Improvement in Extruder Melt Temperature Control

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ABSTRACT

Modern extruders require improved control systems.
Three melt temperature control systems are introduced
and critically discussed.

INTRODUCTION

Rising output rates and higher demands on product quality make
it necessary to increase automation of the extrusion process and
to improve its control. The following demands are made on the
extruder:

1) High and constant output rate.
2) A constant state of the melt fed to the die to ensure a uniform
   extrudate quality for constant processing conditions in the
   die and during the calibration and cooling.

The control of the melt temperature in front of the screw tip is
advantageous for attaining a constant state of the melt. The control
of the viscosity could be even better if measurement could be made
during the process. Efforts are being made by IKV toward the solu-
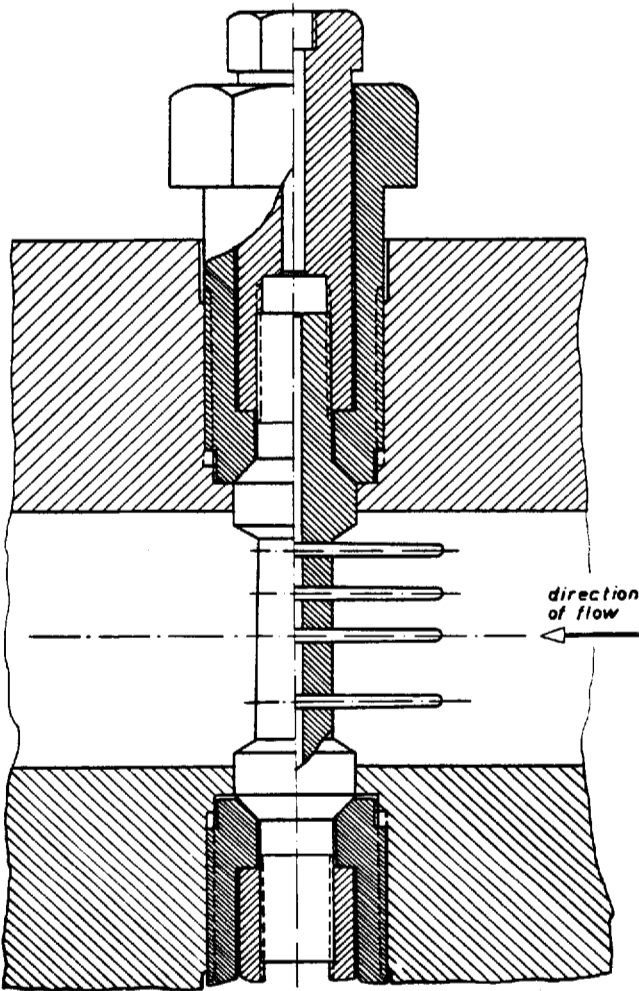tion of this problem.

direction
of flow

FIG. 1. Sensor for measuring the melt temperature at several
points of a channel cross section.

A high and constant output rate can be obtained by an adequate
design of the conveying zone of an extruder according to the extrusion
concept developed by IKV [1, 2]. This method realizes an output

rate independent of the back pressure at the screw tip. The output rate can be kept constant by control of the pressure in front of the die by the screw speed if the melt temperature is also controlled [3].

The control of the melt temperature requires exact measurement. For this purpose we use a sensor based on the principle suggested by TNO-Delft (Fig. 1), which has the advantage of very small errors [4, 5]. It permits the measurement of the radial melt temperature profile downstream from the screw tip.

EXTRUDER MELT TEMPERATURE CONTROL

Possible Control Systems

In general a control of the melt temperature is possible through the heating energy which is fed to or removed from the extruder barrel, or by the frictional energy generated in the stock itself. We tested the following control systems (See fig. 2):

System 1: Melt temperature control by a cascade control system using the melt temperature as the primary controlled variable and the wall temperatures as the secondary controlled variables.
System 2: Melt temperature control using the heating energy of the last zone at the screw tip as the correcting variable, without the wall temperatures as the subsidiary controlled variables.
System 3: Melt temperature control using the frictional energy as the correcting variable by adjusting a conically shaped valve in front of the screw tip.

