Predictive-Adaptive Temperature Control of Molten Glass

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***Abstract* - The temperature of molten glass is critical for the production of glass containers on automated molding machines. The temperature of the glass determines the quantity of glass in the gob which is placed in the mold and thus affects the quality of the finished container. There are frequent temperature fluctuations in the glass as it exits the main furnace and three PID-controlled heat/cool sections are required to stabilize the temperature before the gobs are cut for the molds. The long response time of these loops, combined with production rate changes and the physical changes in the glass as a function of temperature, make Proportional-Integral-Derivative control difficult. This paper discusses the application of a new predictive-adaptive controller for the control of glass temperature. The new controller was able to reduce temperature settling times following set point or production rate changes from 4 to 6 hours to between 2 to 3 hours. This control improvement resulted in a significant reduction in rejected containers as well as less maintenance and controller re-tuning.**

I. Introduction

The production of glass containers presents many control and instrumentation problems. Precise control of the molten glass temperature is particularly difficult due to the changes in the physical properties of the glass as a function of temperature. Typically, the glass temperature must be measured and controlled within 1 to 2°C out of a range of 1,100 to 1,300°C in order to produce acceptable containers in the molding machine.

The molten glass is produced in a large gas fired furnace from silica sand, soda ash, limestone, and other additives. The furnace uses a combination of surface fired gas heating and immersed electrode electric heating to melt the raw materials. Due to the poor thermal conductivity of the glass, the furnace operates in an alternating gas fired-heat recuperation cycle to reduce fuel costs. This cycling introduces variations in the temperature of the glass as it exits the furnace and prevents the system from reaching a natural steady state.

The molten glass is discharged from the furnace into a distributor where it flows into four separate forehearths. Each forehearth has three sections where the glass temperature is measured and controlled. The section closest to the furnace is called the Rear Section, followed by the Front Section, then the Conditioning Section. The rear section and front section are combined heat/cool zones incorporating natural gas port valves and cooling wind butterfly valves operating inversely to bring the glass to the desired temperature. The last section is the conditioning zone, which is approximately half the length of the two preceding sections and is equipped as a heating zone only (no provision for cooling). The main function of these three zones is to provide a controlled, homogeneous cooling of the glass from the 1,500°C of the main tank (furnace) to the production temperature of 1,100 to 1,170°C. The glass pours out of an orifice in the Conditioning Section and is sheared into discrete gobs. The gobs are guided through the air as they drop by a series of automated chutes for delivery into the forming machine. A simplified diagram of the furnace and forehearths is shown in Fig. 1.

The viscosity of the glass is very sensitive to temperature. If the temperature changes, the amount of glass that pours through the gob cutter will change, affecting the resulting weight of the glass container. Container weight is critical for proper molding in the forming machine. Correct container weight is essential to obtain the desired container volume and appearance; thus it is a primary quality parameter for the finished container.

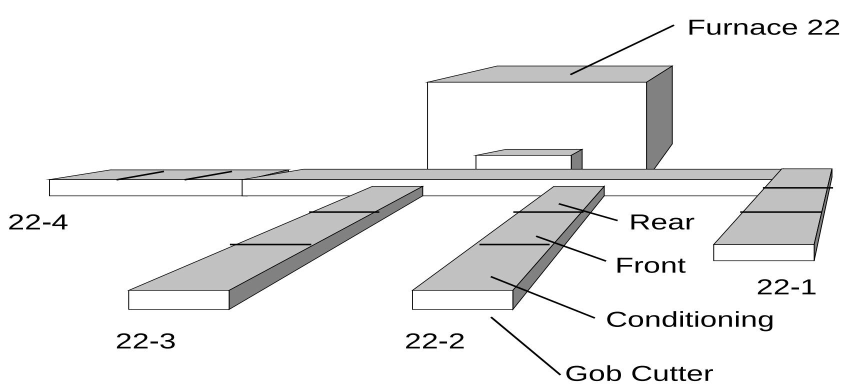

Fig. 1. Simplified Diagram of Furnace and Forehearths.

II. Existing Temperature Control System

The existing control system used programmable Proportional-Integral-Derivative (PID) controllers that were panel-mounted on the factory floor. A PID controller was used to control the glass temperature in each section of the forehearth. The controllers were also connected to a graphical operator interface via a proprietary network for data acquisition and trending.

