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Temperature Control of Heating Cylinder of Injection Moulding Machine by Decoupling Method

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This paper describes an improvement into a temperature control of a heating cylinder of an injection moulding machine. Resin is molten by band heaters through a thick layer in the heating cylinder, and the temperature of the resin is controlled precisely in the heating and melting process. The heating process is modeled as an interactive system, which is composed of a sequential heating process. The heat flow among the heating processes is compensated by a decoupling method and the control system is designed in each decoupled process independently, considering irreversible thermal characteristics of the resin. A lumped parameter model of the heating cylinder is obtained by means of a finite element method and the design margin of the control system is expressed as Gershgorin band. On the other hand, molten resin flow and a frictional heat are generated by a screw revolution intermittently in the heating cylinder. The intermittent process is modeled as a sampling system and a control design margin is obtained experimentally. The effect of the new control method is verified by experiments in conclusion. This study is applicable to other similar distributed parameter systems and intermittent processes as a general analysis and control method.

Key Words: decoupling control, injection moulding machine, temperature control, plastic industry distributed parameter system

1. Introduction

The importance of the control technology and the applications of the injection moulding machine have been increasing, as the progress of plastic materials like engineering plastics, and machine parts and optical parts are replaced by plastic materials. The main purpose of this study is to find the design method of the precise temperature control system of the heating cylinder that controls the heating and the melting process in the injection moulding machine.

Fig.1 shows the schematic diagram of the heating cylinder. The temperature control of the heating cylinder aims at precise states control of the resin in the melting and the heating process through the thick cylinder layer, mixing the molten resin by a screw. One of the important states of the resin is viscosity, and it directly influences to the accuracy of the dimension of the moulded parts.

The characteristics of the process are as follows.

[1] The resin is heated by the band heaters through the thick cylinder layer and there is a large thermal time lag.
[2] The heated and molten resin has irreversible thermal characteristics.
[3] The intermittent flow of the resin exists inside the heating cylinder at the same period of the injection cycle. There also exists the frictional heat that is generated by the screw revolution in the cylinder.
[4] The states of the molten resin change along axial direction of the screw.

The temperature of the heating cylinder is controlled by the band heaters, considering the resin states. The band heaters are divided into 8 heating zones along axial direction of the cylinder for each melting process.

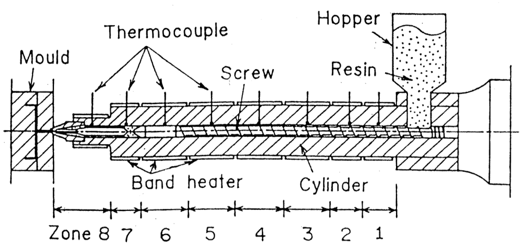

Fig.1 Schematic diagram of heating cylinder

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The distributed parameter system of the heating cylinder and the intermittent frictional heat and the resin flow are modeled as a lumped parameter system with the 8 heating zones, and the temperature control system is designed with the model.

This kind of distributed parameter systems have been conventionally simply controlled by a PID controller, with several temperature sensors installed near to the inner surface of the band heaters empirically. The important factors were neglected, like the thermal time lag through the thick cylinder layer, the thermal interaction among the heating zones, the resin flow, and the frictional heat between the screw surface and the inside surface of the cylinder. The conventional control method could not achieve the precise temperature in each heating zone, and especially in the case of precise moldings products, the accuracy of the dimension was not enough.

To design a precise temperature control system in this study, the thermal characteristics of the heating cylinder is analyzed first, and the heating process is modeled as an interactive system of a continuous series of the 8 heating zones. The thermal interaction is compensated with a decoupling control method, each decoupled system is controlled independently with band heater considering the thermal characteristics of the resin, and the control method is verified through experiments.

2. Modeling of Heating Process

Referring to the thermal relations of the heat flow in **Fig.2**, the thermal characteristics of the heating cylinder is described as following equation of heat conduction.

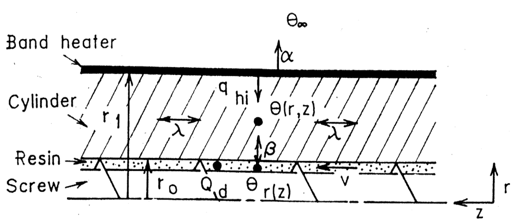


Fig.2 Heat flow in heating cylinder

$$\partial\theta/\partial t=\lambda/wc\cdot\partial^2\theta/\partial r^2+\lambda/wc\cdot 1/r\cdot\partial\theta/\partial r+\lambda/wc\cdot\partial^2\theta/\partial z^2 \qquad (1)$$

w: density of heating cylinder (kg/m^3)
c: specific heat of heating cylinder (J/kg・℃)
λ: thermal conductivity of heating cylinder (W/m・℃)
θ: temperature of heating cylinder (℃)
r: coordinate of radius direction (m)
z: coordinate of axial direction (m)

(1) describes the thermal characteristics under the condition of homogeneous temperature distribution along the circumference direction. The boundary conditions are as follows.