Tests have been run by process simulation using an analogue computer model and with three extruders of different sizes (screw diameters D = 45, 80, and 120 mm) and origin. The controlling characteristics of the three extruders were first examined thoroughly without controllers, i.e., the extruder was tested as the controlled system.

We obtained the following results:

1) When changing the heating energy:

a) The melt temperature and the wall temperature depend proportionally on the heating energy.
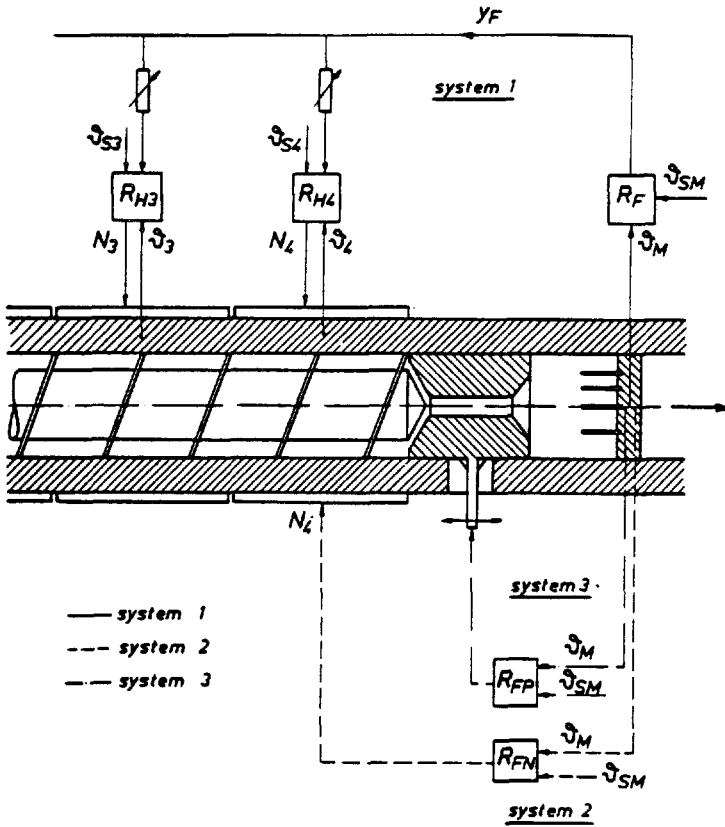
FIG. 2. Systems tested for the control of the melt temperature θ_M.

b) The effect of a change of the heating energy decreases with a
rising output rate.

c) The action of the heating energy is very slow, especially with
big machines.

d) Changes of the heating energy in the heating zones near the
screw tip hardly influence the output rate (in general).

e) The radial temperature differences of the melt right in front
of the screw tip vary only insignificantly after a change of
the heating energy.

f) The wall temperatures indicate a change of the heating energy considerably sooner than the melt temperature in front of the screw tip.

2) When changing the frictional energy:

a) The melt temperature increases progressively with a decrease of the valve opening.
b) The effect of a change of the valve opening does not decrease with a raise of the output rate.
c) A change of the valve opening takes effect rapidly compared to a change of the heating energy.
d) The output rate of conventional extruders without an effective conveying zone is significantly influenced by a change in the valve opening.
e) The radial temperature profile of the melt down-stream from the valve alters when the valve opening is changed.

Full details of our results have been given in previous publications [3, 6, 7]; they are briefly discussed below for the three control systems suggested.

Cascade Control System

Controlling the melt temperature by means of a cascade control system has been proposed by several authors [8, 9, 10]. Up to now, however, notations concerning the optimum adjustment have not existed, especially for the master controller parameters and its dependence on the operating point of the extruder.

The principle of the cascade control system is shown in Fig. 2. The values of the melt temperature θ_M are fed by the thermocouple to the master controller R_F, where they are compared with the set values. Corresponding to the deviation $\theta_M - \theta_{SM}$, the output signal y_F of the master controller R_F corrects the set values of the connected wall temperature controllers R_{Hi}.

If, for instance, the melt temperature is too low, the set values of the wall temperatures are raised. The zone directly at the hopper was not included in the cascade control because of possible changes in the output rate caused by an alteration of the wall temperature.

