Assessment of numerical simulation of industrial glass melter

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Abstract :
A mathematical model for the integrated prediction of the performance of whole glass tank furnace is described. It comprises sub-models for the combustion chamber, the batch melting and the glass tank. The three sub-models were studied by a cyclical iterative way. Useful information about furnace can be supplied by the model as long as the inlet and boundary condition are given. In this paper, model testing against data available under the scope of the ICG-TC21 activities is described. Using of 3D modelling in design is discussed.

Introduction

Model assisted design

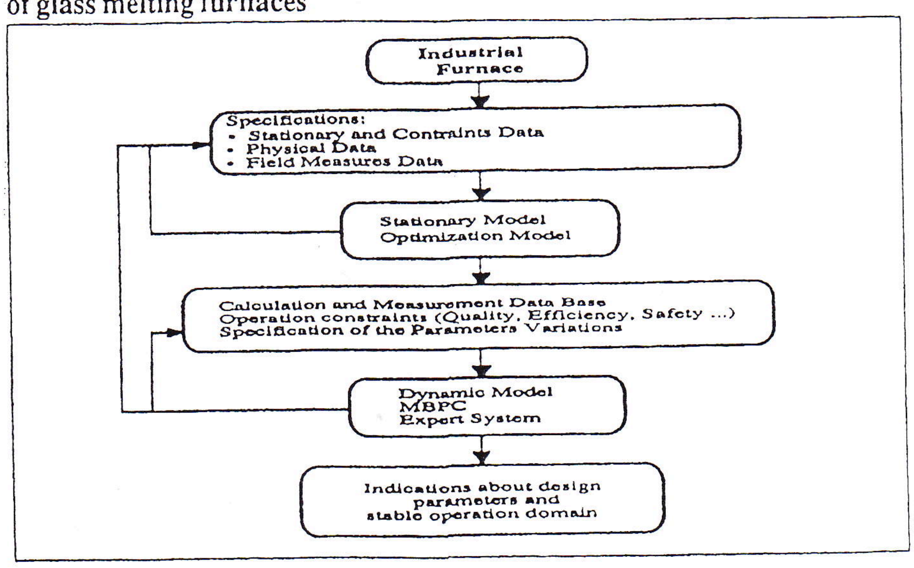
Model based integrated design tools may handle with geometrical, operating and controlling parameters as a basis to analyse the performance, in a rapid prototyping approach, of a large number of technological solutions. Optimisation of furnace operation conditions (minimising the cost of pollutant emissions control and maximising product quality, load flexibility, energy efficiency, process controllability, equipment reliability) is not possible in real time with real costs in basis of the conventional methodologies used at the design stage. New geometrical arrangements, new control strategies, new operating targets and variables have to be arranged in an integrated approach. Integrated design of the industrial furnaces will benefit from recent developments in heat transfer 3D and dynamic modelling allowing to overcome conventional techniques, empirical rules and very simplified heat transfer analysis which continue to be used in industrial environments.

The use of modelling for glass melting furnaces may provide detailed knowledge of complex phenomena occurring in this industrial equipment. Application of this knowledge to the study of new design and operation concepts will allow optimisation, integration and intensification.

Model based integrated design is a powerful tool enabling a detailed evaluation of the equipment performance reliability, maintenance and product quality at design stage. Physically-based modelling will allow geometry, control and operation parameters unified treatment, without neglecting the decisive effects of the interaction of several equipment components. This will allow the study of a very large range of original conception strategies enabling the set-up of non conventional solutions and strategies.

In the present paper a 3D modelling tool testing is reported. The final objective of the present work is to make this modelling tool capable to be included in the integrated design automatic loop proposed in figure 1.

Figure 1 : Proposed integrated structure for model assisted conception of glass melting furnaces



Modelling techniques, based in CFD concepts, have been developed in recent years. Physically-based mathematical prediction of fluid flow and heat transfer inside industrial scale furnaces is nowadays possible with an accuracy level suitable to be used in design of new geometry arrangements, operating conditions and control strategies. Fundamentally, two physically based modelling approaches will be employed :

- 3D modelling procedures in which fluid flow and heat transfer are predicted in detail for central components of the system, for stabilised stationary operating conditions;
- zero/one-dimensional dynamic modelling in which the time-dependent behaviour is calculated for the whole furnace system.