$q(r_1)=q_{hi}$: heat flow per second per area given by i-th band heater (i-th from the hopper side) through outer surface of heating cylinder (W/m^2)
$q(r_1)=\alpha[\theta(r_1)-\theta_\infty]$: heat flow per second per area from outer surface of band heater (W/m^2)
α: heat transfer coefficient at outer surface of heating cylinder (W/m^2・℃)
θ_∞: temperature of atmosphere (℃)
$q(r_0)=\beta[\theta(r_0)-\theta_r]$: heat flow per second per area at inside surface of heating cylinder (W/m^2)
β: heat transfer coefficient at inside surface of the heating cylinder (W/m^2・℃)
θ_r: temperature of resin (℃)

(1) is normalized as (1') and ' means normalized values below,

$$\partial\theta'/\partial t'=\partial^2\theta'/\partial r'^2+1/r'\cdot\partial\theta'/\partial r'+\partial^2\theta'/\partial z'^2 \qquad (1')$$

where boundary conditions are also normalized as follows.

$q'(r'_1)=q_{hi}'$
$q'(r'_1)=\alpha'\theta'$
$q'(r_0')=\beta'[\theta'(r_0')-\theta_r']$

$r=lr'$, $z=lz'$, $t=t_0t'$, $\alpha=\lambda\alpha'/l$, $\lambda/wc=l^2/t_0$
$\beta=\lambda\beta'/l$, $\theta-\theta_\infty=\theta_0\theta'$, $\theta_r-\theta_\infty=\theta_0\theta_r'$
$q=\lambda\theta_0 q'/l$, $q_{hi}=\lambda\theta_0 q'_{hi}/l$.

The distributed parameter system has been conventionally approximated by difference equations [1), 2)]. A finite element method (FEM) is introduced to calculate a state equation in this paper to improve the accuracy of the approximation [3)]. Triangle elements for FEM are shown in **Fig.3** as an example. The state equation is calculated from (1') as follows,

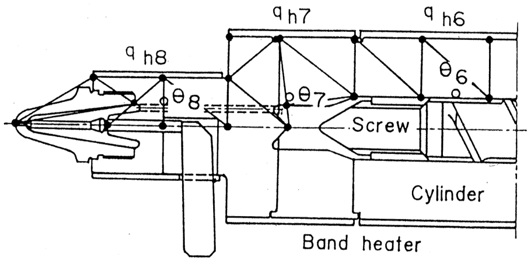


Fig.3 Element partition of the axial section

$$[\mathbf{K}']\{\Theta'\}=[\mathbf{C}']\{d\Theta'/dt'\}+[\mathbf{F}'] \quad (2)$$

$$\theta'^{*}=a_1'+a_2'r'+a_3'z' \quad (3)$$

where Θ' is a vector of node temperature of triangles, $[\mathbf{K}']$ is a heat conduction matrix, $[\mathbf{C}']$ is a heat capacity matrix, $[\mathbf{F}']$ is a vector of heat flux, θ'^{*} is approximated temperature of θ' at coordinate (r', z'), a_1', a_2', and a_3' are expressed by Θ' and the coordinate of node in a triangle element.

Then, the transfer function $g_{ij}'(s')$ between supplied heat flow q_{hj}' by the band heater of j zone and $\theta_i'^{*}$ is calculated. **G'** is defined as a total transfer function matrix that has the element $g_{ij}'(s)$. The example of $g_{ij}'(s)$ is shown below.

$$g_{87}'(s')=(1.59+0.53s'+4.9\times10^{-2}s'^2+1.4\times10^{-3}s'^3)\cdot(1+1.3\times10^{-6}s'^4-5.2\times10^{-7}s'^5)\,/\,(1+6.7s'+3.93s'^2+0.74s'^3+6.4\times10^{-2}s'^4)\cdot(1+3\times10^{-3}s'^5+8.5\times10^{-5}s'^6) \quad (4)$$

Fig.3 shows the FEM elements for calculation of g_{87}' with 20 nodes in the left part of the cylinder, but in (4) over s^7 terms are neglected to simplify the model. To check how far the terms can be neglected, Bode diagram of the transfer function are calculated for several cases in **Fig.4**. Over m-th power of s terms are neglected for each line in Fig.4, and the dimension of the numerator of the transfer function is m-1 degree.

