# IDENTIFICATION AND ADAPTIVE CONTROL OF A GLASS FURNACE

By

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## Introduction

The Research Group for Automation of the Central Research and Design Institute for Silicate Industry (CRDISI) has been working for some years on the automation of technological processes in the silicate industry, in co-operation with the Department of Automation of the Technical University of Budapest (DATU). CRDISI yields the technological background, provides for the hardware tools and the basic software to the common work. The implementation of up-to-date process control algorithms, the design and execution of control experiments are incumbent on the DATU. In 1974 the Institute for Silicate Industry set up a so-called Portable Process Computer Laboratory (PPCL) to solve control problems arising in the cement, ceramic and glass factories in Hungary. Data logging, monitoring and control programs were developed for several problems [1, 2].

Our first problem was to model the second furnace of the Bellied Glass Factory in Orosháza (Hungary) and the control of the level of the melted glass in the furnace.

## The glass furnace

The plant is a continuously operating tank furnace (Fig. 1). Feeding in the raw material is done by two feeders with pusher-type shovels. Rate of feeding depends on the stroke length of the shovels determined by the position of an excenter.

The melted glass arrives due to it's natural stream to the working end. The feeders are connected to the working tank. At the feeder ends there are gob-feeders operating on gravimetric principle. The feeder is batching the glass in form of gobs to the blow machine at a predetermined rate.

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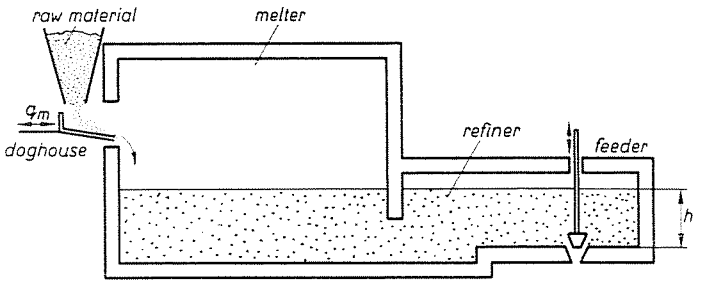


*Fig. 1.* Glass furnace

The heat needed for operation is provided by the burners built into the side of the furnace. The caloric value of the gas required for burning is achieved by mixing two kinds of gases having different caloric values. The natural gas with a low caloric value is mixed with a natural gas of high calorific power. The quantity and proportion of the poor and rich gas and the combustion air may be controlled by means of a valve. Direction of firing changes in every 20 minutes. Heat is recovered from the flue gas leaving the furnace by regeneration. The flue gas leaving the furnace is led through one of the recuperator chambers. The flue gas heats the lattice and enters cold the chimney. The cold air is warmed up in the other recuperator chamber to enter the furnace. The two chambers change roles at the change of the firing direction.

From the point of view of technology it is of importance to observe the temperature, the pressure and the glass level.

The most important requirement to be met in respect of feeding is to keep the glass level on a constant value. If the furnace pressure is higher or lower than the atmospheric pressure, flames may shoot out from the opening or cold air may stream into the furnace. The pressure inside the furnace is to be kept constant, somewhat above the atmospheric pressure. Temperature of the melted glass affects the chemical reactions taking place in the glass. The lower limit of temperature is determined by the purification of the glass at slowing glass flow. Due to the gas precipitation the upper limit of the temperature is determined by the foaming power, which spoils the thermal efficiency of the furnace. For the automatic control the following control loops have been developed:

— control of the glass level;
— temperature control;
— control of the furnace pressure;
— control of the proportion of poor and rich gas;
— control of the proportion of the poor gas to the combustion air.

All the controllers are of the *PI* type, except the level control, which is a three-position controller.

## Theoretical modelling

The connection between the characteristic quantities of the melting process can also be determined on the basis of physical considerations. The plant has three output signals:

— glass level ($h$)
— temperature ($T$) and
— furnace pressure ($p$),

and it has three input signals:

— batching ($q_m$),
— quantity of the poor gas ($q$),
— quantity of the flue gas ($q_f$).

The quantities of the rich gas and air, respectively, are not included in the input signals, since these are set by means of proportion controllers. Due to the asymmetry the furnace is behaving in a different manner at left- and right- side firing.

