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Injection Molding Process Control - A Review

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ABSTRACT

This paper reviews control strategies employed in the injection molding process. For clarity, the controlled variables have been categorized into all phase control, phase dependent control and cycle to cycle control. All phase control includes variables which must be monitored and controlled at all times i.e. in all the phases. Control of variables which are triggered during a specific phase are discussed under phase dependent control. In cycle to cycle control, use is made of the previous data in order to predict future trends and take corrective actions thereof. The cyclic, dynamic and unsteady state nature of the injection molding process has been discussed with respect to the conventional PI and PID controllers as well as the more advanced control schemes such as self tuning control, optimal control, and statistical process control. Suggestions involving specific advanced control schemes and recommendations for future research in injection molding process control has also been made.

INTRODUCTION

In 1985, the U.S. plastics industry, which is the largest in the world, produced 21.6 million metric tons of plastic resin valued at $19 million (1) That year the U.S. consumed more plastic than steel, copper and aluminum combined. Furthermore, the U.S. sales have grown at an annual rate of 4.7% since 1977. According to James Giggey, vice president of polymer product for Du Pont, "by the end of this decade, plastics could be second in growth only to the service sector".

Plastics are appearing in such widely diverse applications as airplanes, houses, clothing, and the human body. Most artificial joints and even the artificial hearts today are largely made of plastic. Plastics are replacing the steel cans on the supermarket shelves and the metals on the interior and the exterior of cars. A new plastic called Lisa is replacing neon in many display signs.

As the applications of plastics increases additional demands will be placed on the natural properties of the plastics and on the manufacturing processes. The production of intricate parts with extremely high tolerance and quality finish impose stringent quality manufacturing and process control requirements.

Process control concerns itself with the ability to predict and control the part quality during the molding cycle (2). The overall control task can be divided into two distinct levels, the task level and the execution level. The task level deals with the determination of appropriate reference signals and trajectories. The execution level concerns itself with the manipulation of control variables in order to comply with the command signals determined at the task level. There are a number of issues associated with both these levels of control which include:

- injection molding control requires a cross-disciplinary understanding of chemical and mechanical engineering, as well as optimization, computer science and statistics. Its analysis requires knowledge of mass and energy transfer, non-Newtonian fluid flow, finite elements and unsteady state heat transfer with internal heat generation.
- injection molding is a dynamic process. This is evident from the presence of time in the fundamental state equations obtained by the reduction of the constitutive heat, mass transfer and material state equations. This complex interdependency of state variables, renders univariate control ineffective. Thus alternatives to conventional PI or PID control algorithms are required. This is further compounded by hereditary effects. The output and the states at any moment depend on the history of the previous states in a time cummulative manner (3).
- injection molding is a cyclic process. This along with the dynamic nature of the injection molding process makes it difficult to attain a steady state value. It is due to this inherent property of the injection molding process that the applications of advanced control algorithms for injection molding lags far behind those in extrusion. There are various references to the application of advanced control schemes to extrusion (4-13).

The control of a process can be improved by either equipment refinement or by employing better control strategies. Developments in equipment such as hydraulic components has led to considerable improvements in the performance and reliability of injection molding machines (14,15). Many of the variations formerly causing inconsistent part quality such as flashing, short shots, burning and overpacking can now be reduced when appropriately controlled (16). Considerable advances have also been made in the field of computer hardware. The advent of 16 bit and more recently 32 bit microprocessors have greatly enhanced their computing power. Due to their low cost, parallel processing and distributed control systems wherein microprocessors are used for dedicated purposes, can now be implemented.

Even with the best equipment and computer hardware, it is the control strategies which determine how well the process will work. Therefore advanced control schemes should be employed to fully exploit the advantages offered by the improved equipment.

Initially and even today many of the injection molding machines are equipped with controllers that can only react. These are essentially univariate in the sense that the corrections are taken without taking into account its interaction with other changes that might already be taking place. In a process like injection molding wherein the process variables are highly interdependent, such controllers can throw the whole process out of balance. To partly circumvent such a problem, controls that are capable of making calculations and decisions are required. They make use of microprocessor based control logic and can be designed for automatic trouble shooting and self-calibration (17,18). References to such controls go back to 1970's (19-26). More recently Cincinnati Milacron has introduced its dynamic matrix program capable of automatically fine-tuning the injection molding machine.

The controls of the near future however would not only be capable of making calculations and decisions but would also be capable of reasoning (27).

This would require application of AI techniques and the development of expert systems for the injection molding process.

In this paper we will address the above mentioned issues at length. For clarity, the overall control of the injection process has been classified into all phase control, phase dependent control and cycle to cycle control. The all phase control is one that is active throughout the molding cycle. Melt temperature control that belongs to this class is discussed in section I. Phase dependent control scheme is one that is triggered during specific phases. Control of variables that are activated during plastication, filling or holding phase are discussed in section II. Section III describes cycle to cycle control, wherein corrective actions for the present cycle are taken based on the past information about the process. The article concludes with recommendations for future research work.

I ALL PHASE CONTROL

The 'all phase' control strategy is defined to include variables that are continuously controlled throughout the molding cycle and are equally important in all the phases. The controlling variable might change with the phase but the final controlled variable remains the same irrespective of the phase. Melt temperature, which is a fundamental variable in the injection molding process, needs to be continuously controlled and held to a specific level. A change in melt temperature affects a number of variables which include the melt flow rate, the nozzle pressure and the cavity pressure (28). It is therefore desirable to have accurate melt temperature control in all the phases. During the plastication phase, the barrel temperature can be used, while during the filling phase, the nozzle temperature might be used as a indirect measure of melt temperature. During the holding phase, the melt temperature is a critical parameter in the PVT relationship.

A number of models for melt temperature have been proposed (29-33). Ma (29) proposed the following simplified relationship

$$T_m^b = \phi 1(N, P_m, T_b, \delta_1) \quad (1)$$

where T_m^b = melt temperature in the barrel

N = screw rotational speed

P_m = melt pressure

T_b = barrel temperature

δ_1 = disturbance caused by material property variation and/or screw geometry variation due to wear.

A stochastic model of the form given below was identified by Patterson et al. (30)

$$y(k)\bullet(1-a_1q^{-1}-a_2q^{-2}- \ldots) = u(k-d)\bullet(b_o-b_1q^{-1}-b_2q^{-2}- \ldots) + n(k) \quad (2)$$

where

$y(k)$ = the output of the k^{th} sample

$u(k-d)$ = the input of the $(k-d)^{th}$ sample

$n(k)$ = the noise at the k^{th} sample

q^{-1} = the backward shift operator $y(k)\bullet q^{-1}=y(k-1)$

d = number of lags

$a_1, a_2, \ldots, b_0, b_1, \ldots$ are the model parameters obtained from analysis of experimental data.

While Peter (33) suggested the following relationship

$$T_m^b = a(T_b+b) + m\ P_b + \text{error} \qquad (3)$$

where

T_m^b = melt temperature in the barrel

T_b = barrel temperature

P_b = hydraulic back pressure during plastication

a,b & m are constants determined experimentally

Eq. 1 shows that the melt temperature is a function of the screw speed, melt pressure and barrel temperature. However it does not include hydraulic back pressure, which, as shown by Border, et al. (34) and Peter in eq. 3, has a direct effect on the melt temperature during plastication. For the purpose of control, a model of the form given by eq. 2 is more suitable.

The effect of screw rotational speed on the melt temperature has been reported to be negligible (35-36). As a result, many modern control schemes have been based on the barrel temperature and/or back pressure. For example, Chandra (37) has proposed a control strategy that uses both barrel temperature and back pressure to control the melt temperature. The overall block diagram is shown in figure 1. The screw tip temperature, indicative of the melt temperature, is fed back and compared with the reference value. The error is then fed into the melt temperature controller which determines the reference temperature set points for the various zones. The error is also used to determine the back pressure corrections. Temperature controllers are proportional-reset type and the back pressure controllers are of PID type.

