65th Conference on Glass Problems
Charles H. Drummond, 111

Advanced Feeder Control Using Fast Simulation Models

Oscar Verheijen, Olaf Op den Camp and Ruud Beerkens,
TNO Glass Group, The Netherlands
Ton Backx, IPCOS Netherlands, The Netherlands
Leo Huisman, Eindhoven University of Technology, The Netherlands

Abstract

For the automatic control of glass quality in glass production, the relation between process variable and product or glass quality and process conditions/process input parameters must be known in detail. So far, detailed 3-D glass melting simulation models were used to predict the effect of process input variables, such as fuel consumption and fuel distribution, load and load distribution, and electrical boosting, on the flow pattern (residence times, short cut flows), temperature distribution and redox state of the glass in the furnace. For feeder control, the main objectives are stable temperature and temperature uniformity in the spout section of the feeder just before the glass melt is delivered to the forming process. However, computations of detailed 3-D simulation models are very time-consuming: one steady state simulation of a complete furnace including refiner(s) typically takes about a day. This time demand indicates that the currently used detailed 3-D simulation models are not suitable for rigorous (CFD) model based Model Predictive Control (MPC). To make the 3-D simulation models suitable for control purposes, simulation tools that are much faster than real time with still a high level of reliability are now developed. These fast simulation tools (GPS: Glass Process Simulators) open up a wide variety of applications of glass furnace models: process monitoring, what-if scenarios and model based predictive control (MPC) of temperatures or glass melt quality or redox/color. Now we realized time-transient simulations with GPS for feeders, which are about 10000 times as fast as real time. This paper will show the capability of an MPC that is based on fast GPS to control temperature and temperature uniformity of one of the feeders connected to an emerald-green container glass furnace.

Introduction

At the moment, most feeders or forehearths of glass-melting furnaces are controlled manually. Feeder control is usually based on manual adjusting temperature set-points in different zones of the feeder. Mostly, these zonal temperature set-points are set such that a weighted average of the temperature readings of the 9-grid thermocouple arrangement close to the spout entrance reaches the desired value and to obtain minimum differences in the 9 couple readings. By adjusting the zonal temperature set-points, the operator adapts the total amount of fuel (or more specifically the total amount of energy in case also energy is supplied by means of electrical boosting) that is being used to realize and maintain the desired glass melt temperature (uniformity) at the feeder exit. As the temperature distribution in the glass melt throughout the feeder depends on feeder pull rate and glass melt redox state, the desired glass melt temperature in the feeder strongly depends on the product type (product type weight, color, associated pull) that is produced. Therefore, during product changeover, it is the task of the operator to modify the feeder zone temperatures such that the new desired glass melt temperature is reached within the shortest period of time and stable production can be continued. In general, feeder control strategy is based on operators' experience and is often operator dependent. For reproducible feeder control, automatic control of glass melt temperatures (or any other variable that determines feeder performance) is almost indispensable and can lead to considerable energy savings.

In the recent years, process control systems have become available for automatically control of important temperatures, taking over this part of the job of an operator, who can spend his/her time now on other important tasks such as furnace maintenance. Since PID controllers are much to slow and have no predictive capability (i.e. do not give feed forward response on disturbances to keep the temperature within a limited range), model based predictive control (MPC) is being used. MPC is dedicated software running on a regular PC that computes the required control actions (to obtain desired temperatures or other process variables) and communicates these control actions to the DCS (distributed control system) of the furnace by changing the set-points of the conventional controllers that are available within the DCS. For glass furnace feeders, the models in MPC describe the temperature changes in the feeder when changes in process settings such as pull, fuel input over the zones, and/or electrical boosting are made. A reverse response model is used to determine how to adapt the individual inputs (process settings) of the feeder to ensure temperature control as close as possible to the desired levels even for changeovers (following a pre-defined temperature course). Although conventional MPC systems become more and more accepted in the glass industry, their advantages with respect to manual control is limited, as they do not change the basic control strategy of keeping, in this case, the weighted average of the temperature readings of a 9-grid thermocouple arrangement at the feeder exit within a limited range. Derivation of so-called black box models for these conventional MPC controllers requires industrial tests. By interference in the actual glass-melting tank and/or feeder, flow pattern and temperature distributions are disturbed, which sometimes offsets the process and may lead to increased project reject and expensive man-hours to re-stabilize the process. Besides this, due to the increased computational power of PC's, MPC allows for more sophisticated control in which not one single (averaged) temperature is kept stable, but a total crown profile or melter bottom temperature profile is prescribed (MIMO = multi input – multi output).