The gain curve almost equal within the range of 5dB for each m, but phase curves are different in high frequency area for small m. A point $\omega'=1$ in Fig.4 is an effective upper limit of frequency, and the approximation accuracy is enough in lower frequency area of $\omega'=1$, when the transfer function is calculated in the range of $m\geqq3$. The following results are calculated with the case of m=3, and the approximation is enough judging from the experimental results in Chapter 4.

The heat conduction is modeled in (1'), as a next step, the resin flow is modeled. There is heat transfer between the inside wall of the heating cylinder and the resin flow. The heat transfer is expressed as follows,

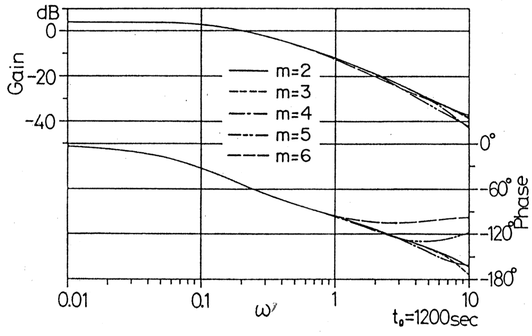


Fig.4 Bode diagram of g_{87}'

$$\partial\theta_r'/\partial t'=v'\cdot\partial\theta_r'/\partial z'+\beta_r'(\theta'-\theta_r')+Q_d' \quad (5)$$

where $v=lv'/t_0$ (m/s), $\beta_r'=2\gamma\beta'/r_0$, $\gamma=wc/w_pc_p$, $Q_d=\lambda\theta_0Q_d'/l^2\cdot\gamma$ (W/m^3), w_p is density of resin (kg/m^3), and c_p is specific heat of resin (J/kg·℃).

Heat conduction is neglected in (5) because of a small factor comparing to the heat conduction of the heating cylinder. v' is an average velocity of resin flow in the axial direction, and proportional to a screw revolution speed n.

The first term of the right part of (5) is heat transfer by the resin flow, and the second term is heat convection between the inside cylinder wall and the resin flow. The third term is frictional heat that is produced by the screw revolution and the resin flow. The resin actually flows intermittently with the same as an injection period, and it transfers heat only in the period of screw revolution time τ within the total period T. v' and Q_d' in (5) are average values during period T. The intermittent flow is analyzed in the next Chapter.

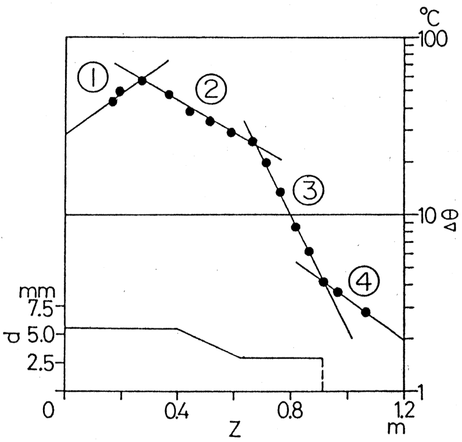


Fig.5 Distribution of $\Delta\theta$ and d

A constant electric power is supplied to the band heaters to measure the influence of the resin flow and frictional heat. First the temperature profile along the axial direction of the heating cylinder is maintained constant at 210℃. Then the variation $\Delta\theta$ of the temperature profile is measured under the condition of the resin flow. The experimental result is shown in **Fig.5**.

The horizontal axis is an axial distance from the hopper, and the vertical axis in logarithmic scale is $\Delta\theta$. The result is divided into 4 areas depending on the state of resin flow and its cooling or heating effect. The resin is almost solid and cooling effect is large in the area ①, and frictional heat is minimum. Some part of resin is molten and solid resin exists at the same time in the area ②, and both the effect of frictional heat and cooling are large. The resin is completely molten and temperature of the resin is high in the area ③, and the effect of frictional heat is largest in all areas. The molten resin is reserved in the area ④, and the effect of frictional heat and cooling is smallest in all areas. On the other hand, the gap depth d of the screw flight is large and constant in ① and the beginning of ②, and there is incline of d in the end of ②. d is small and constant in ③. The gap depth d is shown in the bottom of Fig.5. The state of the molten resin is decided by the gap depth[4].

The area which has the same constant gap depth in Fig.5 is considered as the frictional heat is constant and defined as one homogeneous process. Each area is divided into two control units, as a result, total control zone number is 8, and all zones have a thermocouple and are controlled by a band heater. The total heating process is a sequential process of above 8 zones and described as an interactive system, and the decoupling control method is introduced in the next Chapter to control each zones independently.

3. Decoupling Control System Design, Experiments and Discussion

The model obtained in the prior chapter is an interactive system of heat conduction among zones of the heating cylinder, including the resin flow and the frictional heat. The thermal interaction is compensated by a feedback control using measured temperatures in each zone and the feedback values are calculated using the transfer function g_{ij}. The frictional heat can not be calculated and compensated, but the value is constant as far as the injection parameters are constant. As a result, the thermal interaction is compensated only for the heat conduction of the cylinder, and the control design margin is introduced for the effect of the frictional heat and it is decided for each injection parameter.