The barrel temperature control algorithm used by Chandra was

$$T_b^c = T_b^o + \Delta T_b \qquad (4)$$

where

$$\Delta T_b = K_1 \sum_{i=1}^{\infty} e_i \, \Delta t \quad \text{if } e > 6°\text{F}$$

$$= K_2 \quad ; \text{if } e < 6°\text{F}$$

$$= 0 \quad ; \text{if } e < 1°\text{F}$$

$e = T_r - T_a$

T_r = reference temperature.

T_a = actual measured temperature.

T_b^c = corrected barrel temperature reference

T_b^o = operator set barrel temperature reference

ΔT_b = incremental barrel temperature correction

Δt = sample time as a function of position interrupts

K_1, K_2 = constants determined by process dynamics

while the pressure control algorithm used was

$$P_b^c = P_b^o + \Delta P_b \tag{5}$$

where

$$\Delta P_b = K_3 \, e + K_4 \, \Delta e/\Delta t + K_5 \sum_{i=1}^{\infty} e_i \, \Delta t$$

P_b^c = corrected back pressure reference

P_b^o = operator set back pressure reference

ΔP_b = incremental back pressure correction

K_3, K_4, K_5 = constants determined by process dynamics

From eq. (4) it is apparent that no temperature corrections are taken when the error is less than 1°F; proportional action is taken when the error is less than 6°F; and integral action is taken for errors exceeding 6°F. Once the temperature error is within a certain dead zone, pressure corrections are made to restore it to its operator set value. Experimental results with polystyrene have shown that the average response of the controller for their particular machine was 5°F/min. (37).

Since the melt temperature has a faster dynamic response to back pressure compared to the barrel temperature, a control strategy which provides short term changes of back pressure while simultaneously changing barrel temperature would be effective. However it should be noted that the injection molding plant is time varying and hence controllers with fixed parameters such as a PID controller will not be efficient. In particular, with the passage of time the machine heats up and its characteristics change, which requires a corresponding change in the PID controller parameters. This can be efficiently handled by self tuning or adaptive control wherein the controller parameters are continuously updated based on the updated plant information.

Ma (38) has described a control strategy where only the barrel temperature is used to control the melt temperature. He also accounts for viscosity changes through the barrel temperature correction unit. Test results recorded by Ma for a step input of melt temperature showed that the response reached to within ± 1°F of the final steady-state value after about 19 minutes. It is the barrel temperature instead of melt temperature that is typically controlled. The thermal conductivity of polymers is about 1/100th that of steel. Therefore, the control of melt temperature by controlling the barrel temperature is slow and often ineffective (39). Patterson, et al. (30) reported a sluggish response with zero steady state error using a PID controller and the stochastic model of the form given by eq. 3. Sluggish response can be attributed to the large dead-time associated with the melt temperature response to heater power. The addition of a dead-time compensator, such as Smith predictor, was found to improve the speed of response. Another remedy might be to employ predictive control algorithms which allow prediction of the controlled variable ahead in time by an amount equal to the dead time associated with the controlled variable.

II PHASE DEPENDENT CONTROL

This section discusses those variables whose control is triggered in a specific phase. In general it is difficult to classify a controlled variable as belonging to a specific phase and for that reason while assigning any variable to a particular phase, only their relative dominance was considered. Controlled variables have been subclassified into those pertaining primarily to the plastication phase, injection phase or holding phase of the molding process. The fundamental variable to be controlled during the plastication phase is the melt temperature. Ram velocity, viscosity and peak cavity pressure are important during filling. Transition from fill phase to hold phase can be time, position, velocity or pressure dependent and is discussed in section B4. During the holding phase the key variables to be controlled are hold pressure, specific volume and the melt temperature. A control scheme called PVT control which utilizes the state equation that quantifies the interdependence of pressure, specific volume and the melt temperature is discussed under holding phase control. Control of plastication phase, fill phase and the holding phase along with the associated parameters will now be discussed in greater detail:

A. PLASTICATION PHASE

During the plastication phase, the plastic undergoes a phase transformation. Solid plastic granules entering the barrel through the hopper are plasticized as a result of a complex thermomechanical process. The most important output variable to be controlled is melt temperature, whose control has already been discussed in all phase control and will not be discussed any further.

B. FILL PHASE CONTROL

During the filling phase the melt is forced through a nozzle into the mold. The fill rate is related to the melt molecular orientation which in turn affects the final product quality and can influence common problems like flashing and short shot. The important output variables to be controlled in this phase are the melt pressure, rate of filling and melt viscosity.

B1. Cavity Pressure Based Control

Cavity pressure control is the most widely employed closed-loop process control method (40). Plant, et al. (41) showed that cavity pressure is a direct indication of what is occuring inside the mold. Cavity pressure is sensitive to changes in injection pressure, injection rate, screw speed, back pressure and cushion. Injection rate has the highest sensitivity and as such is the best candidate for the controlling variable.

Implementation of cavity pressure control requires the installation of a pressure transducer, preferably mounted inside the mold cavity. However in practice, certain situations occur where placement of the transducer inside the mold cavity is undesirable, and in some cases impossible. Some applications have surface finish requirements that are so high that the discontinuity produced by the transducer located inside the mold cannot be tolerated. These problems are further aggravated in the case of multiple cavity molds. The only remedy in such cases is to base the control schemes on indirect measures of cavity pressure such as separation on the parting face of the mold (42), pressure exerted on the knock-out pin (43), or the pressure measured upstream of the nozzle. The use of these indirect methods is also often dictated by economic considerations.

Fara, et al. (44) have shown that the nozzle pressure, a measure of cavity pressure, is very closely related to hydraulic pressure and therefore hydraulic pressure, being directly measurable, is better suited as a controlling variable. Details of implementation of PI and PID controllers tuned according to ITAE criterion for controlling hydraulic pressure and nozzle pressure have been provided in (44). Simple dynamic models obtained experimentally have been used rather than the complex theoretical models described in (45-53). The values of the best parameters of the dynamic models relating the variations in servovalve opening to variations in hydraulic pressure and nozzle pressure. are provided in (54,55). Kamal, et al. (56) have compared the effectiveness of PID and Dahlin controllers as applied to nozzle and cavity pressure.

Figure 2 shows the cavity pressure distribution as a function of time. As seen from the figure the pressure distribution can be divided into fill pressure, peak pressure and the holding pressure.

Ma (29) has suggested the following relationship for the fill pressure

$$P_f = \phi_2(V, T_m^{\gamma}, \delta_2) \qquad (6)$$

where

P_f = the fill pressure

V = the injection speed

T_m^{γ} = the melt temperature in the runner

δ_2 = the external disturbances

which shows that the fill pressure can be controlled by proper control of injection velocity, provided the melt temperature is known. However it does not include the effect of hydraulic pressure explicitly. During the filling stage when the cavity is not yet completely filled, the fill pressure is very low and as such is not much suited for control. It is the injection velocity that is more important during filling stages as it affects the shear stresses and shear rates induced in the plastic which have great influence on the final product quality.

Cavity pressure becomes important once the cavity is filled. The moment the cavity is filled, the cavity pressure sensor registers a peak. This peak cavity pressure is a very widely used control variable, as it defines part resolution and can be utilized to solve such common problems as flashing, sink marks and short shots. For example, short moldings can be remedied by increasing the peak cavity pressure, and flashed parts can be reduced or eliminated by decreasing the cavity pressure (57). Peak cavity pressure is generally kept sufficiently high to insure that all cavities in the part are properly filled (58). In the statistical process control of peak cavity pressure, the upper control limit is fixed at a pressure above which flashing would occur and the lower control limit is determined at a pressure below which short shots would result.