Control of the molten glass temperature is a difficult problem due to:

- The response time of the temperature control loop is quite long (between 20 to 40 minutes);
- The combined heating/cooling control actuators are nonlinear;
- Production rate changes effect the gain and lag time for the temperature control loop;
- Thermal and mechanical properties of the glass change with temperature producing nonlinear dynamics.

Operation of the forming machine involves both changes in production rate for a given container as well as changes in the type of container to be produced (referred to as a "Job Change"). Following a production rate change or a Job Change, the glass temperature would typically take between 4 to 6 hours to settle at the set point temperature and enable the forming machine to produce the expected yield of acceptable containers (referred to as "Standard Pack"). It was not uncommon for the glass temperature to require as long as 10 hours to stabilize. In some cases, the glass temperature continued to oscillate around set point for much longer periods and would require several hours of attention by a knowledgeable instrument technician to adjust the PID controller tuning and stabilize the process. Another problem was the operators becoming impatient with the PID controllers and then switching to manual control. This action often prolonged settling time because incorrect control actions would be made by the operator.

III. Adaptive Control

A new predictive-adaptive controller was installed at the plant for control of the molten glass temperature on forehearth 22-2. This forehearth was chosen because it was the most difficult to control due to its near alignment with the furnace discharge throat. This forehearth was exposed to the largest swings in glass temperature from the furnace because the glass spends the least time in the distributor section, which is temperature controlled and tends to buffer the temperature swings from the furnace.

The adaptive controller was implemented on a Personal Computer (PC) platform and was linked to the PID controllers using a serial connection to the existing controller network. Glass temperature, set point, and the control mode were read from the PID controllers over the network. The PID controllers were configured for a "Tracking" control mode, which would allow the control actions originating from the adaptive controller to be passed on to the field actuators. This configuration provided the operators with either Manual, PID, or Adaptive Control. This allowed the operators to continue to use a familiar interface and provided some security as the existing control system was still available as a back-up to the adaptive controller. When the PID controller was switched to Adaptive Control, the PID algorithm was bypassed and the adaptive controller assumed control of the process.

The adaptive controller is unique because of the technique used to model the process. Dynamic Modeling Technology (DMT) is a new method of process transfer function modeling developed at the University of British Columbia[1]. DMT reduces the effort required to obtain accurate process models. DMT is able to automatically build a transfer function model using a series of orthonormal Laguerre functions. The Laguerre function series is defined as:

$$l_i(t) = \sqrt{2p}\,\frac{e^{pt}}{(i-1)!}\frac{d^{i-1}}{dt^{i-1}}\left[t^{i-1}e^{-2pt}\right] \quad (1)$$

where: i = 1 to N
p = Laguerre Pole
t = time

A process transfer function can be approximated by summing each function in the series where each function is multiplied by an appropriate coefficient or weighting factor:

$$g(t) = \sum_{i=0}^{i=\infty} c_i l_i(t) \quad (2)$$

where: $g(t)$ = Process transfer function
c = i^{th} Laguerre coefficient

The DMT modeling method is able to represent higher order process transfer functions and is inherently able to model process dead time. The user does not have to provide detailed knowledge of the process in order for an accurate transfer function to be obtained resulting in a great reduction in the effort required to model the process. The DMT model is used as a basis for the design of the predictive-adaptive regulatory controller.

Using DMT, the adaptive controller is able to automatically adapt to changes in gain, time constants or time delay to maintain stable control. The effects of measured process disturbances are also modeled in order to incorporate adaptive feed forward compensation into the control strategy resulting in further performance improvements. The adaptive controller uses its mathematical models of the process to forecast process response so that set point is attained as rapidly as possible with little or no overshoot. The basic algorithm steps used in the adaptive controller are shown in Fig. 2.

The adaptive controller was installed to control glass temperature in the Rear, Front, and Conditioning Sections of Forehearth 22-2. The temperature of the glass in the Rear Section was input as a feed forward for the Front Section temperature controller. The temperature of the glass in the Front Section was input as a feed forward for the Conditioning Section temperature controller. These feed forward inputs allowed the adaptive controllers to anticipate the control adjustments required to keep the glass temperatures at set point as the glass temperature in the preceding sections changed.