The decoupling method are classified into three, those are [1] state feedback method[5], [2] frequency domain method[6], and [3] I-PD method[7]. The decoupling method for the injection moulding process is based on [3]. The high differential term of the output feedback loop is neglected as a practical reason, and the temperature of each zone is dynamically feed backed to input with n-differential. This method has high approximation accuracy with the finite element method, and the output is decoupled up to the high frequency area when the dimension of the dynamic feedback is high enough (m=3 in Fig.4). The feedback value equals to heat interaction value, and it has an advantage for designing of the decoupling control system, because it is directly related to heat conduction.

On the other hand, it is generally difficult to calculate an accurate model of a thermal process, and an approximation method must be applied to the process. The heat conduction has largest influence on neighboring zones, and the influence decreases suddenly far from the zones. Then the process is modeled in each zone with only neighboring two zones, and the total process is described as a convolution of each model. The design margin is introduced to compensate the approximation error, and an un-decoupled interaction is described with Gershgorin band[8], and the band is used as the design margin. The time response of the temperature is modified with integration element in each main control loop after decoupling, and the overshoot value is designed with Nichols chart.

The feedback coefficient matrix $\mathbf{K_f}'=\{k_{fij}'(s')\}$ for decoupling in **Fig.6** is defined with next equation,

$$k_{fij}'(s')=\{\, k_{fij}'(s') \mid \min \Sigma\, g_{fij}'^{-1}(s')\} \quad i, j=1,2,\cdots,8\ (i\neq j) \quad (6)$$

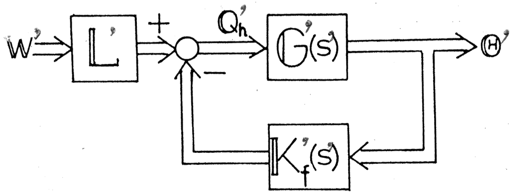


Fig.6 Block diagram of decoupling control system

where $g_{fij}'^{-1}(s')$ is the element of $\mathbf{G}'^{-1}$ of $\mathbf{G}'$ that is obtained in the prior chapter. $k_{fij}'(s')$ is

$$k_{fij}'(s')= k_{fij}'^{0}+ s'k_{fij}'^{1}+ s'^{2}k_{fij}'^{2}+\cdots \tag{7}$$

and expanded as power series of s'. $\Sigma\, g_{fij}'^{-1}(s')$ in (6) is the interaction ratio, and equals to the radius of Gershgorin band in an inverse Nyquist diagram. Although the coefficients of (7) can be obtained with the diagram[1), 2)], it is easy to calculate them with a convolution method in each zone as follows.

The relation between input and output of feedback control system is expressed as,

$$\Theta'=\mathbf{G}'\mathbf{Q}_h' \tag{8.a}$$

$$\mathbf{Q}_h'=\mathbf{L}'\mathbf{w}'-\mathbf{K}_f'\Theta' \tag{8.b}$$

where $\Theta'=(\theta_1', \theta_2', \cdots, \theta_8')^T$, $\mathbf{Q}_h'=(q_{h1}', q_{h2}', \cdots, q_{h8}')^T$, $\mathbf{L}'=\mathrm{diag}(l_1', l_2', \cdots, l_8')$, $\mathbf{w}'=(w_1', w_2', \cdots, w_8')^T$. The relation between $\mathbf{w}'$ and Θ' are calculated as,

$$(\mathbf{G}'^{-1}+\mathbf{K}_f')\ \Theta'=\mathbf{L}'\mathbf{w}' \tag{9}$$

from (8), where $\mathbf{L}'$ is a diagonal matrix for adjustment of the open loop gain after decoupling, and $\mathbf{w}'$ is an input vector for the decoupled control system. Even if the node number of the finite element method is limited to 12 in each zone, the total dimensions of $\mathbf{G}'$ becomes 96 with 8 zones, and the size of matrix is too big to calculate the transfer function matrix accurately.