It has been experimentally demonstrated by Golden, et al. (43) that peak cavity pressure control helps in minimizing overpacked parts. They conducted experiments on a 100 ton, 50 ounce reciprocating screw machine. The controller used by them was a Dynisco-CPC-1-R2VD type. The peak cavity pressure was approximated by the force behind the knock-out pin. They showed that the peak cavity pressure control resulted in parts with lower variance of part weight and part length than the parts produced in the uncontrolled mode. Improvements in impact strength were also reported. The overall production improvement reported by Golden, et al. (43) was 3%.

The sensitivity of peak cavity pressure to the weight of the molded parts was experimentally shown by Takizawa, et al. (42). They used the separation on the parting face of the mold as an indirect measure of cavity pressure. The relationship between maximum mold separation and part weight is shown in Figure 3. It can be seen from the figure, that as maximum mold separation increases, the product weight also increases. Large mold separation often indicates flashed and/or overpacked parts. Sone, et al. (59) used injectmaster, an adaptive controller, which uses feedback information of the mold spacing value, to automatically set injection volume and injection pattern in presence of disturbances like melt viscosity. Injectmaster is coupled with injectrol, a programmed injection unit, whose details are provided in (60).

A time series model of the form given by eq. 3 has been identified by Sanschagrin (61) and is given below,

$$P_p(k) = a_1 \bullet P_p(k-1) + b_1 \bullet P_h(k) + b_2 \bullet P_h(k-1) \qquad (7)$$

where

$P_p(k)$ = the peak cavity pressure during k^{th} cycle

$P_p(k-1)$ = the peak cavity pressure during $(k-1)^{th}$ cycle

$P_h(k)$ = the hold pressure during the k^{th} cycle

$P_h(k-1)$ = the hold pressure during the $(k-1)^{th}$ cycle and

a_1, b_1, b_2 are the constant coefficients whose values are given in (61)

From the previous cycle data of peak cavity pressure and hold pressure, peak cavity pressure required on the present cycle can be determined so as to achieve the desired hold pressure setpoint. Haber, et al. (62) have also determined a similar time series model for peak cavity pressure.

B2. Injection Velocity Control

The entire filling phase can be regulated by controlling the injection speed of the ram. Velocity profiling can be used to achieve a constant melt surface velocity which affects molecular orientation and internal stresses produced in the part (63). Proper velocity profiling also aids in setting the mold clamping force to the minimum as no allowance for disturbance has to be provided (64). Presently, the profile is set by trial and error as no set procedure is available. However, the following guidelines have been laid down for proper velocity profiling (58).

(1) The surface flow speed should be constant.

(2) Injection should proceed quickly to prevent freezing of the melt during injection.

(3) The injection velocity profile must allow for fast filling of the less critical areas such as runners while slowing down at the gates.

(4) The ram velocity must be "broken" the moment the cavity is filled,to prevent overpacking of the cavity, flashing and residual stresses in the part.

Once the profile is determined the problem remains that of following it in the "best" possible manner. However before any controls can be done, a good model is required. Wang et.al. (65) have reported a fouth order model relating the voltage signals proportional to the injection ram velocity and the hydraulic valve opening. They developed a linear model of the continous system with analytically calculated parameters to determine the effective system order and the expected values of the parameters. The actual parameters were then identified using a Recursive Least Square (RLS) parameter estimation technique. As opposed to a fourth order model by Wang, Fara (54) in his thesis reports a model with only a gain term.

Figure 4 shows the block diagram for velocity control. Velocity set points are specified as a function of the injection stroke. When the injection stroke is started, the ram position information is fed to the profiler which provides the velocity reference value. The actual velocity is fed back and compared with the reference and the error determined. Based on this error the controller calculates the oil flow rate and the oil pressure correction required to restore to the correct velocity. Details of the programmed control of ram velocity as a function of the ram position, are provided in (66).

Studies by various authors (67-69) concluded that the servocontrolled injection ram velocity provides a significant improvement in the final product quality. There has been increasing interest in methods based on the observation of ram movement which can be ascribed to the dependance of physical state of the melt on ram movement. Moreover, Haynes, et al.(70) have experimentally proved that the injection rate is much more sensitive than the cavity pressure as an indicator of injection conditions and hence a more suitable signal for control purposes aimed towards higher precision in molding.

The problem of velocity control is primarily that of optimally tracking the velocity profile. In view of the very short duration of filling, it is required that the controller responds very quickly to changes in velocity setpoint. This is turn requires that the response time of the hydraulic unit should be very short. Electromechanical servovalues are available that transmit up to 90% of the rated flow in 25 milliseconds (71). Most PID concontrollers presently used have severe limits on the number of velocity setpoints that can be programmed. This problem can be obviated by employing optimal tracking control wherein the controller anticipates a future change and adjusts accordingly. This subject is presently being investigated by the authors.

B3. Viscosity Control :

Viscosity regulates the pressure losses in the barrel. Any change in the viscosity of the melt will result in a corresponding change in pressure required during filling (72). The higher the viscosity of the melt, higher will be the pressure losses in the barrel and hence higher will be the pressure required during filling. A very low level of viscosity, on the other hand might present problems of flashing. It is therefore desired to keep the viscosity variations to a minimum.

Direct measure of viscosity is very difficult and so most of the control schemes base their actions on indirect measures of viscosity such as in Haynes, et al.(70) where melt fluidity was used as a measure of viscosity. They employed a Rate Sampling Transmitter (RST) to provide a signal proportional to the melt fluidity which is used to automatically adjust the barrel temperature settings so as to hold the peak injection rate at a constant.

Ma (38) used nozzle pressure as a viscosity indicator on the basis of the following reasoning. The shear rate is proportional to the injection rate, whereas the shear stress is proportional to the nozzle melt pressure. Viscosity is then the ratio of nozzle pressure to injection rate, which under the assumption of constant injection rate is proportional to nozzle pressure. Experiments by Ma, showed that the step change response curve reached the set point within 1% at the 11th shot (approximately 11 min.) with better than 0.5% steady state accuracy.

Hutchinson (73) used the injection time as a controlling variable to control viscosity. He used the viscosity index as an indirect measure of viscosity. The viscosity index was reported to be extremely sensitive to any known variation in viscosity. For example, Hutchinson showed that the viscosity index value changed from 0.50 to 0.70 with a 5°F variation in the front zone barrel temperature. Hutchinson also developed a machine equiped to make viscosity index measurements in hundredths of a second. The approach was to vary the injection time within the same cycle by measuring the viscosity index one or two tenths of a second before the end of primary injection. This required a sensitive primary injection pressure. It was thus necessary to have a timer-limited primary injection time. Hutchinson also experimentally proved for polystrene that higher viscosity materials will make a lighter weight part, other conditions remaining constant.

All the above control schemes can be represented by a simple feedback control block diagram as shown in figure 5. The feedback loop consists of a viscosity computation block which computes a measure of viscosity based on nozzle pressure or melt temperature. Based on the viscosity index error (n_e) the viscosity controller produces correction signals which might be any one or a combination of barrel temperature, injection time and the hold pressure.

B4. Controlling Switchover From Fill Phase To Hold Phase

Accurate control of switchover from fill phase to hold phase is very important to assure consistency of part weight. This can be time dependent, position dependent, pressure dependent or velocity dependent. If a time dependent switchover is adopted, the reference time at which switchover is desired is set into the timer. As soon as the reference time is reached, a signal is transmitted to the relief valve which then bypasses additional fluid into the reservoir to maintain a predetermined hold pressure (74). Similar control sequences follow with position dependent switch over and the pressure dependent swithch over. The only difference is that the relief valve is opened when the ram reaches a predefined position or when a predefined pressure is attained in the cavity.

Farrel researchers prefer velocity based switchover. They reason that in case of large molds, the cavity pressure variations might not be sufficient enough to detect when the mold is about to be overfilled. This is further complicated by the large inertia of the massive injection rams of the large machines. Aloise, et al.(75) have described a mold packing event detector, referred to as velocity range monitor, which judiciously switches over from peak to hold injection pressure based on the rate of change of velocity. Figure 6 shows the block diagram for position dependent, velocity dependent pressure and dependent switchover.