For MPC, the simulation models that are used have to be extremely fast (over 1000 times real time) compared to the real process. Conventional MPC systems for feeders therefore make use of experimentally derived models that are determined by means of step tests on the feeder in which the inputs (i.e. fuel distribution, boosting, and load) are changed stepwise. The responses of the feeder (readings from e.g. thermocouples) are measured and correlated to the changes in input.

Herewith, models are derived that directly couple the (expected) response of the feeder to changes in process settings. Usually, the stepwise changes in process settings are chosen very small, as to prevent any disturbance of the feeder. Consequently, the linear models that are determined in this way have a limited area of application. Actually, the model can only be used when process settings do not deviate much from the settings at which the model is determined (the working envelope of the model). When this model is used in a situation outside its working envelope, the controller performance will decrease. In that case, the controller will either determine control actions that are less accurate and slow down compensation of a deviation between the controlled value and its set-point or it might even lead to contra-productive control actions or oscillation which leads to severe system instability. MPC controllers should be designed in such a way that system instability does not occur under any circumstances.

To overcome the limited working envelope of conventional MPC controllers, the use of detailed 3-dimensional computational fluid dynamics (CFD) models (white or rigorous models) is required. About 20 years after the introduction of detailed modeling of flows and temperatures in glass melting furnaces, simulation tools are now used for process design and optimization on a day-to-day basis in several sectors of the glass industry (special glass, glass fibers, TV glass, float glass, container glass)[1]. First of all, simulations are used to obtain a basic understanding of the interaction between the different processes that simultaneously take place in a glass-melting furnace. To determine the impact of changes in design or changes in process settings on the process (or more specifically on the expected glass melt quality), the simulation tools determine indicators to judge the performance of a furnace with respect to melting, fining, refining, and homogenization. Currently, most furnaces are only (re-) designed after evaluation of the expected furnace performance by means of simulation studies. More and more, simulation studies are used to determine possible solution strategies in case of sudden furnace upsets. In principle, CFD models have no limitations with respect to process settings. Therefore, these models are able to cope with the prediction of the dynamic behavior of a glass-melting furnace and feeder over a large working area (large variations in pull rate, color-changes caused by wide changes in glass melt redox state). Such a wide working range and off-line development of the control models makes these CFD models attractive for predictive control purposes in glass melting processes. However, computations of detailed 3-D simulation models are very time-consuming: one steady state simulation of a complete furnace including refiner(s) typically takes about a day, which indicates that the currently used detailed 3-D simulation models are not suitable for MPC. This was one of the reasons to develop simulation tools that are much faster with a high level of reliability. These fast simulation tools (GPS: Glass Process Simulators) open up a wide variety of applications of glass furnace models.

In the framework of a Dutch EET-project, TNO Glass Group and IPCOS in cooperation with the Eindhoven University of Technology have developed a method to set-up fast Glass Process Simulators and based on these simulators, MPC-controllers that enable control for a very large working envelope. In a first step, a fast process simulator (GPS) is derived from a validated 3-D detailed CFD model for the process of consideration (glass feeder or furnace). The resulting GPS is applied to an emerald green container glass furnace of REXAM in Dongen, The Netherlands ([2]: here GPS is used to monitor on-line all relevant process variables and to predict future process performance when changing input parameters). In a second step, an MPC controller was built on the basis of GPS and successfully applied to one of the three feeders of the above-mentioned furnace [3]. The feeder was selected because of the large job changes that are regularly applied to it.

MPC Control Based Upon Detailed CFD Models

The following approach to derive fast simulation models for MPC control was proposed and put into practice to set-up an MPC controller for an industrial feeder. The objective of the controller is to stabilize the temperature of the glass melt that is delivered to the forming machines in order to improve the so-called workability of the glass and to enable a controlled forming processes and optimum glass distribution in the mould. The workability of glass, or the ease with which the glass can be used for forming the final product, depends largely on the viscosity and therefore on the temperature and temperature distribution of the glass melt.

