Regenerative Cycle Optimisation via Physically-Based Dynamic Modelling

by M G Carvalho, M Nogueira and P Silva*

Glass furnace efficiency and operational flexibility is often limited by the difficulties that can arise in handling the transient characteristics of the system. Knowledge of the dynamic heat and mass transfer process in such industrial equipment is required for improvement of furnace design and operation which, mainly, is still based on heuristic assumptions [1].

In this paper a model incorporating the unstable heat and mass balance equations for each component of the furnace is presented. One-dimensional unsteady transport equations are solved for the energy and mixture fraction along the direction of the flow inside the regenerator. The model has been applied to a medium-size regenerative glass melting furnace. Comparisons between modelling results and measurements in a furnace under regular operating conditions show a good agreement between predicted and measured values. Tests for the furnace dynamic response were carried out. A study of the parameters influencing the switching time in relation to regenerator efficiency also is presented and optimal period for the regenerative cycle is proposed.

In high temperature furnaces combustion air preheating is a primary option in order to save energy and reduce the formation of CO_2 and SO_2. In a regenerative furnace the optimisation of the design of the regenerative device and its operation is therefore a priority.

High computational power requirements limit the application of full three-dimensional modelling for dynamic predictions of complex systems such as furnaces or boilers and their associated equipment. As an alternative, an unsteady zero one-dimensional dedicated modelling procedure is proposed.

Physically-based dynamic modelling

Due to the interaction between the dynamic behaviour of the components, a time-dependent calculation of the heat and mass transfer of the whole of the furnace system can only be achieved by considering the interactions between all subsystems. The present simulator assumed the division of the furnace into the regions shown in *fig 1*. They are: Regenerative chamber A; regenerative chamber B (gas flow and checker work plus volume of walls); combustion chamber internal volume; furnace superstructure (crown plus walls of the combustion chamber); glass melt volume; batch melting stage; and batch heating stage.

The regenerative chambers were simulated as a one-dimensional, vertical equivalent system. Energy and mixture fraction convective/diffusive transport equations were solved. The heat transfer rate between the gas flow and brick volume, the significant parameter in the energy storage process, depends on the surface temperature of the brickwork which is taken from temperature profile calculations. The corresponding heat transfer rate was accounted for in the energy transport equations through a source/sink term considering the radiative and convective heat transfer modes. The gas emissivity was calculated through the grey gases mixture procedure of Truelove [2]. The convective heat transfer coefficient was calculated using a standard correlation (Bejan [3]). Heat losses through the regenerator walls were also accounted for.

In the combustion chamber, the main heat transfer process is radiation between the hot gases and the surfaces that are involved. These surfaces are the walls and crown, glass melt free surface, batch top surface and inlet/outlet sections. In the present simulator the transfer by radiation is solved through the equations of Gray and Müller[4].

The batch floating over the glass melt, in this model, is divided into two stages, heating and melting. The energy absorbed in each stage is controlled by the size of the batch surface. Modifications of the equilibrium size (due to changes in operating conditions) have a finite effect on the dynamic behaviour of the furnace. In the present simulation, these phenomena are handled using a single melting transition temperature which is assumed to be attained at the end of heating stage.

The heat transferred from the combustion chamber is not only absorbed by the batch but it also keeps the melt at a high temperature (suitable for homogenisation of the melt and for the refining processes), balancing heat losses through the walls and the heat content of the molten glass leaving the furnace. Heat transfer into the glass melt is predominantly by radiation. The temperature of the surface of the glass melt controls the total heat energy transferred into the glass. Since the glass medium is 'diffuse' the penetration effect of the heat transfer by radiation should not be neglected. In the present modelling procedure, this aspect was considered by solving the temperature profile between the surface and the mass glass volume which was assumed to be at the mean glass temperature.

For each component referred to above, unsteady heat and mass balances are solved. For the solid elements the unsteady temperature profile is solved in the main heat transfer direction. The resulting surface temperatures are used to calculate heat transfer between the solid elements and the gas volumes for which it is assumed that the components are well mixed.