C. HOLDING AND COOLING PHASE CONTROL

After injection of the material into the mold is complete, the packing phase immediately follows. This phase is governed by complex heat transfer phenomena. This is the longest phase consuming about 80% of the total cycle time. The cycle time during this phase is dependent on the maximum rate at which the heat can be removed without leading to uneven cooling which could lead to differential shrinkage resulting in a warped product. It should be noted that this is the final phase and therefore is closest to the ultimate part quality. The important output variables to be controlled include the hold pressure, specific volume of the plastic in the cavity and the melt temperature. A form of PVT control which relates these fundamental variables will be discussed.

C1. HOLD PRESSURE CONTROL

The hold pressure determines how much additional material is forced into the cavity after the cavity has been filled by the peak cavity pressure. Hence its control is important to assure part consistency. The following dependance of hold pressure on plastic variables have been developed by Ma (29);

$$P_h = \phi 3(P_{hyd}, T_m^c, T_{md}, \delta 3) \tag{8}$$

where

P_h = the hold pressure

P_{hyd} = the hydraulic pressure

T_m^c = the melt temperature in the cavity

T_{md} = the mold temperature

δ_3 = the external disturbances

This relationship shows that accurate control of hold pressure will require control over hydraulic pressure, melt temperature and mold temperature. This can only be realized through multivariate control scheme.

During the packing phase the material is under considerable pressure compared to the filling phase. Therefore the linear motion of the screw would displace more weight during packing than it would during the filling phase. The hold pressure also has considerable influence on the dimensional accuracy of the molded part. The effect of cavity pressure on shrinkage has been experimentally demonstrated by Mann (76) for three materials and the results are depicted in figure 7. It can be inferred that dimensionally undersized parts can be remedied by increasing holding pressure while dimensionally oversized parts can be cured by decreasing the holding pressure. An apparatus for providing uniform hold pressure in the mold cavity so as to insure a high degree of uniformity and repeatability in the parts, has been discussed by Ma et al. (77). Their control stategy aims at maintaining the integral of the hold pressure at a given reference value.

C2. PVT CONTROL

The aim of PVT control is to maintain consistency of density throughout the part. PVT control makes use of Spencer and Gilmore equation of state (eq. 9), that relates the temperature of the material, its specific volume in the mold and the pressure being exerted on it, so as to achieve an optimum. Thus PVT control can be distinguished from the controllers that react and can be said to belong to the class of controllers wherein information from two or more formerly closed loops is combined to take a decision. It uses information from 3 formerly closed loops to calculate and decide the optimum value of the manipulated variable which is the melt pressure.

$$(P_m^c+a)(v-b) = RT_m^c \tag{9}$$

where

P_m^c = melt pressure in the cavity

v = specific volume of the melt

T_m^c = plastic melt temperature in the cavity and

a,b & R are the constants.

A typical PVT diagram is shown in figure 8. The aim is to maintain constant specific volume i.e. get a straight line process BC. This requires appropriate changes in melt pressure to compensate for variations in the melt temperature. For constant specific volume eq. 9 gets modified as

$$P_m^c = xT_m^c - y \tag{10}$$

where

$x=R/v-b$; and $y= a$ (both x and y are constants).

A flow chart of the PVT process control algorithm is shown in figure 9. Melt temperature at discrete instances are measured and the pressure setpoints determined using eq. 10, so as to maintain constant specific volume. If the maximum safe range of pressure variation is exceeded a new density set point is determined.

Implementation of PVT control requires additional instrumentation as melt temperature and pressure have to be measured. For example the Sandretto system requires both a cavity pressure sensor and a mold temperature sensor, while Battenfeld system requires only a temperature sensor on each mold half. Battenfeld system uses hydraulic presssure sensor readings to estimate the mold pressure. However, the basic action of both the systems in adjusting the injection pressure to compensate for variations in melt temperature is the same. Laboratory tests by both the manufacturers have shown drastic reduction in the average weight variations of the parts produced during an entire production run.

III CYCLE TO CYCLE CONTROL

Cycle to cycle control is defined to include those control stategies wherein corrective actions are taken in the subsequent cycle based on the information from the preceding cycles. Injection molding is a cyclic process, without a true steady state as is the case with extrusion, and therefore its control is much more complicated. Its control will require time series ARMA models of the type given by eq. 7 which allow us to predict the hold/cavity pressure given their previous cycle values and the cavity/hold pressure setpoint for the present cycle. Shot size control and statistical process control fall in this category and will now be discussed at length.

1. Shot Size Control

The main aim of shot size control is to maintain constant part weight. To achieve this the Spencer and Gilmore equation of state given by eq. 9, and the eq. 11 below are utilized.

$$W = \rho V \qquad (11)$$

where

W = weight of the final product

ρ = part density

V = shot volume

Eq. 9 shows that when the melt temperature changes, part density also changes for a given melt pressure. Eq. 11 however, shows that the shot volume must be varied as density varies to maintain weight at a constant value.

The principle behind shot size control is to determine a cushion reference value that insures constant product weight when maintained at that level (66). Hunkar (78) employs cavity pressure signal as being representative of the part density. He measures the pressure when the ram bottoms, and compares it against a predetermined pressure. The error signal is then utilized to determine a new setpoint for the next cycle that will return the desired cavity pressure when the ram bottoms the next time.

The control logic is explained with the help of figure 10. The cushion is measured via the ram position transducer at the end of the packing phase and is compared with its reference value. The cushion and the shot size errors are fed into the controller, which then generates a new shot size reference for the next cycle. The Barber Colman (79) control loop includes features such as correction gain and limit functions. Correction gain allows corrections to be applied as a percentage of cushion error with a limit on the amount of correction, imposed by the limit function.

2. Statistical Process Control

Statistical process control can be seen as a series of algorithms and methods meant at establishing process consistency, repeatability and predictability. A number of references (80-84) towards application of statistical process control to injection molding are available in the literature.

The application of statistical process control to the injection molding process requires deep understanding of the correlation between critical parameters during the molding cycle. If there is too much variability and intercorrelation, as is the case with injection molding, the statistical process control suggests that changes should be made only when absolutely necessary. Using statistical charts, corrective actions are taken only when the measured parameter is out of specification limits. The main problem here is to establish the limits. This problem can be partly solved by employing learning models. A definition of a good part must be provided in the model. The model then records the various parameters whenever the part attributes are within limits and provides the machine with the various setpoints.

For the purpose of understanding the statistical process control concepts, we refer back to figure 2 and define two set-points as

Set point 1 : t_{fill} (time to fill the cavity)

Set point 2 : P_p (peak cavity pressure)

which are monitored with the statistical process control by drawing $\overline{X}$ and R charts. The charts provide diagnostic information about the process. For example, if set point 1 (i.e. t_{fill}) is out of range, this suggests that there may be problems with injection speed or injection pressure and/or melt temperature. If there are variations in setpoint 2 (i.e. Pp) these can be related to injection pressure and or a variation in the switchover from the fill phase to the hold phase. Statistical process control of fill time will result in parts with reduced stresses and molecular orientation, while statistical process control of peak cavity pressure will aid in overcoming common problems such as flashing and short shot.

Statistical process control can be extended to include most of the critical variables.

