Study of injection mold temperature and cooling time engineering essay

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Majority of complicate plastics products are formed by the injection molding process. Faster production rate and repeatability are the key elements. Although most of the injection molding machines are highly sophisticated in terms of process control yet the control of mold temperature is the most neglected aspect. The mold cooling time contributes a major portion (usually 30 to 60%) of total cycle time. Reduction in mold cooling time is directly associated with profitability. The effect of mold temperature on cooling time and product quality is very important to understand. Here an effort has been made to analyze various aspects of mold cooling.

Introduction

Injection molding is one of the most favorite processing methods among the polymer processors that has revolutionized the polymer processing. Continuous research work carried out by the injection molding machine's manufacturers is the key behind the success of this processing technique. Today's injection molding machines are one of the most sophisticated in terms of process control. Various processing parameters like injection pressure, injection speed, hold – on pressure, cavity pressures etc. are very precisely controlled by close loop control. Latest developments in the field of microprocessors/ microcontrollers technology resulted in PLC's, with very short scan time, for quicker response. Many other developments like advancements in plasticizing screw design, mould safety, all electrical actuators, robotic part removal etc. came into existence in early nineties [1].

Although a lot had happened at the technological front, still the control of mould temperature is the most neglected aspect of injection moulding technology. In spite of well known relationship between mould temperature and cooling time, in other words mould temperature has great effect over cycle time (that ultimately leads to profitability), no serious efforts has, however, been made to extend the advancements in process control up to the mould. As on today most of the processing industries involved in injection moulding business, especially in Asian countries are using either a cooling tower or refrigerated chilling plant and seldom a mould temperature controller for engineering/ specialty polymers. In fact moulders usually do not bother about the mould temperature. In most of the cases, setting of cooling time and adjustment of mould temperature is an experience driven exercise that may not always land up at optimum solution [2].

In this paper an effort has been made to take a deeper insight of various aspects of mould temperature and cooling time by modeling and simulation route. An innovative design concept of mould temperature controller is also discussed which is in its early developing stage.

Heat Transfer in Injection Mould

Heat transfer in injection mould is quite complex in nature. It involves conductive and convective type of heat transfer, although negligible heat loss from mould takes place in form of radiation [3]. The solidification process for molten polymer mass inside mould involves a complex heat transfer mechanism. In order to simplify the problem of heat transfer associated with turbulent fluid flow, here an assumption is made defining a constant temperature between the cavity wall and cooling channels of mould. However in actual practice a temperature gradient will exist depending upon the thermal conductivity of mould steel.

The typical heat path in the cooling stage of injection molding is that heat is conducted from hot polymer to the comparatively cold mold, and then conducted through the mold to the cooling line, where it is removed by convection through coolant [7]. In injection molding, in order to reduce the cycle time, the coolant undergoes turbulent flow. Rapidly flowing fluids are fully turbulent when Re > 10, 000 the transfer of heat is very efficient. Slowly flowing fluids are laminar when Re < 2000 and hear transfer is relatively poor. As such, the Reynolds Number can significantly influence the cooling of the injection molded part.

For turbulent flow, Equation 1 is used to calculate the heat convection coefficient [5],

… (1)

Where: d; diameter of cooling hole (m), V; coolant velocity (m/s), Ï🚺; coolant density (kg/m€ˆ), Î¼; viscosity, h; convection heat transfer coefficient (W/m. K), k; thermal conductivity (W/m². K), L; perimeter of the cooling hole (m).

For this case, Re is > 10, 000, so the flow is fully turbulent.

A simulink model was developed to simulate the variation of mold temperature from start – up to approximately 1 hour and 23 minutes run with following conditions [6];

Table – 1: Conditions for Simulation

Initial Melt Temperature

523 deg. K

Initial Mold Temperature

298 deg. K

Ejection Temperature

364 deg. K

Mass of Mold

200 kg

Specific Heat of mold (P-20 steel)

461. 2 J/kg – k

Cycle Time

30 sec

Injection Time

5 sec

Cooling Time

20 sec

Material

ABS plastic, Grade: Cycolac GPM550

Thermal Conductivity of ABS

0. 22 (W/m. deg. K)

Specific Heat of ABS

2352. 4 (J/kg. degK)

It is usual practice among molders to run injection molding machine for few (10 – 20) cycles without flow of coolant in mold to increase the mold's surface temperature up to the required mold temperature [7]. This is usually done to avoid short – shots, flow lines and other possible molding defects. A dead zone has been incorporated in simulink model for 450 sec (about 15 molding cycle). This effect can be seen in plot. Initially the rise in temperature is rapid (up to 450 sec) compared to rest of the part of plot.