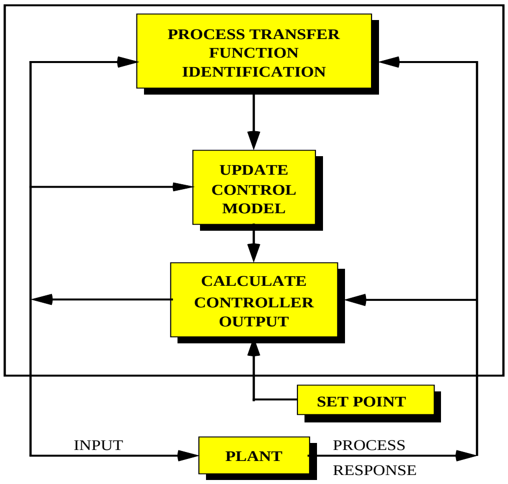

Fig. 2. Basic Steps in the DMT Based Adaptive Controller.

IV. Control Performance Comparison

Control performance was evaluated based on the time required for the glass temperature to stabilize following a production rate change (referred to as a "Pull" change) which typically involves a change in the temperature set point. The ability of the adaptive controller to recover following a momentary gas shutoff was also compared to the existing PID controller's performance. The resulting effect of the glass temperature control performance on the yield of acceptable containers (pack) was then compared.

A plot of the Rear, Front, and Conditioning Section temperatures following a pull change with the existing PID controllers is shown in Fig. 3 (this data was reproduced in essence from a paper strip chart recorder). The highest temperature is at the Rear Section and the lowest temperature is at the Conditioning Section. The temperatures had not settled at set point after more than 5 hours following the pull change.

Fig. 4 shows the performance of the adaptive controller following a similar pull change that also involved a temperature set point change. The temperature stabilized in less than 3 hours, which represents about a 50% improvement in temperature settling time compared to the PID control system.

Operating experience has shown that it is not unusual for the PID controllers to take up to 6 hours or more to stabilize temperatures following a pull change. In some cases, the PID controllers would fail to stabilize the temperatures and the controllers would have to be placed in manual mode until they could be re-tuned by a knowledgeable instrument technician. During this period, the temperature control of the glass would be poor and the yield of acceptable containers would be reduced. By comparison, the adaptive controllers have often been able to stabilize glass temperatures in less than 2 hours and have not required adjustment to maintain their performance.

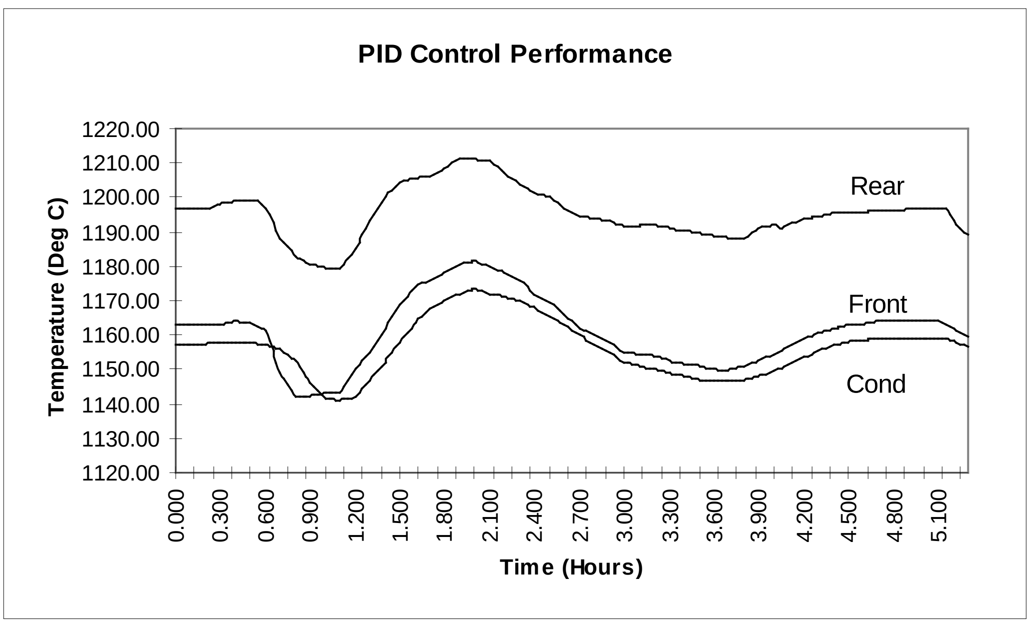

Fig. 3. PID Control Performance on a Pull Change.