IV. RECOMMENDATIONS FOR FUTURE WORK

A number of control strategies, their advantages and disadvantages have been given. With this is mind the following recommendations for future research have been identified

- Research is required in the area of stochastic identification and control methods. Transfer functions relating combinations of process parameters should be identified and a general "covariance" matrix of the form shown in figure 11 should be constructed.
- Once the interactions of all the manipulated variables is determined, multivariate control schemes can be applied to determine the optimum controller for the injection molding machine as a system.
- Considerable research is also required at the task level. At present most of the settings are done by trial and error. This results in considerable time wastage during initial machine set-up. Algorithms should be developed that will aid in determining optimum setpoints and profiles for various controlled variables.
- Control should be made more intelligently. This will require the application of AI techniques and expert systems to injection molding process. The complex interdependency of the various variables can be put in the form of rules which will form a knowledge base. Data base will then consist of the material characteristic over the complete processing spectra. The advent of low cost very large scale integrated (VLSI) microprocessor chips, capable of storing the complex programs required for decision process, has opened the doors for application of AI techniques to injection molding controls.
- Sensor development should be encouraged. Many of the control schemes are plagued by the unavailability of cheap and rugged sensors. This allows only indirect measurement of many of the fundamental plastic variables and hence result in suboptimal control. For example,

barrel temperature has been used as indirect measure of melt temperature while mold separation and force behind the knock out pin have been used to indirectly estimate the cavity pressure. Improved sensors would also aid in reducing the measurement noise and hence should give a new direction for application of advanced control algorithms such as optimal control.

- There should be an increased use of plastic variables as control parameters. This is due to the fact that plastic variables are the true indicators of the condition of the plastic inside the mold in contrast with machine variables which are indicative of the condition of the machine. Direct measurement of these plastic variables is difficult at present, as the sensors have to be located inside the mold.

Many advances in the field of automatic controls of injection molding machines have been made in the last decade particularly in terms of increased computational capacity. The availability of powerful and inexpensive computer capabilities at the shop level present a great opportunity towards achieving the goal of zero-defect manufacturing. What is presently critical is the development of adequate methods to take advantage of the increased hardware proficiency. There is a vast knowledge of controls (85-87) that remains to be applied to injection molding process. The coupling of artificial intelligence techniques which use flexible reasoning, with advanced multivariate control, presents the greatest promise.

Acknowledgement

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Agrawal, Fig. 1

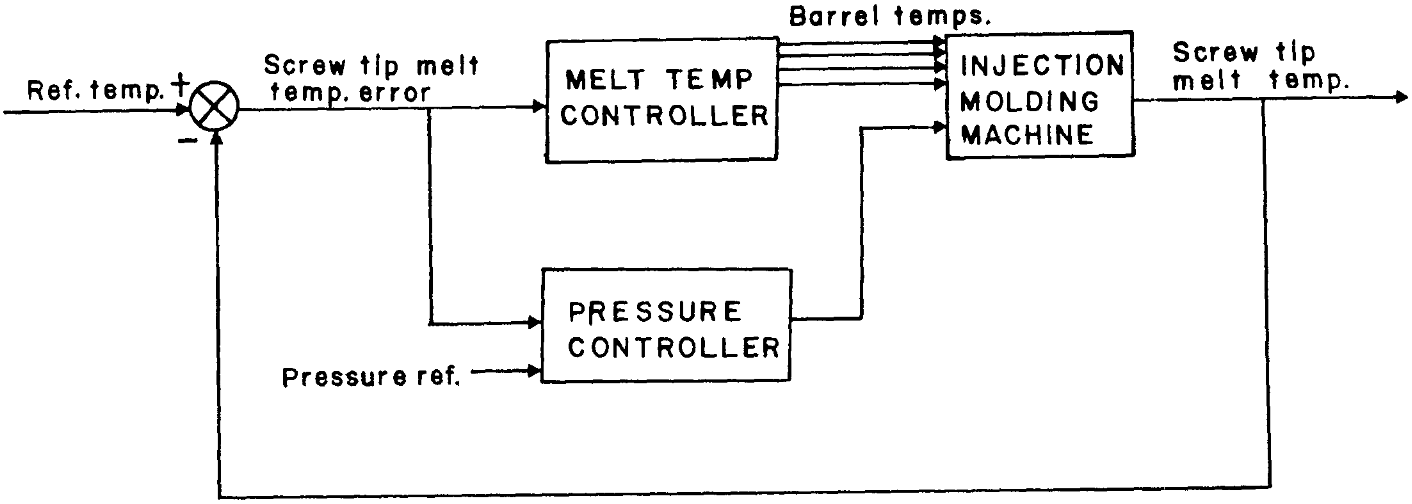
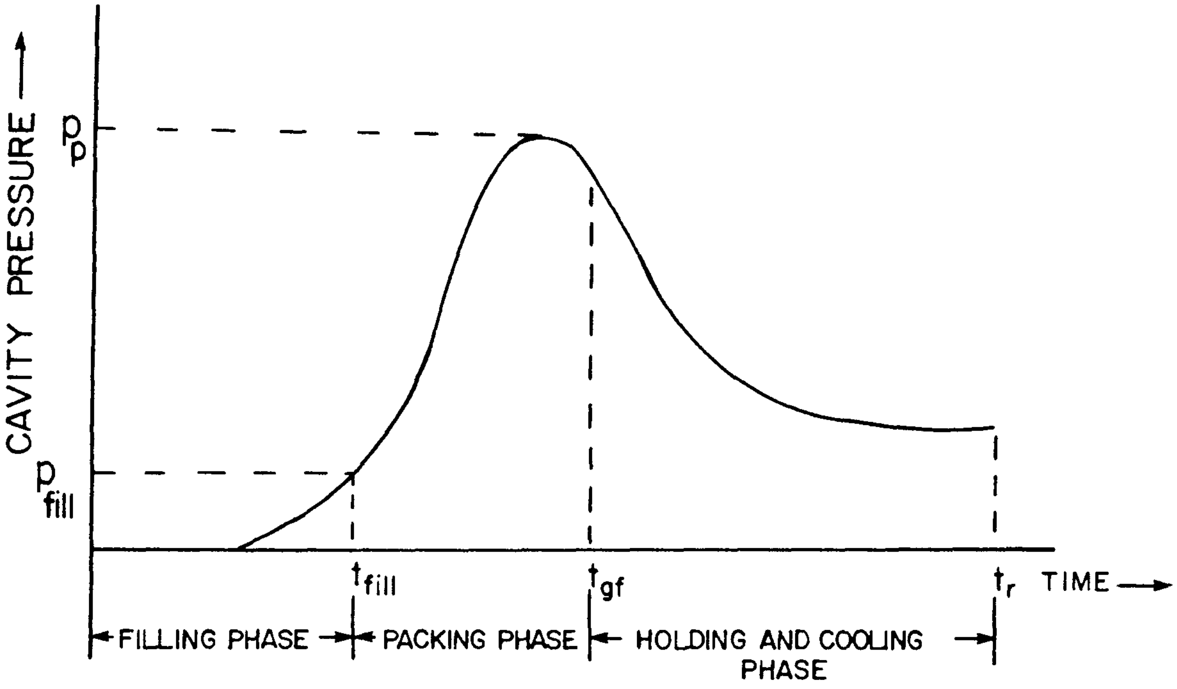


Fig. 1. Block diagram of melt temperature control scheme.

Agrawal, Fig. 2



t_{fill} → time to fill the cavity
t_{gf} → time at which gate freezes off
t_r → time at which end product released
p_{fill} → fill pressure
p_p → peak cavity pressure

Fig. 2. Cavity pressure distribution.

Agrawal, Fig.3

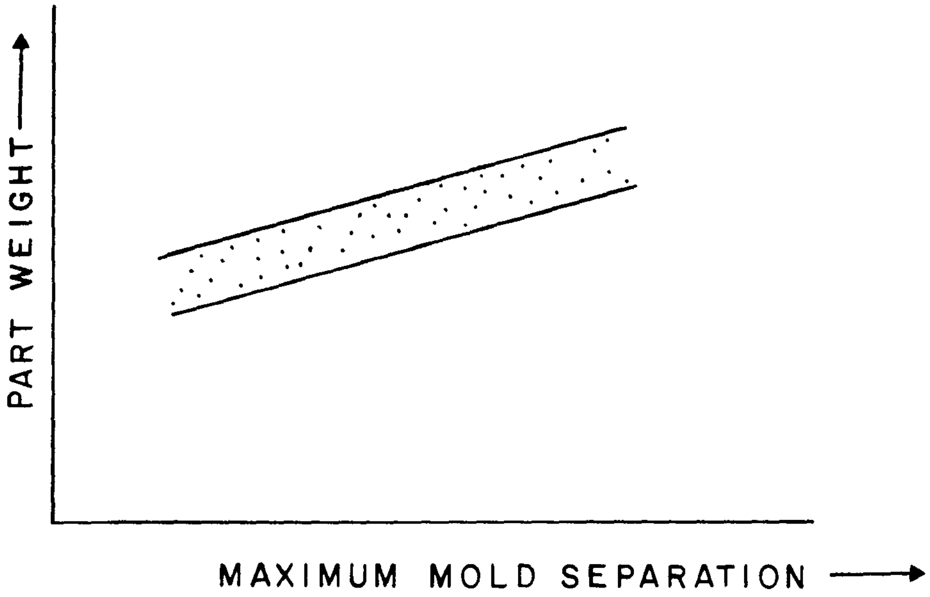


Fig.3. Dependence of part weight on peak cavity pressure ie. maximum mold separation.