We used a three term controller (proportional plus integral plus derivative) as master controller and proportional plus derivative controllers for the control of the wall temperatures. The extruder barrel was provided with electrical resistance heating and air or water cooling.

The following items, on which the quality of control obtained by means of a cascade control depends, were first investigated by analogue computer models:

1) How are the control parameters of the master controller R_F

to be estimated for various extruders and operating conditions in order to obtain an advantageous control action?

2) How high must the intensity of the influence of the master controller on the wall temperature controllers of the several heating zones be chosen?

3) Have the parameters of the wall temperature controllers R_{Hi} any influence?

The most important results of the analogue computer simulation were tested in respect to their transferability to the three extruders.

On the whole the experiments on the analogue computer and the three extruders yielded the following results: The parameters of the wall temperature controllers have to be chosen in such a way that the control actions are well damped in the case of a sole control of the wall temperature (i.e., without a master controller). The adjustment rules of Ziegler-Nichols [11], for instance, can be used for the estimation of the control parameters of continuous action controllers. It is insignificant whether continuous action or discontinuous action wall temperature controllers are used.

The intensity of the master controller's influence on the last heating zone of the barrel at the screw tip is of primary interest in regard to the control aspects; the intensity of the influence on the remaining heating zones must be chosen according to aspects which concern the process in such a way that no significant effect on the quality of control arises.

The last and most important result is that equations, which are valid for all the cases examined (the complete range of screw speeds of three different extruders) and which can be easily applied in practice, can be given for the estimation of optimum master controller parameters. They are:

$$V_{RF} = 0.6(\Delta\theta_j/\Delta\theta_M)$$

$$T_{NRF} = T_{UM}$$

$$T_{VRF} = 0.25\ T_{UM} \quad\quad \text{or} \quad\quad T_{VRF} = 0$$

Application shall be explained using Fig. 3. It is only necessary to record the development of the wall temperature θ_j and the melt temperature θ_M with a disconnected master controller after a shift
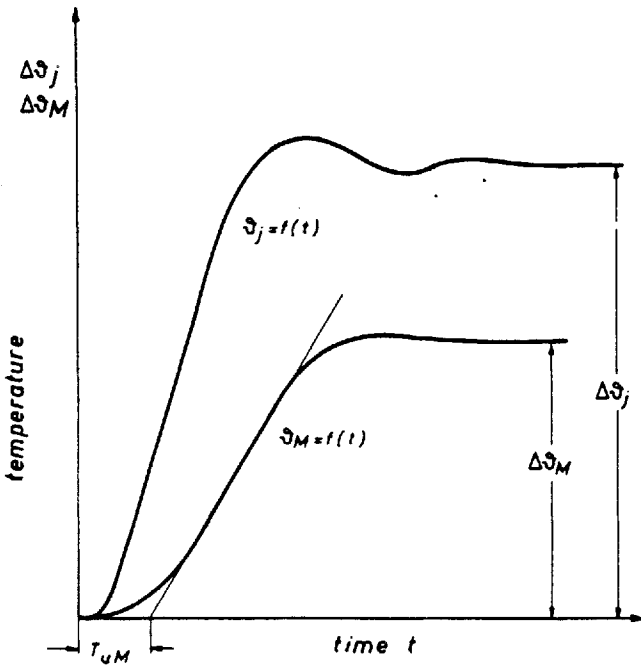

FIG. 3. Determination of the extruder characteristics $\Delta\theta_j$, $\Delta\theta_M$, and T_{UM}.

of the set value of θ_j of the last heating zone at the screw tip. From the resulting temperature differences $\Delta\theta_j$ and $\Delta\theta_M$, the ratio $\Delta\theta_j/\Delta\theta_M$ is found, and with this the gain amplification V_{RF} is calculated. (This points out the correction $\Delta\theta_{sj}$ of the set value of the proportional action of the master controller will perform in the case of a deviation of θ_M from its set value θ_{SM}: $V_{RF} = \Delta\theta_{sj}/(\theta_{SM} - \theta_M)$.

The integral time action and the derivative action time are calculated by means of the characteristic time T_{UM}, which can be taken from Fig. 3 according to the course of the melt temperature. A proportional plus integral plus derivative controller shows certain advantages for balancing the influence of disturbance variables compared to a proportional plus integral controller (i.e., $T_{VRF} = 0$).