To support the utilisation of these modelling techniques, parallel computing systems can be used to make possible fast processing and consequent large number of optimisation parameters. Strong man-machine interfaces usable in industrial environment and the installation of automatic procedures to control the model based optimisation process may make modelling tool exploitable by non-research engineers. The use of these modelling procedures to test geometrical dimensions, operating set-points and control parameters, requires the presence of optimisation algorithms to handle with such multi-input/multi-output problem. The complexity of the problem is enlarged by the number of technological constraints which normally have to be considered. Dedicated optimisation algorithms will be specially developed to take profit from the capacities of parallel processing. Those, coupled with strong man-machine interfaces may turn possible the development of model based design station for optimised furnace conception.

Developed 3D modelling tools

Combustion chamber model, batch melting model and glass tank model have been individually developed [1-5].

Each of these model components may not correctly simulate industrial process of glass melting. A new generation model able to predict the main thermal physical phenomena occurring in whole glass tank furnace is required. The present paper describes a package model which includes three sub-models: the combustion chamber, the batch melting, and the glass tank, able to simulate the combustion process,

Figure 2 : Predicted temperature field in the combustion chamber

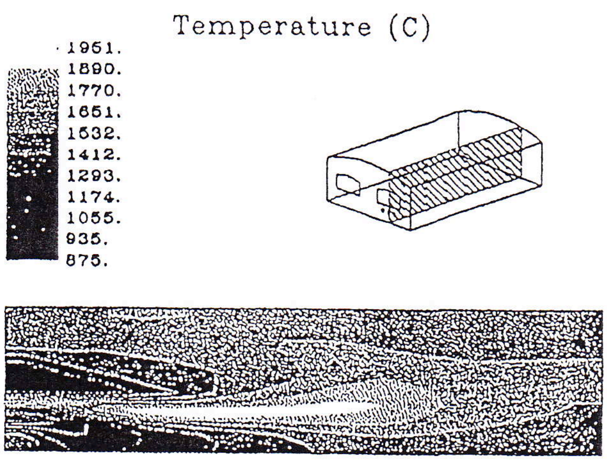


Figure 3 : Predicted flow pattern in the combustion chamber

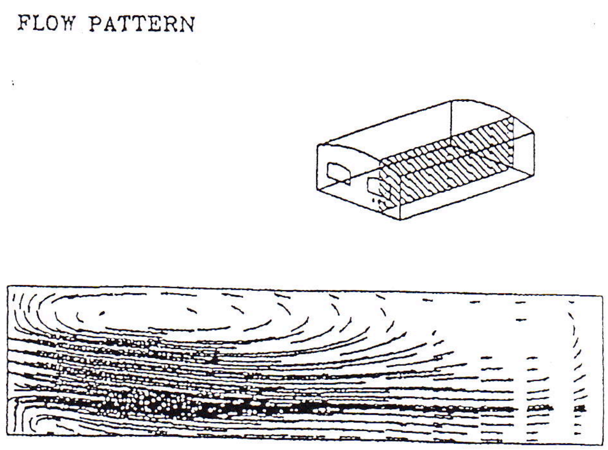


Figure 4 : Predicted flow pattern in the combustion chamber

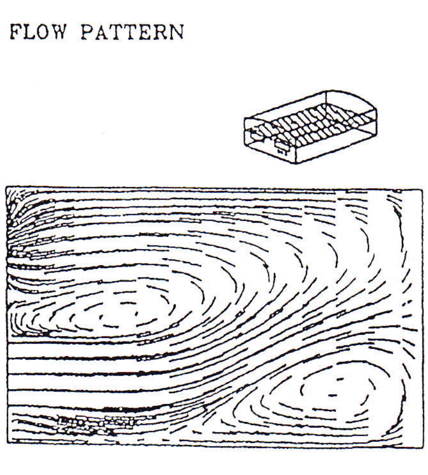


Figure 5 : Predicted NO distribution in the combustion chamber

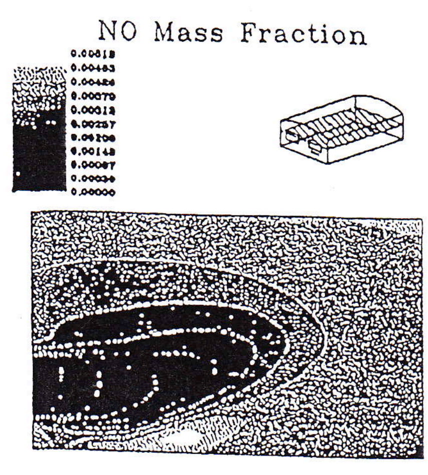


Figure 6 : Predicted O_2 distribution in the combustion chamber

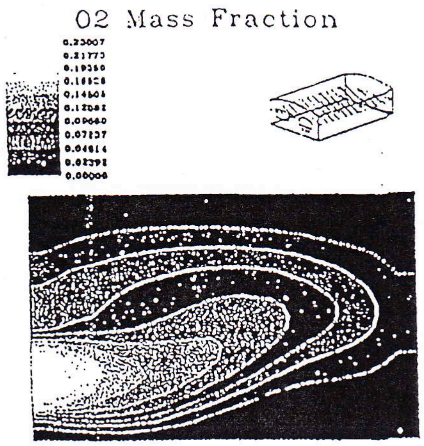


Figure 7 : Predicted heat flux from the combustion chamber to the top surface of batch blanket and free surface of glass melt