Then the total system is divided into 8 subsystems with neighboring 2 zones and a transfer function matrix in each subsystem. The 8 subsystems are convoluted in one total system. The node number is 10~14 in each zone according to the complexity of the shape of the cylinder. The i zone and i+1 zone are convoluted as next equation, under the condition of both zones are decoupled from i-1 zone and i+2 zone.

$$\boldsymbol{G}' \fallingdotseq \begin{pmatrix} \boldsymbol{G}_{i-1}'^{-1} & & \boldsymbol{0} \\ & \boldsymbol{G}_{i}'^{-1} & \\ \boldsymbol{0} & & \boldsymbol{G}_{i+1}'^{-1} \end{pmatrix} \tag{10.a}$$

$$\mathbf{G}_i'=\begin{pmatrix} g_{i,i}' & g_{i,i+1}' \\ g_{i+1,i}' & g_{i+1,i+1}' \end{pmatrix}=\begin{pmatrix} p_{si,i}' & p_{si,i+1}' \\ p_{si,+1\,i}' & p_{si+1,i+1}' \end{pmatrix} \Big/ q_{si} \tag{10.b}$$

$\mathbf{G}'$ is composed of block matrix $\mathbf{G}_{i-1}'$, $\mathbf{G}_i'$, $\mathbf{G}_{i+1}'$. For example, when i=4, $\mathbf{G}_{i-1}'$ is the transfer function matrix of zone 1, 2, 3, $\mathbf{G}_i'$ is of zone 4, 5, 6, and $\mathbf{G}_{i+1}'$ is of zone 6, 7, 8, where p_s and q_s are polynomials of transfer functions, ε is an interaction ratio between neighboring zones, and if ε 0, $\mathbf{G}'^{-1}$ is described as follows.

$$\boldsymbol{G}'=\begin{pmatrix} \boldsymbol{G}_{i-1}' & \varepsilon & \boldsymbol{0} \\ \varepsilon & \boldsymbol{G}_{i}' & \varepsilon \\ \boldsymbol{0} & \varepsilon & \boldsymbol{G}_{i+1}' \end{pmatrix} \tag{11}$$

2 zones and other neighboring zones are assumed thermally isolated, $\mathbf{G}_i'$ is calculated with the finite element method, and the feedback coefficients $k_{fij}'(s')$ are obtained as,

$$\mathbf{G}'^{-1}+\mathbf{K}_f' = \begin{pmatrix} q_{si}'p_{si+1,i+1}'+k_{f\,ii}'\Delta & -q_{si}'p_{si,i+1}'+k_{f\,i,i+1}'\Delta \\ -q_{si}'p_{si+1,i}'+k_{f\,i+1,i}'\Delta & q_{si}'p_{si,i}'+k_{f\,i+1,i+1}'\Delta \end{pmatrix} \Big/ \Delta \tag{12.a}$$

$$\Delta=p_{s\,i,i}'p_{s\,i+1,i+1}'-p_{s\,i,i+1}'p_{s\,i+1,i}' \tag{12.b}$$

non diagonal elements equals to 0, then next equations are obtained.

$$k_{f\,i,i+1}'(s')=p_{si,i+1}'q_{si}'/\Delta \tag{13.a}$$

$$k_{f\,i+1,i}'(s')=p_{si+1,i}'q_{si}'/\Delta \tag{13.b}$$

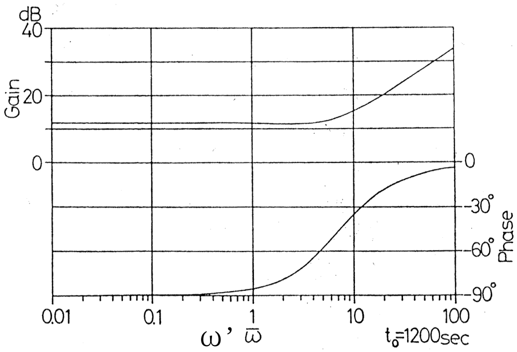


Fig.7 Bode diagram of $k_{f\,87}'(s')$

The Bode diagram of $k_{f\,87}'(s')$ is shown in **Fig.7**. The transfer function is expanded to power series of s' as (7), the dynamic feedback is designed from the lower dimension of the power series and decoupled in an appropriate frequency area. The Gershgorin band is obtained for the above decoupled system and drawn in **Fig.8** with broken line and circles, and solid line and circles are Gershgorin band for the interaction system before decoupling. The figure is the example of the

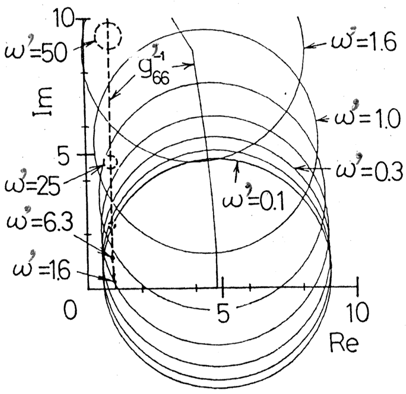


Fig.8 Inverse Nyquist Diagram g_{66}^{-1}'
and Gershgorin band

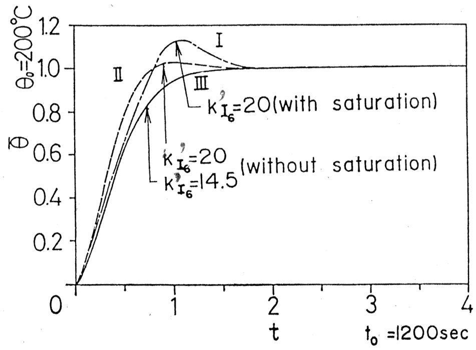


Fig.10 Step response of Fig.9
(i=6, l_6=1,k_{f66}=30)

decoupling system, that is, 0, 1st, and 2nd power term of s' in (7) is dynamically feed backed to the input. If more accurate decoupling is necessary, the higher power term of s' is dynamic feed backed.