A new approach to set-up control models:

- The approach starts with setting up a separate GPS based on a detailed CFD model for the feeder under consideration. This GPS is of course thoroughly evaluated and validated, as the performance of the controller will depend largely on the quality of the original model.
- Subsequently, dynamic tests are performed upon the GPS model instead of applying step changes on the real feeder. The simulation tests couple the modeled response of temperatures and flows in the feeder to modeled changes in the input. A special mathematical technique, Proper Orthogonal Decomposition (POD see [4, 5, 7, 6]) of temperature field predictions, is applied to further increase the speed of the modeling tasks and consequently the currently applied reduced models are very fast. This approach has two major advantages. Firstly, the tests do not need to be performed on the real feeder, preventing disturbance of the production process. Secondly, the results of these tests become easily available within a short period of time as GPS is very fast compared to the original CFD-simulations and less tests are needed to identify the response of temperatures and flows in the feeder to changes in the input compared to the conventional approach.
- A method has been developed to derive a kind of reverse response model to determine control input parameters enabling the achievement of constant temperatures and set points at the exit of the feeder even for the case of disturbances in the melt entering the feeder or disturbances in the feeder itself.

The resulting control model, that is derived from these tests using GPS, can be used for a large set of working points (e.g. a large range of loads) instead of for one single working point, as the response of the feeder to large variations in disturbances and process settings is determined. Consequently, the control model does not have to be rebuilt when a different working point for the feeder/furnace is selected due to e.g. the production of a different product (as long as the type of glass does not change). It is a fast way of setting up a complete and accurate control model without any risk for production. However, the reduced model is only applicable for one type of glass. Special mathematical techniques [5, 6, 7] are currently in development to enable model-based control for even larger operating windows and for controlling glass color changes.

The resulting control scheme for the industrial glass melt feeder is shown in figure 1. The temperatures in the feeder are controlled via the set-points of three PID controllers that adjust the fuel supply to the three heating zones in the feeder. These PID set-points are set by of the results of the MPC, which reads the values of the 9-grid thermocouple at the feeder exit and predicts the values of the input parameters to keep these thermocouple readings within a certain narrow range or to follow a pre-defined temperature course: based on the fast reduced model, describing the dynamic behavior of the feeder, the MPC determines the optimal values of the PID set-points such that the desired temperature (uniformity) at the feeder exit is attained. Next to the control objectives (desired temperature and temperature uniformity at the feeder exit), also several constraints are imposed to the MPC: the glass melt temperatures in the feeder may not exceed and drop below certain values; also the rate of fuel adaptation is constraint to avoid instabilities in the feeder. These constraints limit the flexibility of the feeder operation. Using the reverse response model, the optimal feeder settings (optimal PID set-points to ensure stable production at the desired glass melt temperature (uniformity)) can be determined easily.