Further details concerning these adjustment rules can be found in Ref. 12.

According to the adjustment rules there will be a different optimum adjustment of the controller for every screw speed. The optimum adjustment for high screw speeds can cause surging control actions at low screw speeds. This is shown in Fig. 4: for the extruder with a screw diameter of 45 mm the optimum controller adjustment for 50 rpm ensures a secure action for 170 rpm also; the optimum controller adjustment for 170 rpm causes overshooting at 50 rpm. The variations of the optimum controller parameters for different operating levels are bigger for small extruders than for large ones.

Finally, two more examples: in Fig. 5 a change of material from LDPE to HDPE is shown for an extruder with 80 mm screw diameter. Figure 5a shows the development of θ_M and of the wall temperatures θ_3 and θ_4 of the last two zones for the sole control of the wall temperatures; Fig. 5b shows the same for the cascade control. Only in the last case does θ_M return to the desired set value by means of an adequate reduction of the set values of the wall temperatures for Zones 3 and 4.

Figure 6 shows the mode of operation of the cascade control with an extruder of 120 mm screw diameter. In Fig. 6a the set value of the melt temperature is reduced by 5°C exactly and without overshooting. Figure 6b demonstrates how the melt temperature is led back to its set value after a change of the screw speed; in this
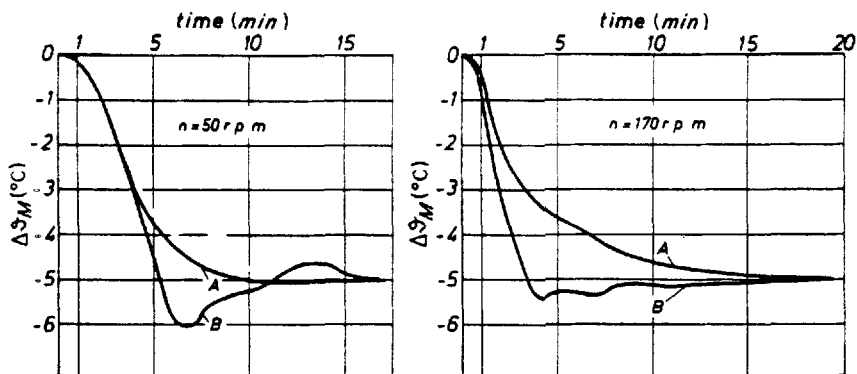
45mm —extruder; $\Delta\vartheta_{SM} = -5\,°C$
A: optimum adjustment for n=50 r p m
B: optimum adjustment for n=170 rpm

FIG. 4. Reduction of the melt temperature with a 45-mm
extruder at screw speeds of 50 and 170 rpm.

case the adjustment of the controller, however, was not an opti-
mal one. Comparison of Figs. 4, 5, and 6 shows how the neces-
sary correction times grow with extruder size.

Sole Control of the Melt Temperature without Wall Temperatures as Subsidiary Controlled Variables

Control of the melt temperature by the last heating zone at the
screw tip seems to be the obvious system. This was tested with
the analogue computer and with an extruder with a 45-mm screw
diameter. The results shall be omitted as they only demonstrate
the disadvantages of this system compared to the cascade control.