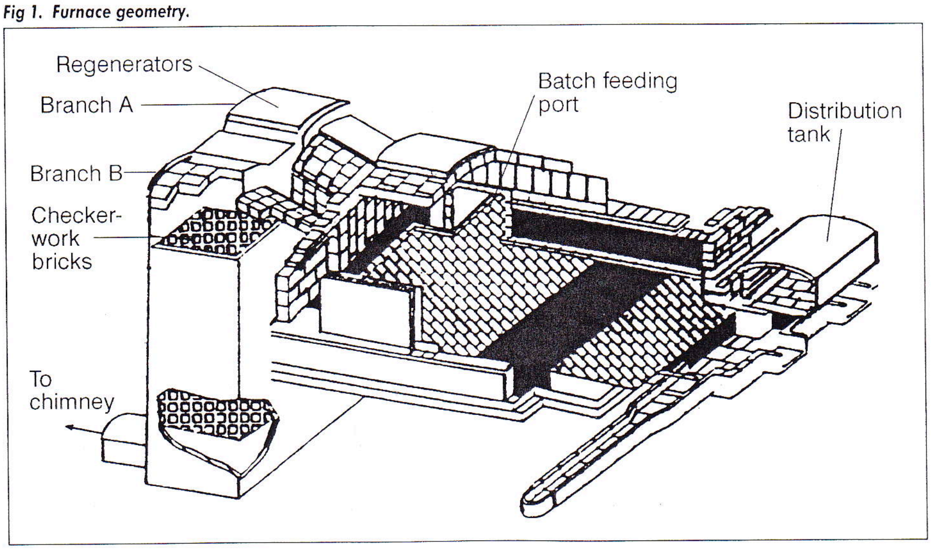
Application and results

The model was applied to a glass container furnace installed at Barbosa Almeida in Portugal. Typical values, which describe the essential features and the operation pattern of the regenerative furnace, are as follows: Fuel flow rate - 0.18kg/sec; air-fuel ratio - $17kg_{air}/kg_{fuel}$; batch feed rate - 90 tonnes/day; regenerator height - 12.65m chamber (internal volume - $96m^3$), glass tank volume - $48m^3$. The setpoint for the furnace crown temperature is 1873K. The regenerator switching period, current, is 40min.

Forecasts for the furnace dynamic behaviours, which were obtained for regular operating condi-

Page 502 ▶

Fig 1. Furnace geometry.



---

* M G Carvalho, M Nogueira and P Silva, Instituto Superior Tècnico, Dept of Mechanical Engineering, Lisbon, Portugal. Fax 01 849 9242.

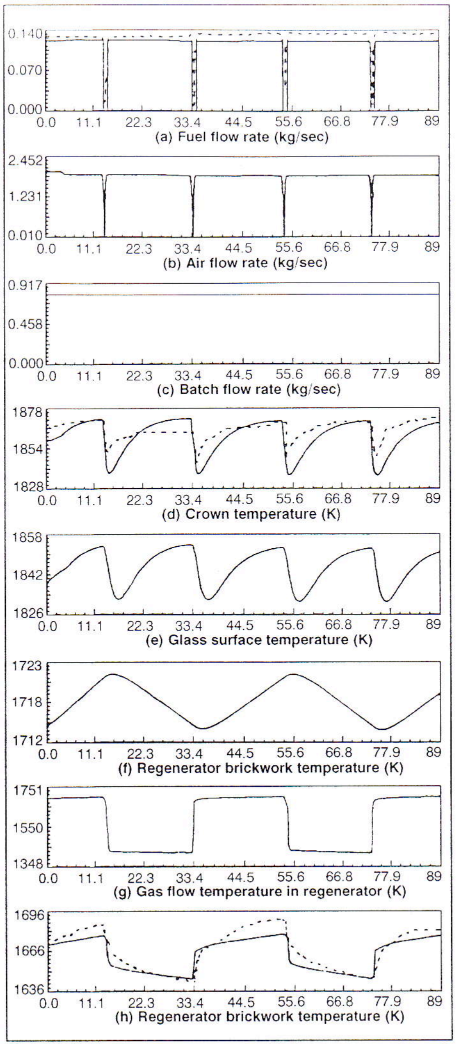


Fig 2. Predicted and measured time-dependent profiles of: (a) fuel flow rate; (b) air flow rate [kg/sec]; (c) batch flow rate [kg/sec]; (d) furnace crown temperature [K]; (e) glass furnace temperature [K]; (f) brickwork temperature in the top end of the regenerators [K]; (g) gas temperature in the top end of the regenerative chamber [K]; (h) comparison of measured and predicted temperature in the regenerative chambers [K].

tions, are presented in *fig 2*. In this figure several actuators and simulated measured variable are shown for a simulation time corresponding to approximately two periods (of 40min) as follows:

- Actuating variables: Fuel flow rate (controlled, in a closed loop, by the crown temperature setpoint), kg/sec *fig 2a*; air flow rate (regulated by a constant air/fuel ratio), kg/sec *fig 2b*); batch flow rate (given by the imposed pull rate), kg/sec *fig 2c*.
- Simulated censored variables: Crown temperature, K *fig 2d*; glass surface temperature, K *fig 2e*; temperature at the centre-line of a brick element in the top end of the brickwork filling one of the regenerative chambers, K *fig 2f*; gas temperature in the top of the brickwork filling one of the regenerative chambers, K *fig 2g*; comparison of measured and predicted temperature in the regenerative chambers, K *fig 2h*.

The furnace crown simulated and measured temperature profiles are presented and compared in *fig 2d*. In both real and simulated systems the fuel flow rate is controlled by the crown temperature. The resulting fuel flow rate in the real and simulated system may be compared in *fig 2a*. The averaged value of the difference between predicted and actual fuel setpoints is below 9%.