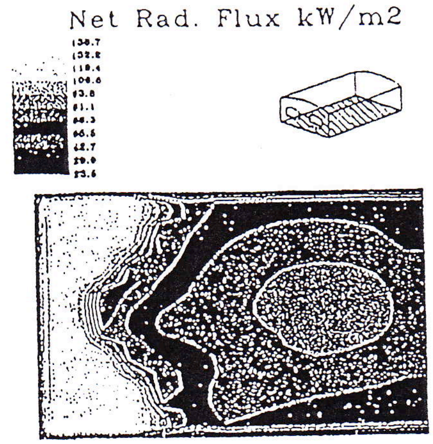


Figure 8 : Predicted temperature field in the glass tank

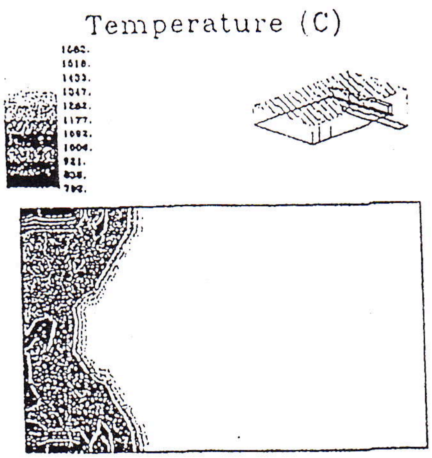


Figure 9 : Predicted temperature field in the glass tank

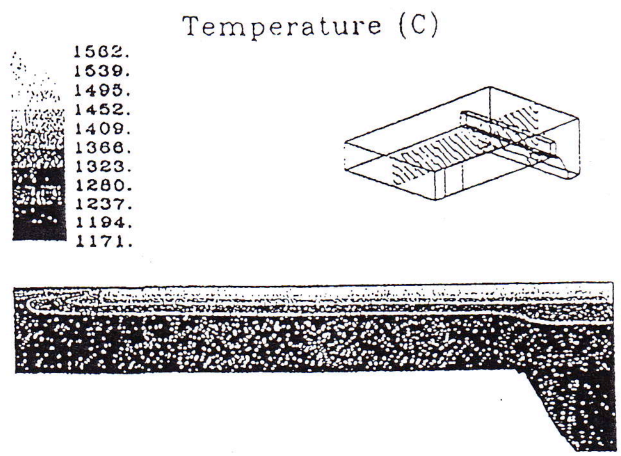


Figure 10 : Predicted flow field in the glass tank

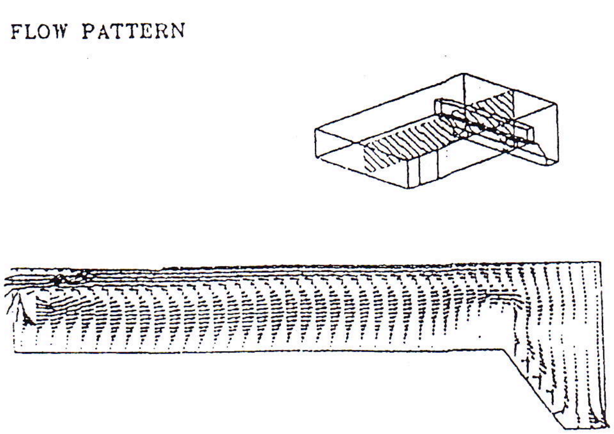
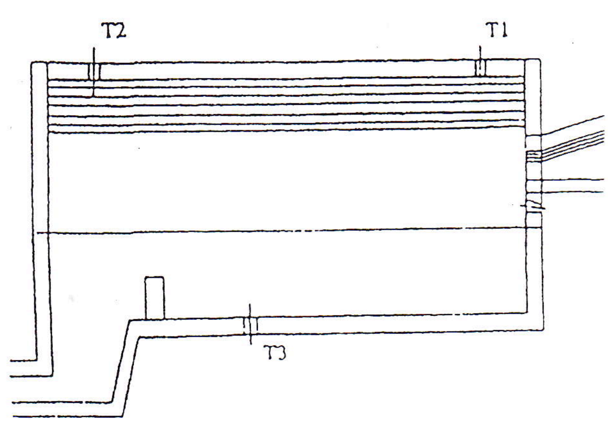


Figure 11 : Sketch of end-fired glass tank furnace



batch melting process, and the flow and heat transfer of the molten glass in glass tank furnace. The three sub-models were studied by a cyclical iterative way.

Numerical simulation

Mathematical modelling

Individual mathematical models (combustion chamber, batch melting and glass tank) have been already described by previous publication. [1,4,5] The present paper will concentrate in the coupling procedure. A package model, a three-dimensional mathematical model simulating the physical phenomena occurring in a glass tank furnace, has been developed. The model is based on the solution of conservation for mass, momentum, energy and combustion related chemical species, and comprises three main coupled sub-models: the combustion chamber, the batch melting, and the glass tank.

The combustion model incorporates physical modelling for the turbulent diffusion flame, soot formation and oxidation, NO formation and dissociation and radiative heat transfer. The time-averaged equations for the conservation of momentum were used as well as the equation for the conservation of energy. The two equation turbulence model k-ε was considered appropriated. The combustion model is based on the ideal of a single step and fast reaction, together with a statistical approach able to describe the temporal nature of the turbulent fluctuations. The discrete transfer radiation model was used in this study. [1]

The batch melting model incorporates physical modelling for the heat transfer and melting down process. The chemical reaction was assumed to take place at a defined temperature. The phase change was presumed to occur over a temperature range between chemical reaction temperature and molten temperature. [4,6,7]

The glass tank model incorporates physical modelling for the flow and heat transfer of the molten glass. The radiation transfer inside the molten glass bulk was handled by using an effective thermal conductivity in the energy equation. [5]

Coupling algorithm and numerical solution

The simulation of the whole glass furnace was performed in an integrated method. The three main sub-models were coupled by a cyclical iterative way, matched by the relation between the heat flux from the flame to the molten glass surface and the top surface of the batch blanket, and the heat flux from the molten glass to the bottom surface of the batch blanket. The whole procedure is calculated until «convergence» of the coupled process is achieved. Interface temperature between the flame and the batch, the flame and the molten glass, the molten glass and the batch were calculated by a cyclical iterative way.