G'$^{-1}$ is diagonal matrix and totally decoupled with dynamic feedback whose coefficients are calculated with (13) for i=1, 2, ⋯ , 8. The feedback coefficients $k_{f\,i,\,i}$'(s') are also calculated and integrator coefficients $k_{f\,Ii}$'/s' in **Fig.9** to realize a desired response in each decoupled zone. Judging from (13), $k_{f\,i,\,j}$'(s') will not be influenced by $k_{f\,i,\,i}$'(s'), and it is not necessary to calculate the feedback coefficients again for decoupling. The desired response in each zone is described as,

$$g_{mi}' = 1/ (1+ \alpha_1 s'+ \alpha_2 s'^2+\cdots) \qquad (14)$$

referring to the value of α_i in 9), g_{mi}' is decided and $k_{f\,i,\,i}$'(s') , $k_{f\,Ii}$' are calculated. Furthermore, the optimized response is obtained with computer simulation, and $k_{f\,i,\,i}$'(s') , $k_{f\,Ii}$' are adjusted. **Fig.10** shows the simulated results of the response. As there is a possibility that the resin is deteriorated by high temperature in zone 6 to zone 8, the overshoot value is designed minimum in these zones.

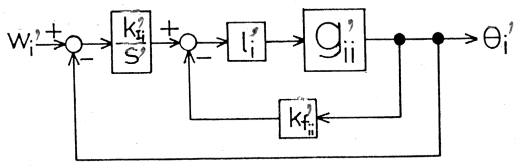


Fig.9 Block diagram of feedback
control system in zone i

Case Ⅲ in Fig.10 is applicable to these zones and case Ⅰ or Ⅱ is desired in other zones. The effect of the non-decoupled interaction for the overshoot value is estimated with Nichols chart using open loop characteristics of the control system, and Gershgorin band is drawn in the chart using next equation,

$$\mathbf{z} = \mathbf{a} + be^{j\phi} \quad (0 \leqq \phi \leqq 2\pi) \qquad (15.a)$$

$$\xi = 20 \log \mathbf{z} \qquad (15.b)$$

$$\xi = \arg (\mathbf{z}) \qquad (15.c)$$

where **a** is vector locus of a closed loop system, and b is radius of Gershgorin band, $be^{j\phi}$ is Gershgorin plate, and ξ is phase coordinate in Nichols chart. The example of Nichols chart and Gershgorin band are shown in **Fig.11**.

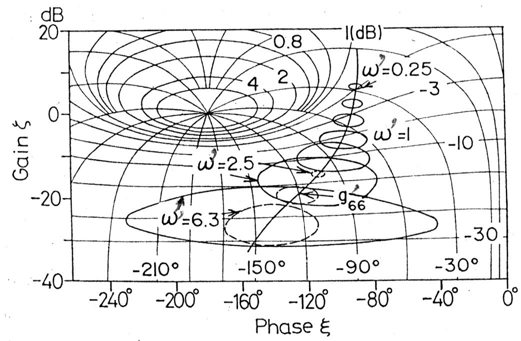


Fig.11 Nichols chart of g_{66}'
and Gershgorin band

The solid line and circles are the Gershgorin band of the non-decoupled system, and broken line and circles are Gershgorin band of the decoupled system. The width of the band is design margin, when the gain $k_{f\,Ii}$' is calculated for the control system. However there is a saturation for heater power and the response becomes Ⅰ in Fig10, and it is necessary to reduce the control gain in normal operation, the heater is not saturated in any case. The desired response is easily obtained with few experiments in the next chapter.

As the next design step, (5) is approximated with a lumped parameter system, to express the effect of the resin flow and the frictional heat as follows,

$$d\theta_{ri}'/dt' = v'(\theta_{ri-1}' - \theta_{ri}')/\Delta z' + \beta_r'(\theta_i' - \theta_{ri}') + Q_{di}' \qquad (16)$$

where Q_{di}' is described with exponential function of the resin temperature[1) 2)], and the first order approximation is

$$Q_{di}' = A' b e^{-B'\theta_{ri}'} \quad A'(1-B'\ \theta_{ri}') \qquad (17)$$

The heating cylinder is also expressed as a lumped parameter system in each zone. The heat conduction is assumed to be decoupled,

$$d\theta_i'/dt' = -a'\theta_i' + b'w_i + c'\beta'(\theta_{ri}' = \theta_i') \qquad (18)$$

where a', b', and c' are coefficients of characteristics of the decoupled system. (16) is the case that has a constant resin flow and frictional heat.