The amplitude of the crown temperature is higher in the predicted results than in the measured values. This difference may be due to the larger influence of the thermal inertia of the refractories on the measured value than on the simulated ones, mainly originated by geometry uncertainties related with the location of the crown thermocouple in the refractory layer.

The temperature of the surface of the glass is strongly related to the crown temperature. This fact is apparent comparing *fig 2d* with *fig 2e*. However, the amplitude is lower in the glass melt surface than could be expected from the glass melt thermal inertia effect. The oscillating effect caused by the regenerative cycle is clear in these temperatures which characterise the furnace operating conditions. This is damaging for the furnace thermal efficiency because the heat transfer rate between the combustion chamber and the glass melt surface is affected in the first part of the regenerative cycle. In fact, comparing *fig 2d* with *fig 2e*, a smaller temperature difference between the crown and the glass surface may be observed in the first part of the regenerative half-cycle. However, this negative effect is clearly overcome by the high air preheating temperature achieved by the regenerative system.

Very high temperatures obtained in the top end of the regenerator can be seen in *fig 2f* and *fig 2g*. In *fig 2f* the temperature on the centre-line of a brick element, for the highest level of the checkerwork, is presented. This temperature was calculated through the 'equivalent brick' approach described above. In this figure the phase shift between the temperature profile along the centre-line and the switching period is apparent. In *fig 2 g* the temperature of gas flow in the top end of the regenerator is represented. The high temperature present in this curve corresponds to the hot half cycle during which the waste gases are heating the regenerator brickwork.

From the results of *fig 2f* and *fig 2g*, it may be observed that in the hot half cycle the gas and brick temperatures are very close when compared with the difference between the air and brick temperature. This effect is due to the radiative heat transfer between the waste gas flow and the surface of the brickwork elements. At the working temperature of the regenerator hot end, the radiation becomes very important and clearly predominates over the convective heat transfer mode. This effect is only present in the waste gases flow where the significant presence of carbon dioxide, water vapour and carbon deposits allow a significant transfer between the gas and the solid surfaces.

In *fig 2h* the temperature measured by a thermocouple installed approximately 1m below the brickwork hot end is compared with numerical predictions of the temperature in the thermocouple cover. The comparison between measured and predicted values presents a maximum difference of 11°C which is a very acceptable value considering the difficulties associated with the modelling of the combined radiative and convective heat transfer between the temperature sensor, the gas flow and the surrounding refractory surfaces. However, the time-dependent behaviours of measured and predicted value show a significant difference which may be due to the local influence of the walls and possible peculiarities in the geometry of the thermocouple installation.

In Table I three different regenerative cycle periods are compared through their regenerative heat exchanging efficiency. The results show the small influence of the regenerative period in the heat exchange efficiency. This fact is due to the strong influence of the regenerator overall thermal capacity, which corresponds to a very high time constant, when compared with the time constant of the individual brick elements. The results show that the averaged regenerator heat exchange efficiency increases when the switching period decreases.

Conclusions

The time-dependent thermal behaviour of a glass melting furnace has been predicted. Unsteady heat and mass balance equations were solved for each equipment component. Predictions of the time-dependent profiles of the crown temperature, regenerators temperature and glass surface temperature have been presented and the modelling results compared with measured values of the crown temperature and regenerators. Good agreement was found, in spite of the strong simplifications embodied in the model and the uncertainties associated with some measured values.

In both model and real system, the fuel flow rate is controlled by the crown temperature for which a setpoint of 1873°K was stated. A time-averaged deviation between the predicted and measured fuel flow rate below 9% was obtained. ■

Acknowledgments

This work has been performed with the JOULE project 'Energy Saving and Pollution Abatement in Glassmaking Furnaces, Cement Kiln and Baking Ovens'. Also the scholarship of JNICT, CIENCIA/BOLSAS, contract BD/39/90-IB, is acknowledged. The support given by the BA, Fabrica de Vidro Barbosa & Almeida is also acknowledged.

References

1. Thring, M W, 'The science of flames and furnaces', Chapman & Hall, 1962.
2. Truelove, J S, 'Mathematical modelling of radiant heat transfer in furnaces', Heat Transfer & Fluid Service, Chemical Engineering Division, Aere Harwell Report HL76.3448/KE, 1972.
3. Bejan, A, 'Convection heat transfer', John Willey & Sons, 1984.
4. Gray W A and Miller R, 'Engineering calculations in radiative heat transfer', Pergamon Press, 1974.

Table I. Regenerative cycle period influence on the regenerator heat exchange efficiency.

Regenerative cycle period	Time averaged regenerator efficiency at the cycle end	Regenerator heat exchange heat exchange efficiency
30 min	80.4%	94.1%
40 min	80.0%	94.2%
50 min	79.7%	94.5%