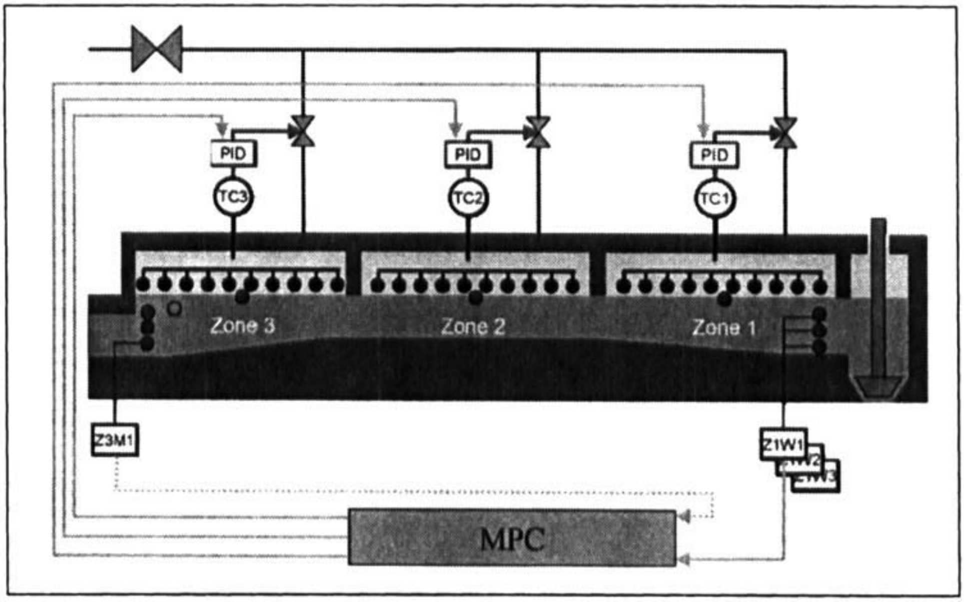

Figure 1. Control scheme for the industrial feeder. Blue arrows to PID controllers are the controlled settings of the PID controllers.

Although the feeder entrance temperature (uniformity) is measured continuously, in the here presented feeder control field test, this information has not been taken into account so far. Incorporation of the entrance temperatures in the MPC (indicated by the dotted line in figure 1) would allow the MPC to anticipate in the feeder (by adjusting the PID set-points) on temperature disturbances from the refiner. In the current feeder layout, an inline glass melt redox state sensor is positioned at the entrance of the feeder, acting as an early warning signal for redox disturbances in the glass-melting furnace (see figure 2). In the furnace to which the MPC controlled feeder is connected, up to 92 % foreign mixed recycling cullet is used acting as a source for redox variations. These redox disturbances may affect the temperatures in the feeder of the glass-melting furnace by changing radiation properties of the glass melt. Taking the signal of this redox signal into account in the MPC allows the feeder controller to compensate for the effect of redox changes on feeder temperatures.

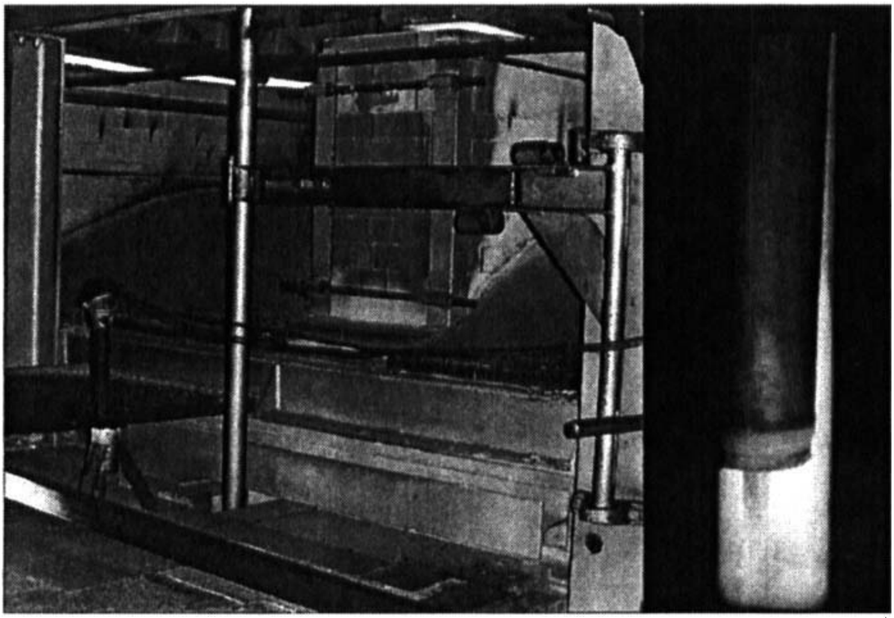

Figure 2. Inline feeder redox sensor positioned at the entrance of an emerald-green container glass producing glass furnace.