Thus it seems to be expedient to consider

— the quantity of the poor gas on the left side ($q_l$) and
— the quantity of the poor gas on the right side ($q_r$) as independent input signals (Fig. 2). Let us consider the most essential connections between the single characteristics [3].

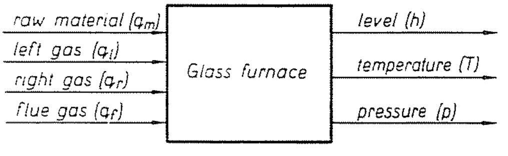


*Fig. 2.* Model of the glass furnace

The glass level fundamentally depends on the quantity of the fed mixture and on the quantity of the melt discharged. The influence of the quantity of the material fed in can be observed only after a time delay $\tau$. The stream between the two spaces of the tank can be characterized by the time constant $T_1$. Thus

$$\frac{H(s)}{Q_m(s)} = \frac{A_1 e^{-s\tau}}{s(1+T_1 s)}.$$

When the direction of firing is changing, the furnace first gets cooler, then warmer. This process can be described by summing up two exponential curves with different signs:

$$\frac{T(s)}{Q(s)} = A_2 \frac{1-T_4 s}{(1+T_2 s)(1+T_3 s)}.$$

The furnace pressure is determined by the temperature and quantity of the gas leaving the furnace:

$$\frac{P(s)}{Q_f(s)} = \frac{A_3}{1+T_5 s}.$$

## Design of experiments and quantitative evaluation of records

Long-continued consultations with the technological experts and observations during normal operation have preceeded the design of experiments. The plan was made to excite the process in different working points so that the interventions are independent of each other. The 20 min. period in the change of firing and the allowed maximum fluctuation in the level were the limitations from the process side. During the investigations the production should not be interrupted.

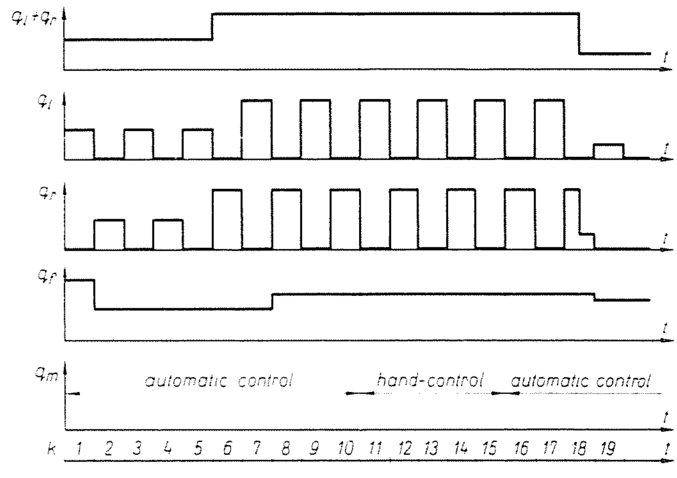


*Fig. 3.* Plan of the experiments

The plan of the experiment is seen in Fig. 3. At the beginning of the experiment the control loops of the temperature and the pressure were opened. The set point was changed partly at the change of firing and partly in the middle of the cycle of firing.

Taking the intended modelling of the firing into considerations a sampling time of $T_0=5$ sec. has been chosen.

Our final aim was to design a controller, thus a shorter part of measured records was selected for further investigations. This registrate, incorporating a complete heating cycle (left and right), as well as the manual modification of bathing within a certain section, are seen at the description of the identification.

## Identification

The model types can be determined by the empirical analysis of the time curves, the structure analysis to investigate the dead time and the order, while the proper parameters have to be determined by parameter estimation.

From the known processes serving for estimating the parameters, the second extended matrix-method has been considered as the most efficient one and applied in the course of examinations [4]. The widely spread method of structure estimation is based on the repeated estimation of the parameters for different structures. Different indices are possible to characterize the goodness of identification. Plotted as a function of dead time and order they designate the best structure [5].

### Vault temperature

The temperature will be determined by quantity of the poor gas. Considering the asymmetry of bilateral firing and/or of measuring, input signals of the model are the poor gas streams on the left and the right side. The fluctuation of the noise each minute influenced more the dynamical behaviour of the model with a time constant of minute order than the periodical gas changes every 20 minutes. As a consequence, out of two input signals of process and noise, the latter one is dominant.