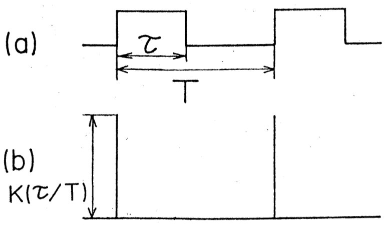
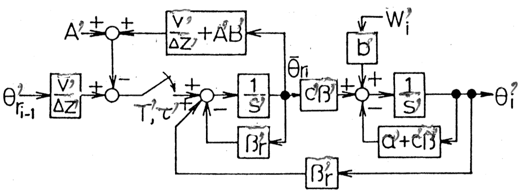
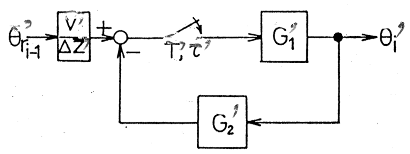


Fig.12 Time chart of intermittent resin flow



(a)



(b)

Fig.13 Block diagram of heating cylinder and intermittent flow model

As the resin flow is intermittent in fact, (16) ~(18) are re-described with a sampling system. The injection cycle is T and the intermittent period of the resin flow is τ as shown in **Fig.12**. The sampling system is drawn as **Fig.13 (a)** and summarized as (b), where

$$G_1 = c'\beta'/(s'+a'+c'\beta')(s'+\beta_r') - c'\beta'\beta_r' \qquad (19.a)$$

$$G_2 = (v'/\Delta z' + A'B')(s'+a'+c'\beta')/c'\beta' \qquad (19.b)$$

The sampler in Fig.13 is closed during τ period, and τ is small enough comparing the time constant of the system, then it is assumed τ 0, and τ is replaced by constant gain K(τ/T). Using Z transformation method, the stability of the system is judged from the equation

$$1+G_1G_2(z') = 1+K'(\tau/T')\cdot(v'/\Delta z'+A'B') \cdot Z\{(s'+a'+c'\beta')/(s'+a'+c'\beta')(s'+\beta_r') - c'\beta' k_r'\} \qquad (20)$$

$K'(\tau'/T')\cdot(v'/\Delta z'+A'B')$ is a function of T' and τ', when the injection condition is once decided, it is constant and has no dynamic characteristics. The value is calculated independently from Z transformation of (20).

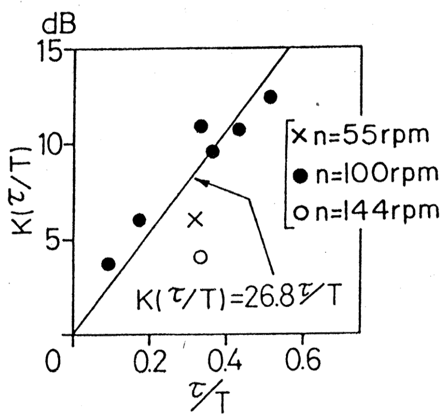


Fig.14 K(τ/T) versus τ/T

The experiment has done under the condition that the heat conduction of the heating cylinder is decoupled and the gain is increased up to an limit of stability, and then the parameter τ/T is changed with constant v and n. The resin flow causes the oscillation of the temperature exceeding the limit of stability. Experimental results are shown in **Fig.14** with black circle points. The horizontal axis is the parameter τ/T, and the vertical axis is the amplification of the oscillation, and is equal to the K(τ/T), where T=8.8 ~47sec. Then n is changed and the same results are obtained in Fig.14 as a cross mark and a white circle point, and K(τ/T) is maximum at n=100rpm for various n.

The experimental results mean that the apparent gain is changed by the resin flow and the frictional heat for the control system. The control gain should have the design margin equal to the experimental value K(τ/T) for each injection parameters.