In the case of variations of the set value of the melt temperature,
the differences between the best control actions of the two systems
are rather small (see also Fig. 8); for deviation controls, however,
the simple melt temperature control is considerably less effective
than the cascade control. The changes of the optimum controller
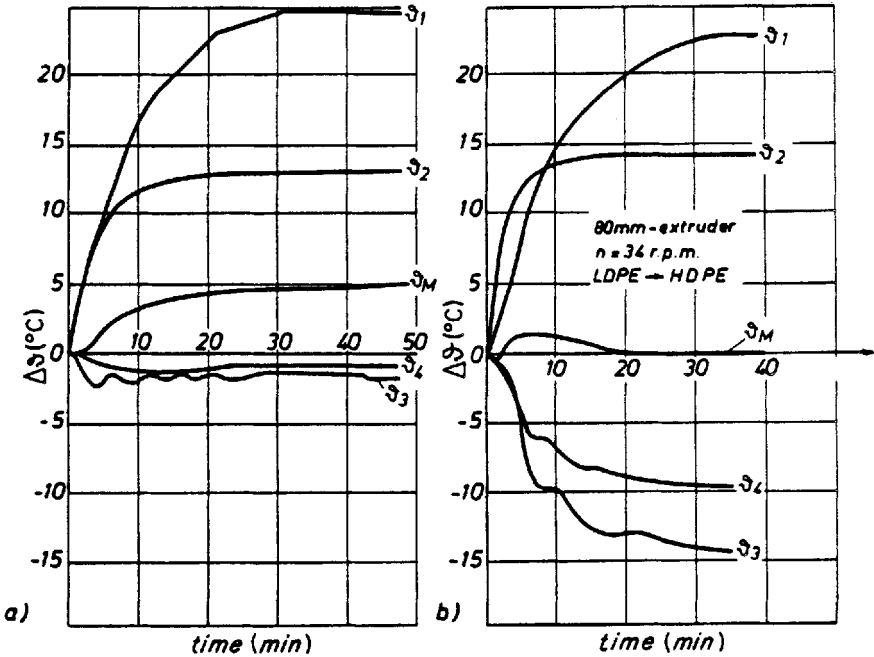adjustment caused by variations of the operating point are much

FIG. 5. Change of material with an 80-mm extruder.
(a) Sole control of the wall temperatures. (b) Cascade control.

larger for the simple melt temperature control than for the cascade
control. Therefore an adaptation of the controller characteristic to
the operating point must be provided (adaptive control). Because of
this the sole control of the melt temperature is rather more expen-
sive than that of the cascade control. Finally, the axial temperature
profile of the extruder barrel is more distorted by the simple melt
temperature control than by the cascade control.

Compared to the simple control of the melt temperature by the
last heating zone, the cascade control proves to be advantageous
in every aspect.

Control of the Melt Temperature by Frictional Energy

The possibility of controlling the melt temperature by the altera-
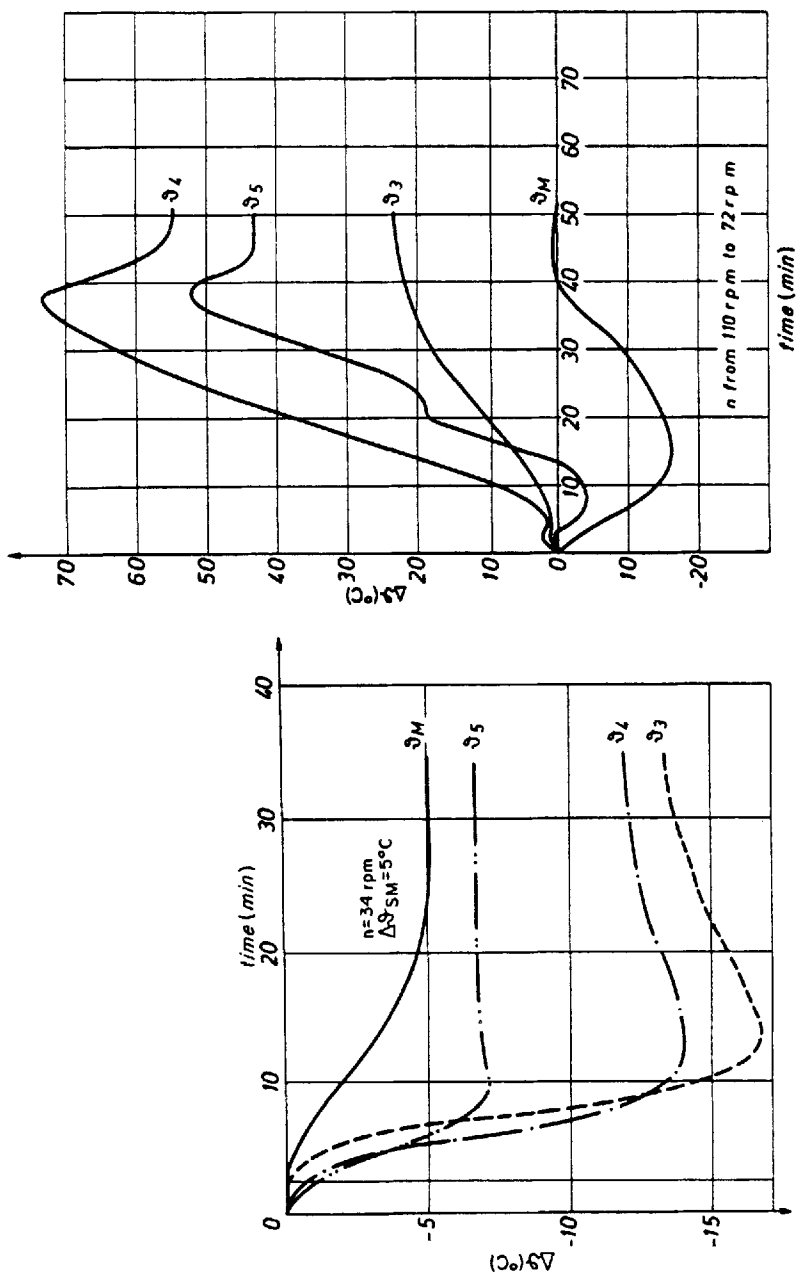tion of a valve (adjustable annular shearing gap) according to Fig. 2