Fig 1: Graphical representation of Model using Simulink

Fig 2: Simulation Result for mold temperature for more than 150 cycles from startup.

It is clear from the plot shown in fig – 2, that under the conditions as defined in table – 1, mould will take about 1hour to reach steady state temperature of about 320 deg. K

Dependence of Cooling Time over Mould Temperature

Cooling time is defined as the time required to reduce the temperature of molten polymer up to ejection temperature. Usually ejection temperature of moulding is few degree (20 – 30 degC) below the heat deflection temperature (HDT) of material to insure distortion free removal of moulded part. Cooling time starts just after complete filling of cavity up to ejection. A rough estimation can be made for the cooling time, using the correlation given below;

... (2)

... (3)

s; part thickness (cm), Î±; thermal diffusivity (cm. sq/ sec), Tm; melt temperature (°C), Tw; mold temperature (°C), Te; ejection temperature (°C), K; thermal conductivity (W/m-°K), Ï ; density (gm/cc), Cp; Specific heat (KJ/Kg-°K)

It is clear from simulated result shown in fig. – 2 that mould temperature is not a constant, in fact it is not only a variable from startup temperature to steady state temperature but also it changes during each cycle, fluctuating about cycle average temperature [5].

In order to simulate the cooling time for one injection cycle the instant energy balance equation for cooling of given geometry of part can be written as;

... (4)

This equation can be solved using finite element method with suitable boundary conditions i. e. constant boundary temperature or constant heat flow rate. For simplification of problem, a square shaped, ABS plastic part has been chosen. The two dimensional drawing and 3-D view of the part under analysis is given below;

Fig-3: Two Dimensional orthographic view and three dimensional view of ABS Plastics part under analysis.

ABS plastic material was selected for above geometry of part, the processing conditions and properties of the polymeric material are given below;

Table-2: Processing conditions and properties of material

Initial Melt Temperature

523 deg. K

Initial Mold Temperature

323 deg. K

Ejection Temperature

345 deg. K

Material

ABS plastic, Grade: Cycolac GPM550

Density

1005 (Kg/m€ˆ)

Thermal Conductivity

0. 22 (W/m. deg. K)

Specific Heat

2352. 4 (J/kg. degK)

In order to simplify the analysis and to reduce the simulation time, the analysis was done in 2 D. Transient thermal analysis was carried out using ANSYS 5. 4. For the analysis 4-node thermal solid (PLANE55) element type was selected.

Fig-4: Temp distribution at t = 50sec at mold temp = 312 K

The 2 D model was suitably meshed and analysis was done with different mold temperatures, given in table – 3. Polymer melt temperature and part ejection temperature were kept same.

Table – 3: Polymer melt temperature vs. simulated cooling time

Polymer melt Temperature = 523 deg. K

Part ejection temperature = 345 deg. K

Mold Temperature

(deg. K)

Cooling Time

(Sec)

312

62. 5

323

70

333

92. 5

343

130

Cooling time was graphically calculated at a point where the part temperature was below HDT i. e. 345 K, for each of the run. ANSYS Post processor was used to obtain the cooling time vs. temperature data.

(A). Mould Temp = 323 K, Ejection Temp = 345 K and Cooling Time = 70 sec

(B). Mould Temp = 312 K, Ejection Temp = 345 K and Cooling Time = 62. 5 sec

(C). Mould Temp = 333 K, Ejection Temp = 345 K and Cooling Time = 92. 5 sec

(D). Mould Temp = 343 K, Ejection Temp = 345 K and Cooling Time = 130 sec

Fig-5: Dependency of cooling Time over Mold Temperature

It is clear from the above plots that the temperature gradient (between melt and mould) is a diminishing quantity during every moulding cycle. In other words we can say that rate of heat transfer from melt to coolant is maximum at the start of cooling time and reaches to its minimum value at the end of cooling time. This diminishing rate of heat transfer is responsible for longer cooling time resulting higher cycle time [8].