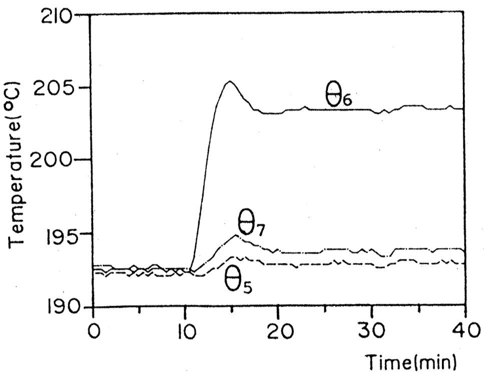
4. Conclusion

The above control method is verified by the experiments with a commercial type of injection moulding machine. The control system is composed of a micro computer, thermocouples as temperature sensors, and band heaters are controlled by PWM method with solid state relays, where the sampling period is 5sec. The experimental results are shown in **Fig.15, 16**. The inputs are changed in stepwise at the 10 minutes of the horizontal axis in each figure. Fig.15 (a) shows the step response of the temperature without decoupling in zone5, 6 and 7 when the input of zone 6 is stepwise changed. (b) is the step response of the decoupling system with feedback k_{fij}^{0}. Although the static interaction in zone 7 is completely decoupled in (b), the dynamic interaction from neighboring zone 6 is remained. The remained interaction is dynamically decoupled by the feedback sk_{fij}^{1}, and the result is shown in (c).

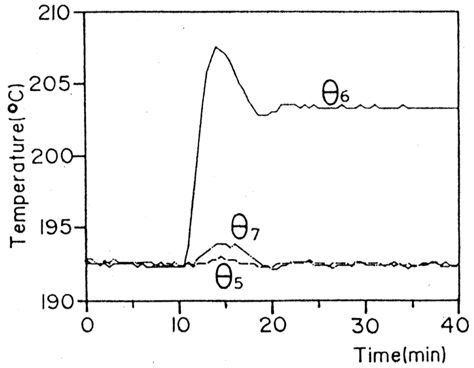
The interaction is almost decoupled by the dynamic feedback of the first power of s. **Fig.16** shows the step response in zone 2 of the decoupled system using the control method in Fig.9. (a) is the response of the case of without resin flow, and no overshoot system is realized. (b) is the case of resin flow under the condition of τ /T=0.33, n=100rpm. Because there is an integrator in the main control loop, the response is not deferent from (a) in static characteristics, but there exists some temperature fluctuation according to the injection cycle. There is a possibility that the response is changed when the gain is increased, in that case the gain is necessary to be decreased proportional to the design margin of the prior chapter.

The proposed method is characterized by the lumped parameter system of the essentially distributed parameter system. The system is divided into 8 zones in heating and melting process and is modeled as an interactive system, the decoupling control method is applied, and finally each zone is controlled independently. The approximated model is obtained with the finite element method, and the design margin is expressed with Gershgorin band. Furthermore, the intermittent resin flow is described and modeled as an equivalent gain margin K(τ /T), and the control system is precisely designed with the model.

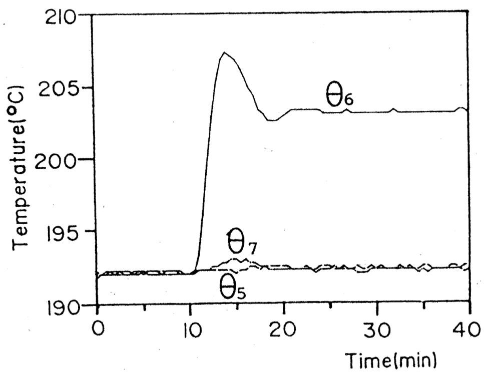
The proposed control design method for an interactive thermal system is applicable to other control object which is necessary to control a temperature precisely.



(a) Without decoupling



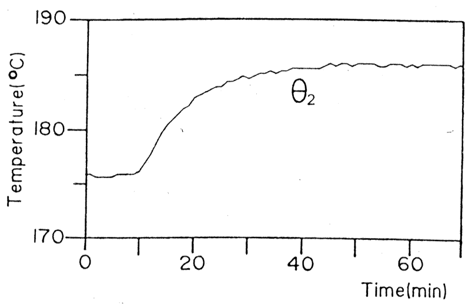
(b) Decoupling by constant feedback



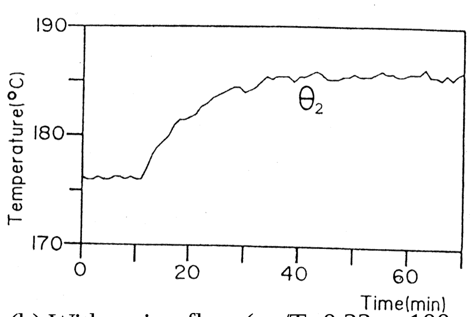
(c) Decoupling by dynamic feedback

Fig.15 Step response of zone 5,6 and 7 (Experimental results)

Great appreciation to Dr. Jotaki is sincerely given for his kind and intimate suggestion to the above study and experiments. The experiments are realized with the continuous help of Mr. Sugiuchi and appreciation is also given to him.



(a) Without resin flow



(b) With resion flow (τ /T=0.33,n=100rpm)

Fig.16 Step response of zone 2
(Experimental results)

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