FIG. 6a. Cascade control with a 120-mm extruder. Reduction of the melt temperature by 5°C.
FIG. 6b. Cascade control with a 120-mm extruder. Deviation control for a change of screw speed.

was examined with an extruder with a 45-mm screw diameter and on
the analogue computer model for an extruder with a 80-mm screw
diameter. Figure 7 shows the development of the melt temperature
after a change of the set value for the extruder with a 45-mm screw
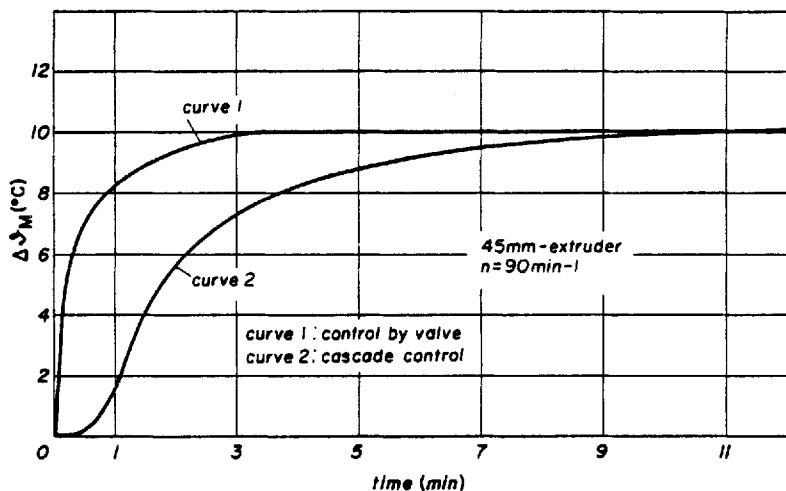diameter: Curve 1 is control by frictional energy, and Curve 2 is
cascade control.

FIG. 7. Melt temperature rise by 10°C with a 45-mm extruder.

Figure 8 shows the corresponding results of the analogue com-
puter model, where Curve 3 is control only by the last heating zone
without the wall temperature as a subsidiary controlled variable.

With the 45-mm screw diameter extruder the valve was adjusted
hydraulically. For this purpose only an integral controller was at
hand. Therefore the results are not as good as the ones obtained
by the analogue computer model with a proportional plus integral
controller. Furthermore the differences between the time behavior
of the heating energy and the frictional energy grow with extruder
size.