To improve the signal/noise ratio the very noisy registratum of temperature has been filtered. The filtering equation was as follows:

$$x^F(k) = \frac{1}{n_1+n_2+1}\left[\sum_{i=1}^{n_1} x(k-i) + x(k) + \sum_{i=1}^{n_2} x(k+i)\right]$$

and only every second sample was taken into consideration, i.e.

$$N = 225; \qquad T_0 = 10 \text{ sec.}$$

The input signals of the model — the measured (smoothed) and the calculated temperature profile — are seen in Fig. 4.

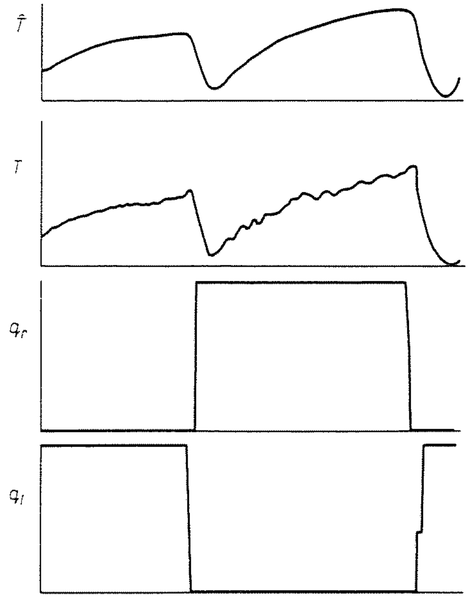


*Fig. 4.* Identification of the temperature

The equation of the model was the following:

$$\hat{T}(k) = 1424.40 + \frac{0.036z^{-1} + 0.155z^{-2}}{1 - 1.748z^{-1} + 0.755z^{-2}} q_l(k) +$$

$$+ \frac{-0.027z^{-1} + 0.229z^{-2}}{1 - 1.748z^{-1} + 0.755z^{-2}} q_r(k);$$

and in the complex frequency domain:

$$\hat{T}(s) = \frac{1424.40}{s} + \frac{0.03\,(1 - 3.34s)}{(1 + 39.57s)\,(1 + 346.1s)} Q_l(s) +$$

$$+ \frac{0.0318\,(1 - 6.57s)}{(1 + 39.57s)\,(1 + 346.1s)} Q_r(s).$$

From modelling the temperature the following conclusions can be drawn:

— The poor gas–temperature model is aperiodical and it is of second order without dead time.

— The time constants are $T_1 = 40$ sec and $T_2 = 5$ min.

## Glass level

The glass level is described by a model integrating on physical considerations. Let us ignore first the level lowering due to changed firing and consider the batch level model alone.

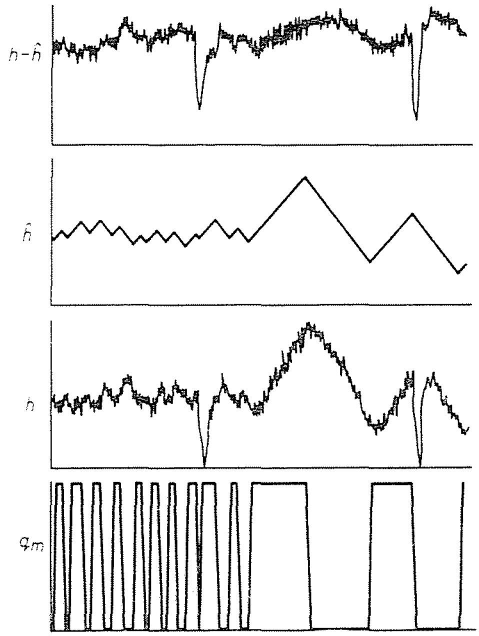


*Fig. 5.* Identification of the glass level

In Fig. 5 the input signal and the measured and estimated outputs for a model of $d=0$, i.e. for a static model having a dead time of unity are seen. The equation of the model is

$$\Delta h(k) = -0.207 + 0.003 q_m(k-1).$$

Considering also the furnace pressure as an input signal, the reduction in level could be described at the change of firing.