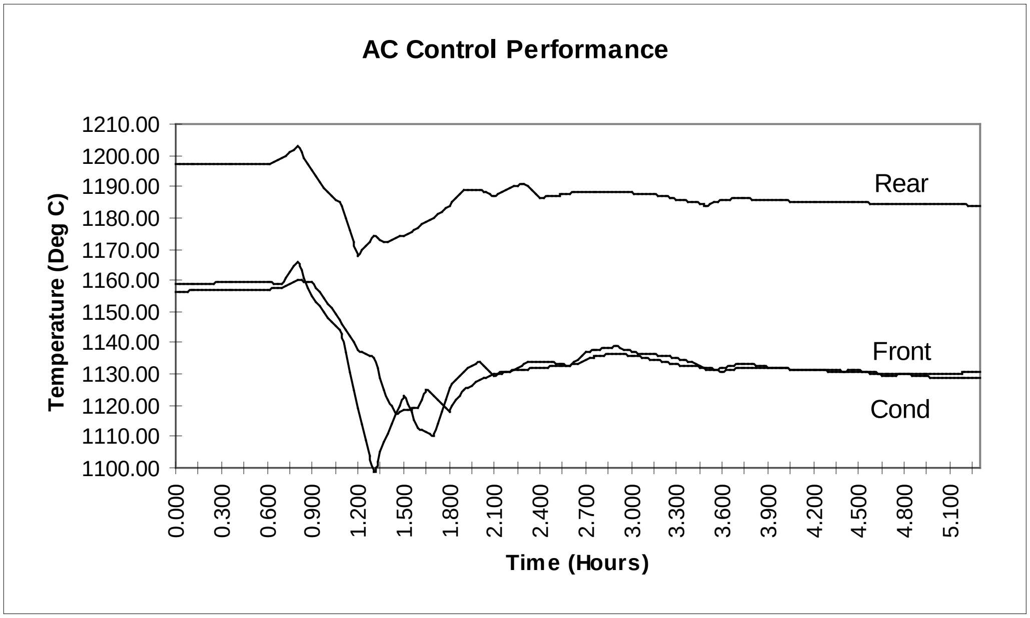

Fig. 4. Adaptive Control (AC) Performance on a Pull Change.

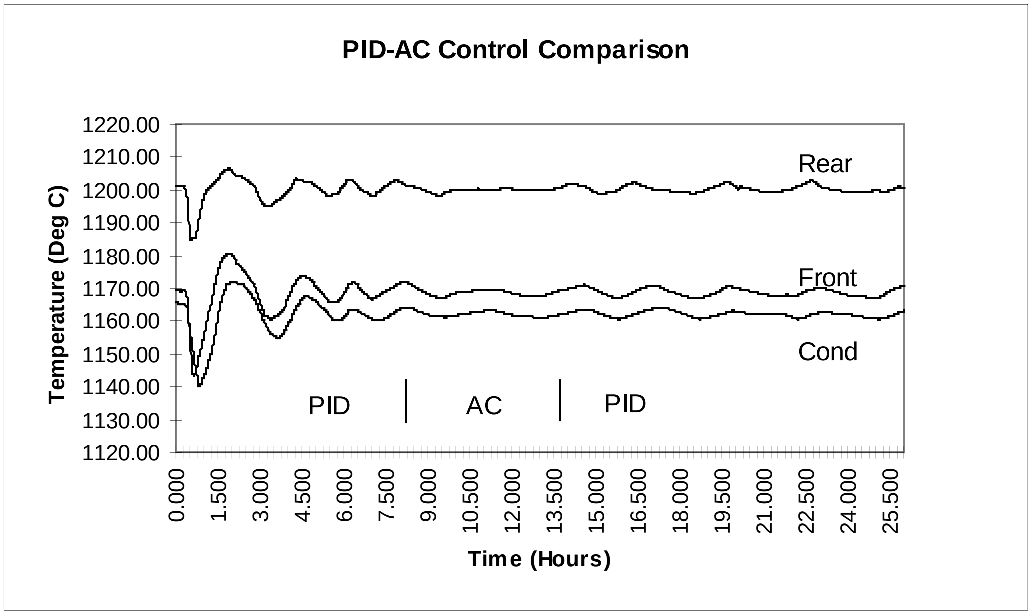

Fig. 5. PID/Adaptive Controller (AC) Comparison.