In both cases the deviation control by frictional energy was
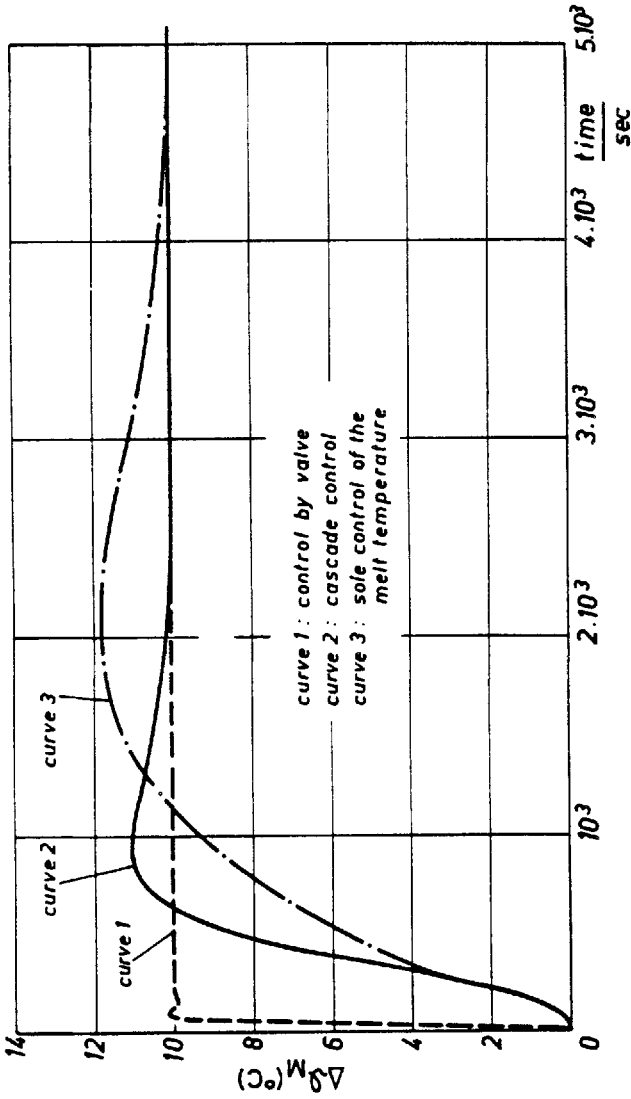more rapid than the one by cascade control. Especially for larger

FIG. 8. Melt temperature rise by 10°C with an analogue computer model of an 80-mm extruder (n = 34 rpm).

alterations of the operating point and for the start-up of larger
extruders the new stable situation can be reached sooner by the
control by frictional energy than by the cascade control. Opposed
to this advantage are some disadvantages:

1) The instrumental effort is higher than for the cascade control.
2) The output rate of the extruder must be independent of the
back pressure (e.g., according to Refs. 1 and 2) or an additional
output control must be provided.
3) Characteristic values for the extrudate quality (mixing effec-
tiveness, etc.) can be influenced more easily than by heating control.

A combination of the cascade control and of control by frictional
energy, which is an attempt to join the advantages of both systems,
was tested with the analogue computer. The frictional energy con-
troller was designed in such a way that it performs a correction
only in the first moment of a control action. Afterward its influence
is reduced proportionally as the effect of the cascade control sets in.
This system produces control actions as effective as the control
exclusively by frictional energy. The setting of the valve, however,
is altered only temporarily. However, in this case an output rate
independent from back pressure is also necessary if temporary
output variations are to be avoided.

SUMMARY

Three systems for the control of the melt temperature at the
entrance of the extrusion die were tested with an analogue com-
puter and with three different size extruders. The cascade control
and the control by means of an adjustable valve produced satis-
factory results. The action of the latter is faster, but it is more
expensive and has problems in respect to the process. At present,
efforts are being made toward the control of the viscosity rather
than the melt temperature. The viscosity will be measured by an
ultrasonic sensor [13]. Furthermore, we are engaged in shortening
the times for the start-up of extrusion machinery.

ACKNOWLEDGMENT

SYMBOLS

n	screw speed
N	heating power
R_F	master controller
R_{Hi}	slave controller of the i-th zone
t	time
T_{UM}	time characteristic of the extruder
T_{NRF}	integral action time
T_{VRF}	derivative action time
V_{RF}	gain amplification

control parameters of the master controller

$\Delta\theta$	temperature difference, temperature variation
θ_i	temperature of the i-th heating zone
θ_j	temperature of the last heating zone (at the screw tip)
θ_M	melt temperature in front of the screw tip
θ_{Si}, θ_{SM}	set values of the temperatures θ_i and θ_M, respectively

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