Agrawal, Fig. 4

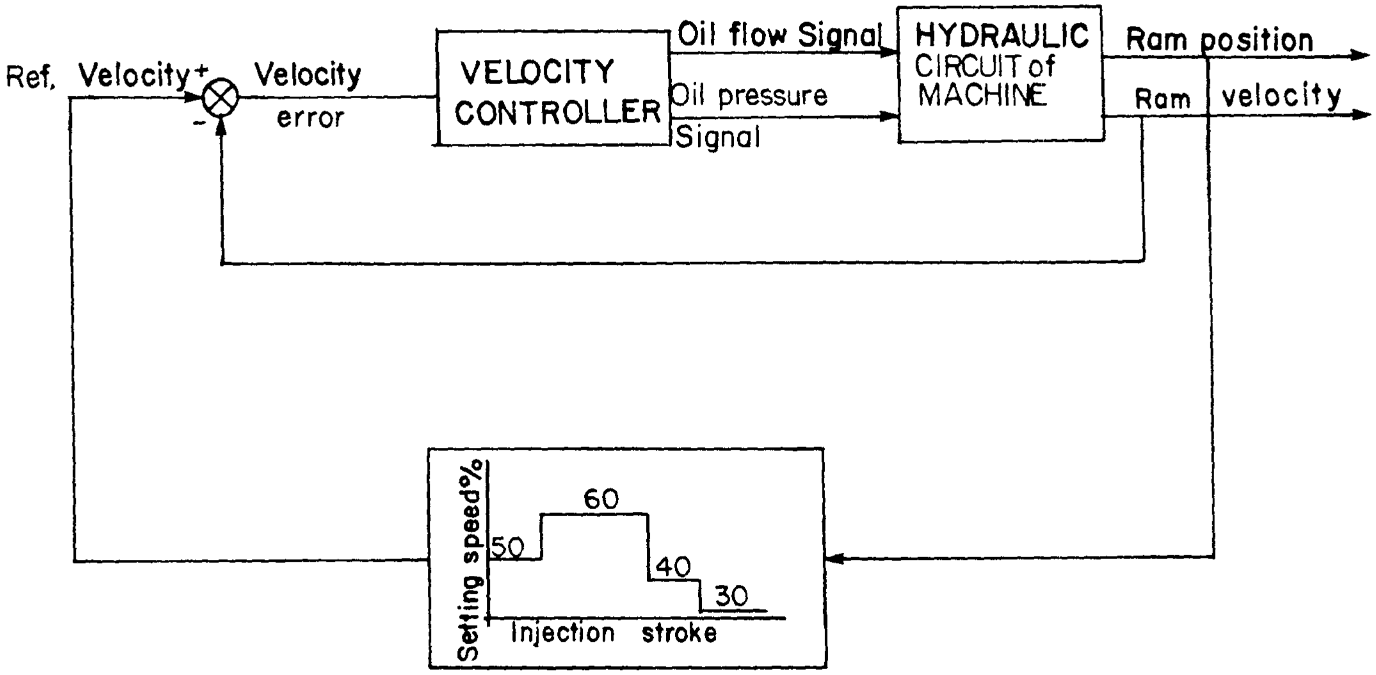


Fig. 4. Block diagram of velocity feedback control.

Agrawal, Fig. 5

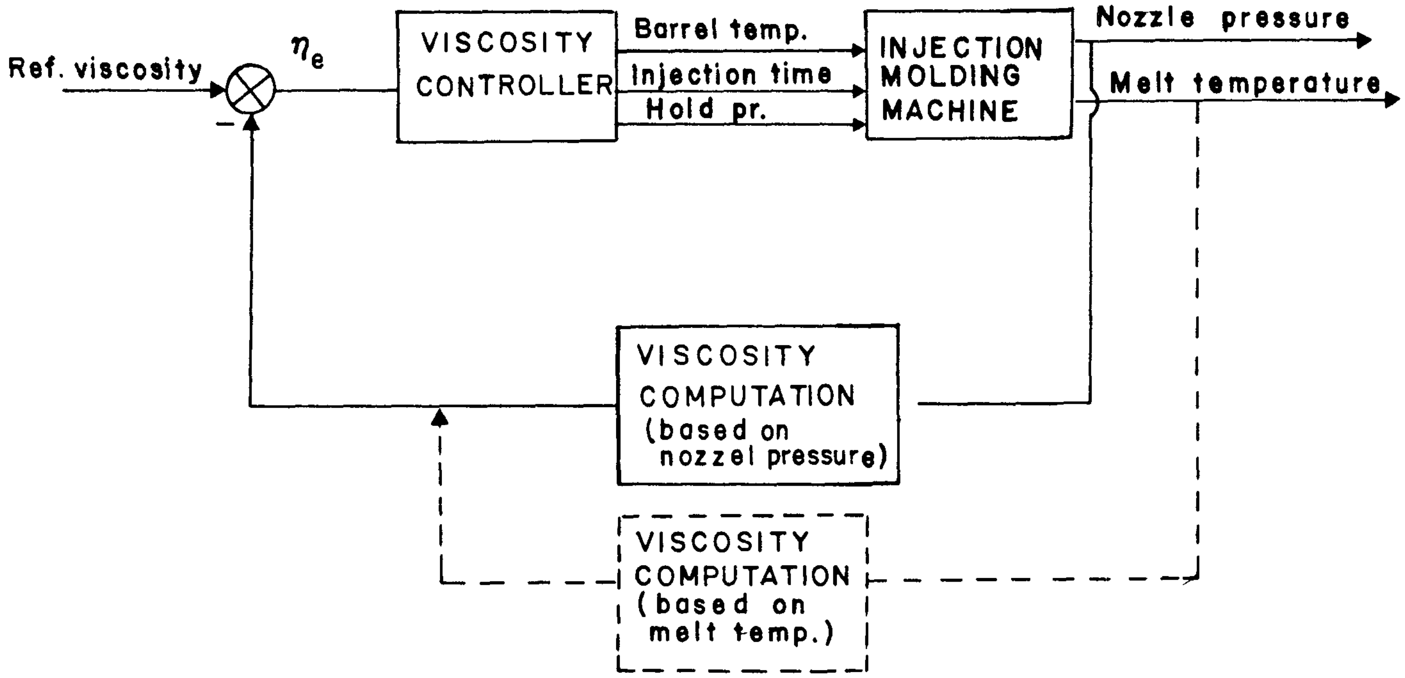


Fig. 5. Block diagram for melt viscosity control schemes with two alternatives for viscosity computation.