Fig. 5 shows an example of a pull change where the PID controllers were continuing to cycle for more than 8 hours after the pull change until the adaptive controller was enabled and was able to stabilize the temperature. Later, the PID controller is re-enabled at 13 hours and the temperature again begins to cycle for more than 12 hours resulting in a lower yield of acceptable containers. Note that in this case the PID controllers would probably have to be re-tuned in order to be able to stabilize the temperatures.

Forehearth 22-2 has about 20 job changes per month. The improved control with the adaptive controller saves approximately 43 hours/month or 533 hours/year of lost production due to the glass temperature not being stabilized at set point. This is about 6% of the annual production of forehearth 22-2.

Occasionally, the gas supply to the forehearth is briefly interrupted causing a disturbance to the glass temperature controllers. The PID controllers were observed to require about 1.5

hours to stabilize and the adaptive controllers required slightly less than 1 hour to stabilize glass temperature.

The ultimate control performance comparison between the existing PID controllers and the adaptive controllers is their effect on the production of acceptable glass containers. Over the last 2 years of operating experience, the plant has observed an improvement in the pack 27% of standard pack for the most common containers produced on forehearth 22-2. This represents a profit increase of $533,820 per year with a resulting return on investment of less than 20 weeks. Occasionally, some specialty containers are produced which require more precise temperature control and as a result are particularly difficult to manufacture. The pack for these containers has been observed to increase by as much as 40 % with the adaptive controllers. The control comparison results are summarized in Table I.

V. Conclusions

Control of molten glass temperature is a difficult problem due to the long response times, non-linear characteristics of the combined heat/cool actuators, changes in the physical properties of glass as a function of temperature, and changes in production rates. The existing PID temperature controllers required frequent re-tuning to provide acceptable control of the glass temperature.

Installation of an advanced predictive-adaptive controller has demonstrated that significant performance improvements could be achieved compared to the PID based control system. The time required for the glass temperature to settle following set point changes or production rate pull changes has been typically reduced by 50% with the adaptive controller. Resultant increases in production of on-spec containers of between 27% above standard pack have been achieved during the past 2 years for common containers and production increases as high as 40% above standard pack have been observed for some specialty containers.

The unique ability of the Dynamic Modeling Technology based adaptive controller to learn the process and feed forward variable behavior automatically and continuously ensures optimum performance at all times. The problems of long development time, long setup time, repeated tuning and poor reliability associated with other advanced controllers such as Smith Predictor and other model-based controller designs are solved with this method. The adaptive controller has resulted in a significant reduction in maintenance as it does not require the frequent re-tuning necessary for the PID based control system.

The superior performance of this adaptive controller reduces process variability and enables the potential quality improvement benefits of supervisory and statistical process control systems to be realized. In addition, the cascade effects of many small improvements provided by tighter control on individual loops can improve the complete process or plant substantially. The DMT control approach is a new tool available to the process control engineer to economically implement the continuous improvement concepts advocated by Deming [2] and Juran [3] in their Total Quality philosophies.

References

[1] Zervos, C.C., and Dumont, G.A., "Deterministic adaptive control based on Laguerre series representation", Int. J. Control, Vol. 48, No. 6, pp. 2333-2359, 1988.

[2] Deming, W.E., "Out of the Crisis", M.I.T. Center for Advanced Engineering Studies, 1989.

[3] Juran, J.M., "Juran's Quality Control Handbook", McGraw-Hill, 1988.

TABLE I.
Control Performance Summary

Control Metric	**PID Control**	**Adaptive Control**	**Improvement**
Temperature Stability After Pull Change	4 to 6 hours	2 to 3 hours	50%
Temperature Stability After Gas Interruption	1.5 hours	1 hour	33%
Pack (Common Containers)	Standard	Standard + 27%	27%
Pack (Specialty Containers)	Standard	Standard + 40%	40%