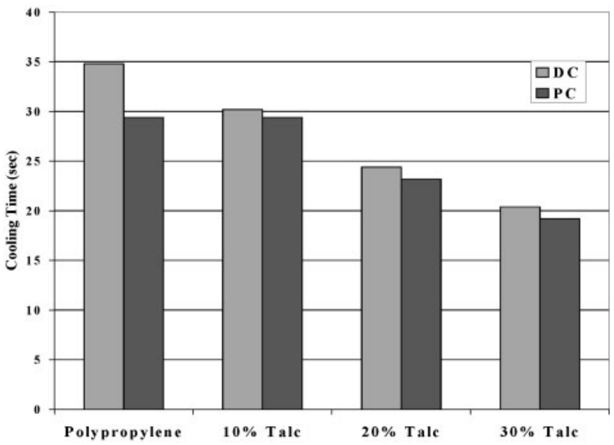
It is to be noted, however, that the position of the controlling sensors was 21 mm from the mould cavity surface. If this distance could be reduced it would be expected that the reaction time of the pulsed cooling controller would decrease and that the effects of the pulsed cooling would become more evident with the conductive compounds than has been recorded in this study.

Talc filled polypropylene

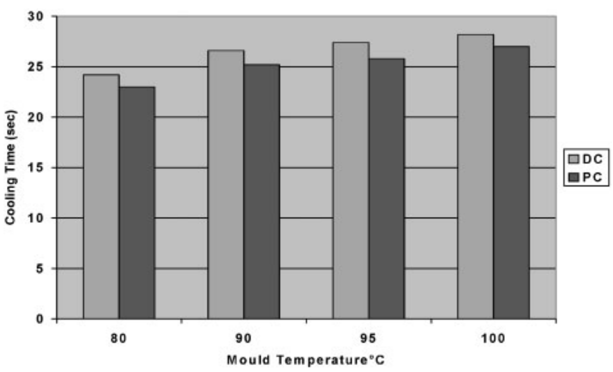
The results for talc filled PP are shown in Figs. 11 and 12. The trend in the cooling time was similar to that observed for the Konduit based compounds. The increase in the level of the talc filler produced a decrease in the cooling time although the effect was not as pronounced as the metal filled conductive compound described in the previous section. The PP compound with 30 wt-% of talc filler reduced the cooling time with direct cooling by 40% of the pure PP cooling time. The result from the 10% talc filled PP using PCT did not, however, conform to this trend (Fig. 11). The experiment was repeated with the same result. An explanation for this was not found during the course of this project. It has been shown, however, that talc flakes have a high degree of anisotropy with respect to their thermal conductivity.[7,8] Injection mouldings of talc filled PP display this feature with the thermal conductivity being significantly higher along the injection direction than that in the direction perpendicular to the moulded surface.[7,8] It is still difficult, however, to explain the results of the 10% talc filled mouldings in relation to the anisotropy of the talc particles.

Polycarbonate

The results for polycarbonate are given in Fig. 13. They show an expected increase in the cooling time with an increase in the mould temperature. The difference between the cooling times for the PCT and conventional mouldings is small compared with some of the PP results. As for the PP experiments, this can be explained by the fact that a greater proportion of heat supplied to the mould by the injected melt is lost to the surroundings at higher than at lower mould temperatures. The use of PCT for the moulding of resin compounds that require mould temperatures above $\sim$80°C will not offer significant benefits on the cycle time compared with the



11 Cooling times for direct and pulse cooling for talc filled PP at mould temperature of 40°C



13 Comparison of direct cooling with pulse cooling for polycarbonate at various mould temperatures

use of conventional mould cooling.[6] There are, however other benefits that PCT can offer over conventional cooling for all injection conditions and these are discussed in the next section.

Other benefits of PCT

The other benefits that PCT can offer over conventional/direct mould cooling are related to the setting up of moulds for production and the efficiency of the system. It has been stated that the conventional method used in this work was not a system that would be normally used in industry. The arrangement used was the independent conventional cooling of the three mould zones by three temperature control units. In order to run this effectively the sensors used by the controllers would have to be installed in the mould in the positions that are recommended for the PCT. The use of independent cooling units for direct cooling of the mould tool would become more impractical as the number of temperature zones in the mould increases. The PCT controller, however, would be a compact unit even for a large number of temperature zones.

Pulsed cooling is also expected to be more energy efficient than conventional cooling. This is based on the principle that conventional cooling requires the constant pumping of coolant whereas the pulsed cooling only works on short pulses of the coolant. A second study[9] on the pulsed cooling technology within the 'Enhanced polymer processing programme', has demonstrated that up to 23% saving in the energy required to cool a mould could be achieved with the use of pulsed cooling compared with conventional cooling methods.

Conclusions

The following conclusions have been drawn from the study.

1. Pulsed cooling of injection mould tools can reduce the moulding cycle time compared with that obtained with conventional/direct mould cooling. The cycle time for the PP moulding was 22% less using pulsed cooling compared with conventional cooling with a mould temperature of 50°C.
2. The main reason for the reduced cycle time using pulsed cooling is that the temperature of the coolant can be significantly lower than that needed for conventional cooling.
3. Pulsed cooling technology offers more compact equipment than conventional cooling. One central cooling unit could feed several moulding machines fitted with pulsed cooling controllers. The controllers would use the same input temperature of the coolant but could control their respective moulds at the different set temperatures.
4. Pulsed cooling has been shown to be more energy efficient than conventional cooling on a single mould tool.[9] This efficiency could be further exploited because a single multi channel pulsed cooling controller could be used to control several mould tools whereas conventional cooling would require a multiplicity of controllers to cover the same number of moulding machines.
5. The benefits of pulsed cooling compared with conventional cooling reduce with an increase in the mould temperature and with the inclusion of a conductive filler in the polymer. However, it is believed that if the positions of the pulsed cooling control sensors were made closer to the mould surface than those used in the study, the benefits from the pulsed cooling would be enhanced.
6. No significant difference in the mechanical performance was measured between the mouldings made in the study by pulsed cooling and those made by conventional cooling.

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