Agrawal, Fig. 6

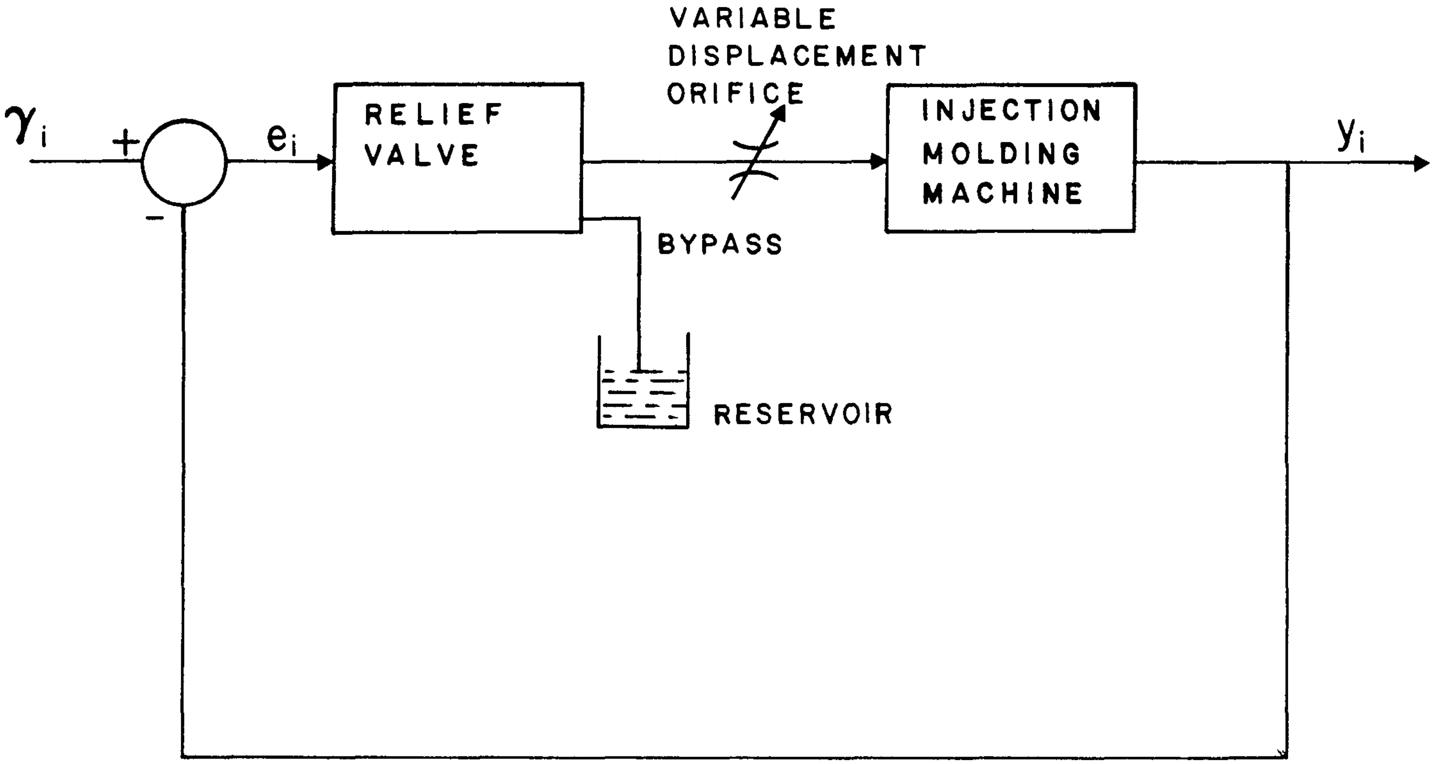


Fig. 6. Block diagram for control of switchover from fill phase. y_1 is the actual ram position signal required for position dependent switchover. y_2 is the actual ram velocity signal required for velocity dependent switchover. y_3 is the actual cavity pressure signal required for pressure dependent switchover. γ_1, γ_2 and γ_3 are the corresponding reference signals.

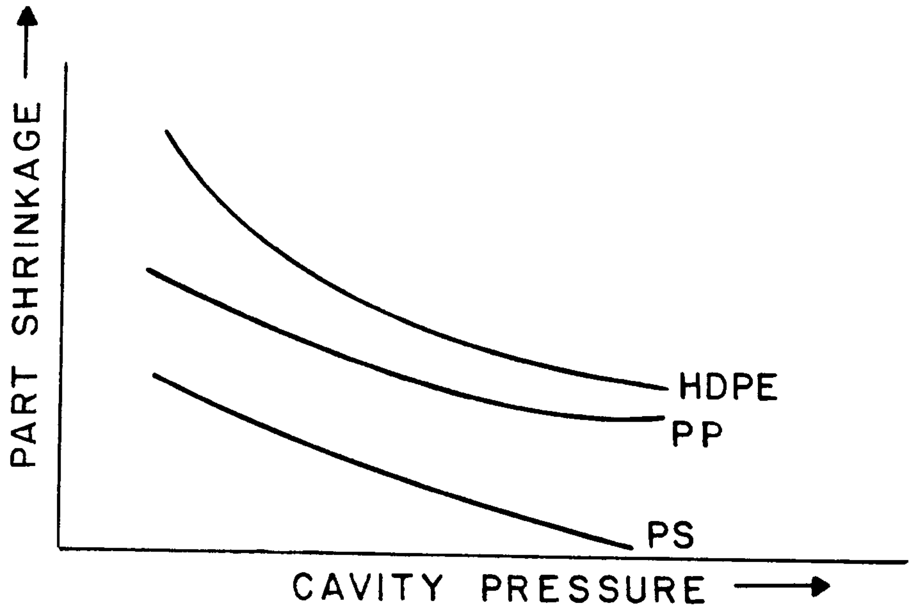
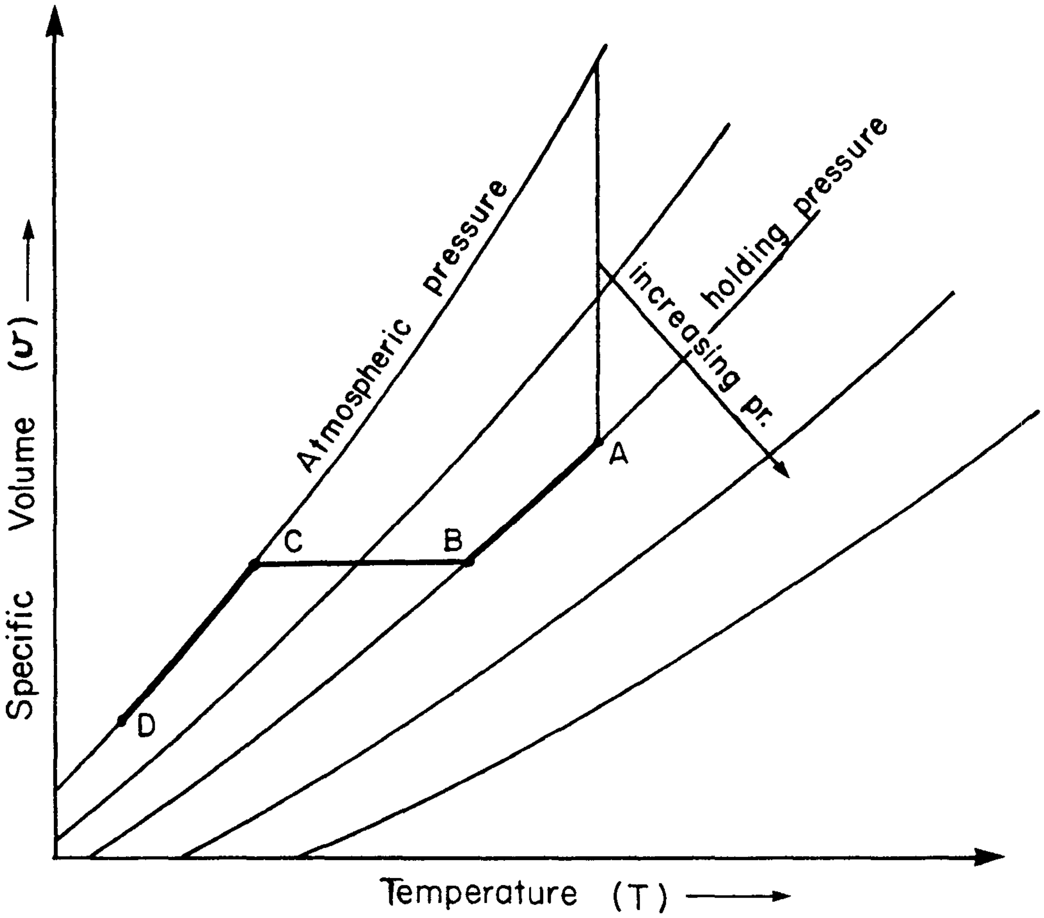


Fig. 7. Effect of cavity pressure on shrinkage for polystyrene (PS), polypropylene (PP) and high density polyethylene (HDPE).