Mould Cooling At Constant Heat Transfer Rate

The cooling time may be defined as the ratio of total heat to be removed (so that ejection temperature is below HDT), to rate of heat removal from the mould via coolants flowing in cooling channels of the mould. As mentioned above that diminishing temperature gradient (due to cooling of polymer melt inside the mould) is responsible for diminishing rate of heat removal during every moulding cycle. In order to have deeper insight, we apply heat balance to mould;

… (5)

It is clear from Fig. – 2 that the temperature of mould increases initially and ultimately reaches to steady state average constant temperature within few hours depending upon the size of mould and moulding. At this stage the rate of heat accumulation in mould will be negligible, therefore at steady state condition of mould;

… (6)

(i). Rate of Heat Input

Rate of heat input to the mould may be considered as impulse input, since the most of the polymer melt (about 90% of shot weight) is injected in very short span of time (), comparatively very less than actual injection and hold time. The heat input rate to the mould;

... (7)

m = shot weight, Cp = specific heat at nozzle temperature.

(ii). Rate of Heat Removal

For simplicity we can assume the design of mould to be cylindrical, where four cooling channels are at 100 PCD, concentric with cylindrical shape of cavity as shown in Fig. – 6,

Fig – 6: Top view – Cylindrical Mould

The rate of heat removal from the mould is function of heat transfer by conduction and convection (we can neglect the heat transfer by radiation). For the cylindrical design of mould and moulding, the conductive and convective heat transfer can be written as [9];

... (8)

... (9)

Ksteel; Thermal conductivity of mould steel (W/m-°K), Dmold & Dpart; Diameter of cylindrical mould and moulding (m), Dchannel; Diameter of cooling channel (m), h; Convection heat transfer coefficient (W/m. K),

Therefore, the net rate of heat transfer will be;

... (10)

It is obvious from equation no. (10). that rate of heat removal (q) will continuously reduce because the Tmelt will tend towards the Tejection. The trend of melt temperature curve with time will be as shown in fig – 5. There may be two different methods to keep the rate of heat removal (q) constant i. e. reduction in coolant temperature (Tcoolant), parallel with (Tmelt) so that temperature gradient is constant during entire cooling cycle. This method has some practical difficulties like limitation of very fast changing temperature of coolant, thermal shock to the mould and lots of energy drain from coolant to atmosphere. In the next approach to maintain constant heat removal rate, the flow rate of coolant can be increased with time to increase the value of film transfer coefficient (h).

Booth of these problems were modeled using Matlab and simulated results are discussed. The following boundary conditions and data was used for simulation;

Table – 4: Boundary Conditions and data

Parameters

Value

Dmold

100 mm

Dpart

15 mm

Ksteel

36. 6 W/m – degK

Dchannel

10 mm

L

1. 5 meters

Tmelt

523 degK

Tejecion

364 degK

Cp

2352. 4 (J/kg – degK) for ABS Cycolac GPM 5500 Grade

Shot Weight (m)

100 gms

Tcoolant

283 degK

Result and Discussion

Simulation result for constant heat removal rate achieved via transient coolant temperature, are shown in fig. – 8 and fig. – 9. The heat removal at diminishing rate curve is of the same pattern as obtained by using Ansys FEA package, shown in fig. – 5.

Fig – 7: Heat removal from mould at constant and diminishing rate.

Fig – 8: Melt temperature, Coolant temperature vs. Cooling Time.

The cooling time is approximately 120 sec in this case whereas for constant rate heat removal cooling time is about 60 sec. That much saving in cooling time is at cost of having arrangement for mould cooling that can vary from 323 degK to 175 degK within 1 minute. Reducing the mould temperature up to 175 degK has many engineering problems; mould sweating will be tremendously high at that temperature.

In next step, flow rate of coolant was varied keeping the coolant temperature constant at 283 degK.

Fig – 9: Melt temperature, Heat removal rate and Film Heat transfer Coefficient vs. Cooling Time

Fig – 10: Reynolds No. and Coolant Flow Rate vs. Cooling Time

The cooling time in this case found to be approximately 80 sec. and the coolant flow rate was initially 400 lpm that was ramped up to 1600 lpm within 80sec of cooling time. The shape of melt temperature curve with time is not a straight line which is identification of constant rate heat removal, but still there is a lot of saving in cooling time. To achieve that much saving in cooling time extremely high turbulent coolant flow rate (Re is approximately 3500000 at the end of cooling time) was used.

Conclusion

The mould temperature and coolant flow rate have great effect over the heat transfer mechanism from mould. Proper adjustment of coolant temperature and flow rate can be useful in reducing the cooling time. Transient coolant flow rate may be used to reduce the cooling time and such mold temperature controllers can be made for achieving reduction in cooling time and ultimately reducing cycle time.