The finite difference/finite volume method was used to solve the equations. As the upstream conditions determine the downstream ones on the batch blanket, a matching downstream technique in its finite difference form was used to the batch model. [4]

Results and discussion

The above referred model was applied to an end-port container glass tank furnace - ICG-TC21 Robin Test Case. Melting area of glass tank was 61 square meter. The pull of the tank was 175 ton each day. The flow rate of fuel oil was 755 kg per hour and inlet temperature of the combustion air was 1180 °C. For the batch blanket, raw materials constitute 55 % by weight and cullet 45 % by weight. Thermal physical properties of the glass batch were calculated using the contents available in [8].

Results for the combustion chamber, the batch melting rate and the glass tank are presented in figure 2 to figure 10. The results obtained from the model were in good agreement with those obtained from the measurement on an operating furnace (table 1 and figure 11).

The time averaged predicted temperature field of the gas turbulent flow field is plotted in figure 2. The high temperature region, near the flame front, is well visible in this figure. Optimal time averaged location of the gas temperature zones may be found using validated and coupled 3D modelling procedures as the presently proposed. For instance, further attenuation of eventually excessive temperature peaks is possible acting on the fuel distribution among burners or on design parameters. A significant feature of the calculated field is the location and magnitude of temperature gradients, apparent in the air/fuel flows shear layer. The calculated time averaged flow field is plotted in figure 3 and figure 4. The horse-shoe shape of flame is well apparent in figure 4 as well as the effect of the secondary recirculations caused by the vertical and horizontal inclinations of the air inlet duct and burner. In figure 5 NO mass fraction in the hot gases inside the combustion chamber is plotted. In this figure the NO dissociation is well evident. In fact, a NO concentration peak may be observed between the air inlet port and the side wall, and important decreasing gradients towards the outlet region may be observed. In this region strong oxygen concentrations may be found together with high temperature levels due to the flame presence. This aspect may be illustrated by the

Table 1: Measured temperature and calculated results

Point	Thermocouple Températur	Calculation Température	ΔT
T1	1525 °C	1512 °C	13 °C
T2	1595 °C	1589 °C	6°C
T3	1340 °C	1331 °C	9 °C

distribution of the oxygen, plotted in figure 6. In this figure a horizontal plane cutting the air entrance is used.

The batch is fed into glass tank by batch charger from the doghouses which located at both side walls. The batch blanket is heated from top surface by heat radiation from the combustion chamber and heated from bottom surface by heat transfer from hot molten glass underneath. When the temperature is above molten temperature, the batch is converted to molten glass and melting down into glass tank. The heat flux from the combustion chamber to the surface of the molten glass and the top surface of the batch blanket is shown in figure 7. The heat flux was calculated by combustion model by a cyclical iterative way. The values of the heat flux are very large in the surface of the batch blanket, because the temperature of the top surface of the batch blanket was much lower than the temperature of the free surface of the molten glass. This effect balances the energy requirements of the endothermic melting reactions.

The laminar glass melt flow pattern is shown in figure 8 to 10. In these figures the temperature field and the flow field are plotted. The temperature of the molten glass is the essential property for the batch melting, glass homogenisation and refining which is dependent on heat radiation from the combustion chamber, heat transfer from the glass melt to the batch blanket and inside glass tank, also act on the convective effects and the productive flow. The weir forces the molten glass flowing near free surface, which has the function of homogenisation and refining. Figure 9 and 10 show the temperature field and flow field of the molten glass at the centre plan of the glass tank with the weir. The effect of the «cold» molten glass getting in the glass-melt buoyant flow causes significant deformation of the flow pattern and temperature field in the vitrification region as shown in figures 6 to 10.

Conclusions

This paper reports a test case used to evaluate 3D modelling capabilities and to study its effective applicability inside furnace design loops. Predictions of the temperature field, the flow field of the glass tank and the combustion chamber, the chemical species concentration distribution, the radiative fluxes, the batch blanket area floating on the surface of the molten glass and the batch melting process were shown. Useful information about whole glass furnace can be supplied by the model with a very acceptable deviation range making possible modelling use for optimal furnace conception. Detailed analysis of the furnace performance is therefore possible from the prediction of spatial distribution of relevant properties inside the furnace enclosure. Taking into account, during the furnace conception process, very detailed knowledge about the physical and chemical process occurring inside the furnace environment is an open possibility.

Acknowledgements

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