Agrawal, Fig. 8



AB → Constant holding pressure
BC → Constant specific volume cooling
CD → Constant pressure cooling
C → Specific volume set point

Fig. 8. PVT diagram.

Agrawal, Fig. 9

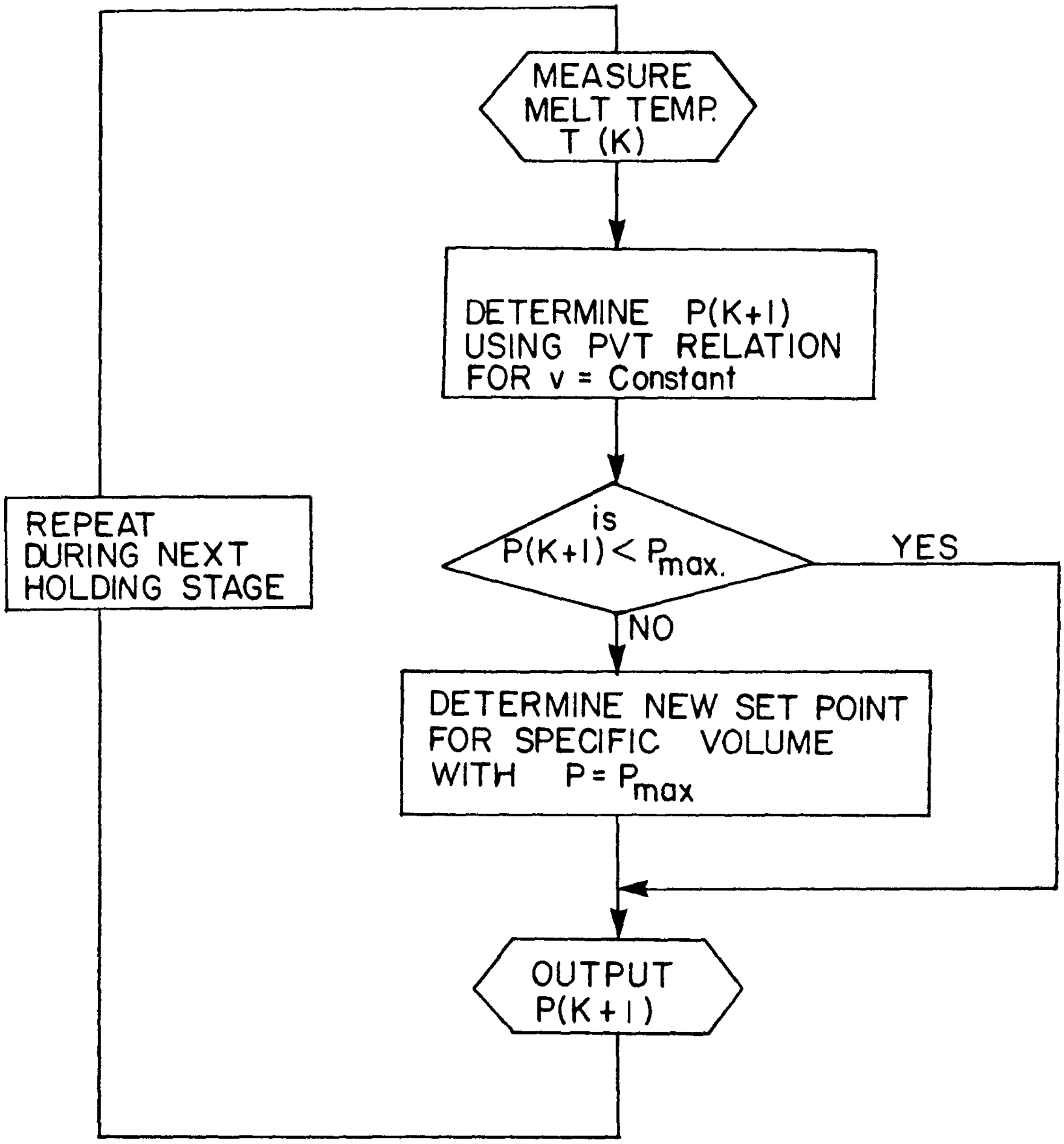


Fig. 9. Flow chart of PVT control scheme.

Agrawal, Fig. 10

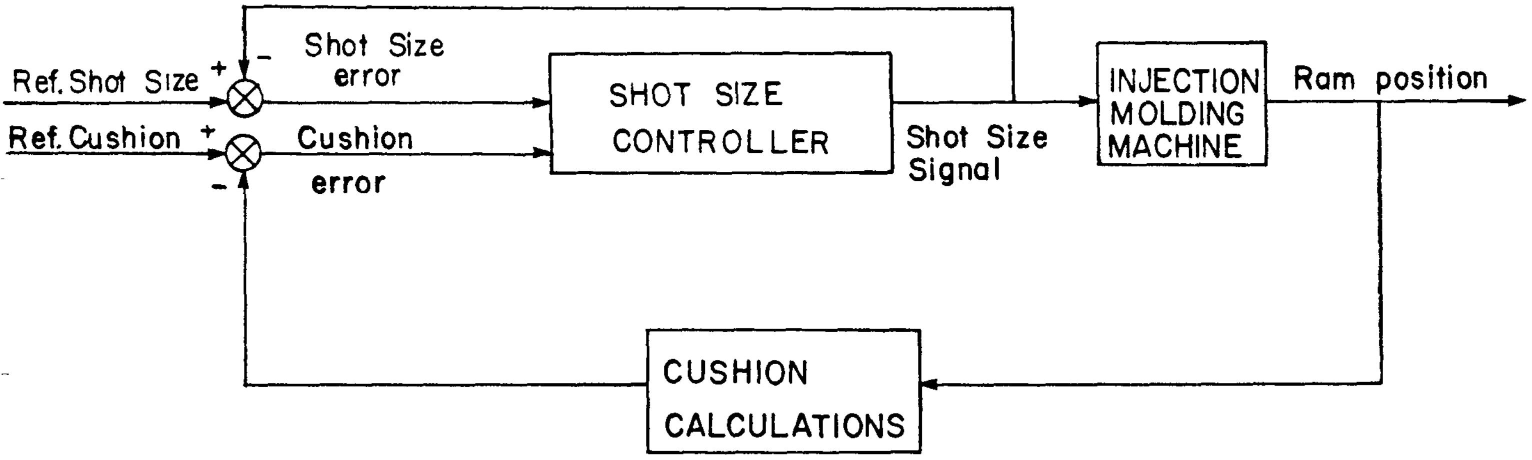


Fig. 10. Block diagram of shot size control scheme.

Agrawal, Fig.11

	X1	X2	X3	X4	X5	. . .
X1	1	P_{12}	P_{13}	P_{14}	P_{15}	
X2	P_{21}	1	P_{23}	P_{24}	P_{25}	
X3	P_{31}	P_{32}	1	P_{34}	P_{35}	
X4	P_{41}	P_{42}	P_{43}	1	P_{45}	
X5	P_{51}	P_{52}	P_{53}	P_{54}	1	

Fig. 11. Correlation matrix. X1,X2,X3,.. are injection molding process parameters and P_{ij} is the coefficient of correlation of the i^{th} pararameter with the j^{th} parameter.