From the model of the glass level the following conlusions can be drawn:

— it is fundamentally dependent on the batch;

— it is of integrating character;

— it has practically no dead time;

— it is mathematically described by a third-degree difference equation but physically it is described by a static (integrating) model.

## Furnace pressure

The furnace pressure can be adjusted by the flue gas snap. Because of the breakdown of this snap during the experiments, only a qualitative model could be established.

## The control experiment

Based on the identification experiments a numerical model of the furnace could be set up. The identification experiments showed the possibility of independent regulation of the level, the temperature, etc. in the multivariable model of the furnace dominated by the main effects.

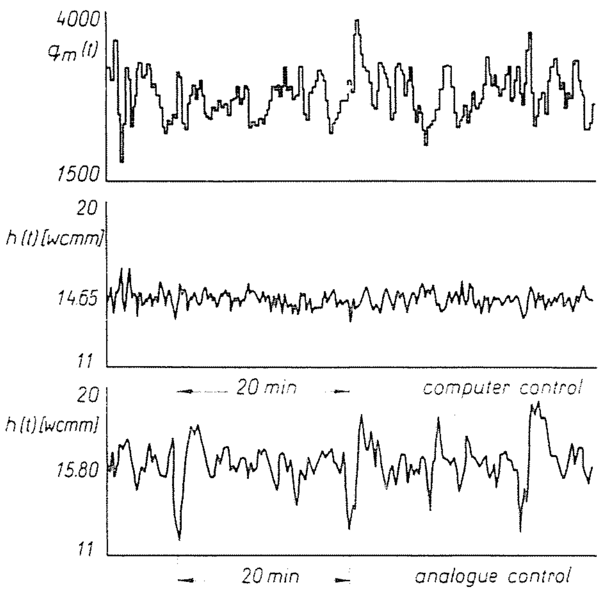


*Fig. 6.* Level control

The quality of the final product first of all depends on the constant level of the melted glass controlling the drop size out of the gravimetric feeders. Therefore a minimum-variance self-adjusting level control was designed operating in DDC. The starting structure of the algorithm was given by preliminary identification, e.g. an algorithm elaborated for integrating type processes could be applied [6, 7]. The traditional and the adaptive controls are compared in Fig. 6.

## Conclusions

The presented study was useful from several aspects. It was one of the first industrial process control experiments in Hungary. Both the hardware — the Portable Process Computer Laboratory — and the software — an adaptive control algorithm — were new in an industrial environment. Even the evaluation of the data logging led to technological relations which could not be read off instrument boards. The traditional control was exchanged for the new, adaptive one without interrupting the permanent production. During the self-tuning control the operation of the furnace became more uniform, a fact confirmed by the local operators, as well.

## Summary

The paper presents the modelling and the control of the second furnace of the Bellied Glass Factory in Orosháza.

Each step of the identification is presented in details: the theoretical modelling of the furnace, the evaluation of the normal measurement records, the planning of experiments, the determination of the structure and the model parameters and the verification of the results. A model of three inputs (batching, fuel gas, flue gas) and of three outputs (level, temperature, pressure) was elaborated. The glass level — which influences the production to the highest degree — was controlled by an adaptive self-tuning minimum variance regulator. In the paper the DDC experimentes are presented, as well.

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d) Replacing in Eq. (20) the small time constant by dead time $T$:

$$w_x(s) = \frac{0.1e^{-s}}{s} \tag{34}$$

$$w^*(z) = \frac{0.1z^{-1}}{z-1} = \frac{0.1}{z(z-1)} \tag{35}$$

$$y_{s4}^*(z) = \frac{1.145z}{z-0.8872} - \frac{0.145}{z-0.1127} \tag{36}$$

$$y_{s4}(t) = 1.145e^{-0.12t} - 0.145e^{-2.183t} \tag{37}$$

In this case the approximation c) is the more advantageous. d) would suit better for a neglected time constant nearer to $T$.

## Summary

The problem of the convergence of digital modelling of control systems is dealt with. The cases where the one-step algorithms of constant interval lead to satisfactory solution are determined in a simple and clear way, based on the linear control circuits of constant parameters.

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