Preliminary Field Test of MPC Feeder Control

The application of the described MPC feeder control has been extensively tested (without redox state information and temperatures (uniformity) at the entrance of the feeder) on various production campaigns during the past months for a production feeder in emerald green container glass manufacturing. Figure 3 shows the impact of the controller on the average 9-point grid temperature, which is the main objective for the controller. In manual control mode, deviations in temperature in the 9-grid exceed +/– 2.5 degrees C, in some instances even more. It is clearly seen that the feeder temperatures become very stable (+/– 0.5 degrees C) once the controller is switched on. It should be noted, that the smallest change in temperature that is detected by the thermocouples is 0.2 degrees C, which makes the capabilities of the controller even clearer. This gives energy savings as well. Besides the increased stability, changes in set points are realized within a short period of time. Even automated transitions between largely different operating points (95 ton/day – 135 ton/day; different glass gob temperatures) have been performed successfully.

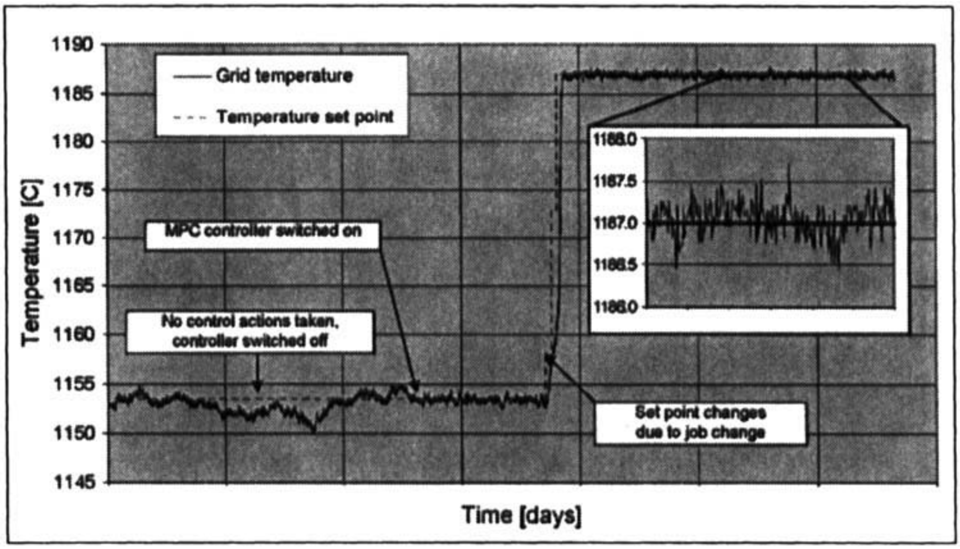

Figure 3. Result of controlling the average grid temperature in the feeder by making use of MPC control according to the approach as described in this paper.

Concluding Remarks

For an industrial emerald green container glass furnace, the application of MPC for temperature control in one of the feeders has been discussed. In this project MPC was based on a rigorous CFD model that provides detailed 3D information of the temperature distribution throughout the whole feeder. The POD based model reduction approach to speed up the calculation time of rigorous CFD models enables accurate model based control of critical process operating conditions without the need for expensive process testing and without any risk for production. Reduced model provides the same 3-D temperature profile information as the original CFD model within 0.2 oC. Simulation speed of the approximate model is at least 10.000 times faster than the CFD based simulations. Basis of MPC is the POD model reduction method. The POD model is derived from validated CFD models. MPC with POD reduced models has proven to be a solid track for model predictive control system designs for processes like glass furnaces or feeders.

The model predictive control system derived from detailed 3-D CFD models covers a large process area (set of possible furnace/feeder settings) instead of one working point. The paper showed that the MPC was very capable of controlling even large transitions or job changes with one model. For the feeder, an increase in temperature stability was shown, going from typical temperature variations of +/- 2.5 degrees C in manual control mode to +/- 0.5 degrees C during MPC. Even more stable production could be achieved taken in the MPC into account also information from:

- The glass melt temperatures at the feeder entrance,
- The redox state (variations) at the feeder entrance measured by an inline redox sensor, and
- Electrical boosting as additional manipulative value to compensate for differences between left and right of the feeder.

ACKNOWLEDGEMENT

The development of the approach that is described in this paper has been supported by EET (Economy, Ecology and Technology), a program of the Dutch government. The authors would also like to thank Sven-Roger Kahl, the manager furnaces of REXAM in Dongen, for his contributions to the project.

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