Dedicated Modelling as Tool for Novel Solutions to Improve Energy Efficiency of Ceramic Furnaces

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The use of physically-based dedicated mathematical modelling for combustion chambers, heating chambers, load, preheaters and other associated equipment of kilns and furnaces, together with the implementation of on-line sensors will provide detailed knowledge of the very complex phenomena occurring in those industrial equipments. Application of this knowledge to the study of new design and optimization of operation concepts, integration and intensification is possible. In the present paper this approach is discussed as well as research priorities, objectives and major achievements at present technological stage. Relevant developments under current joint European research projects are referred.

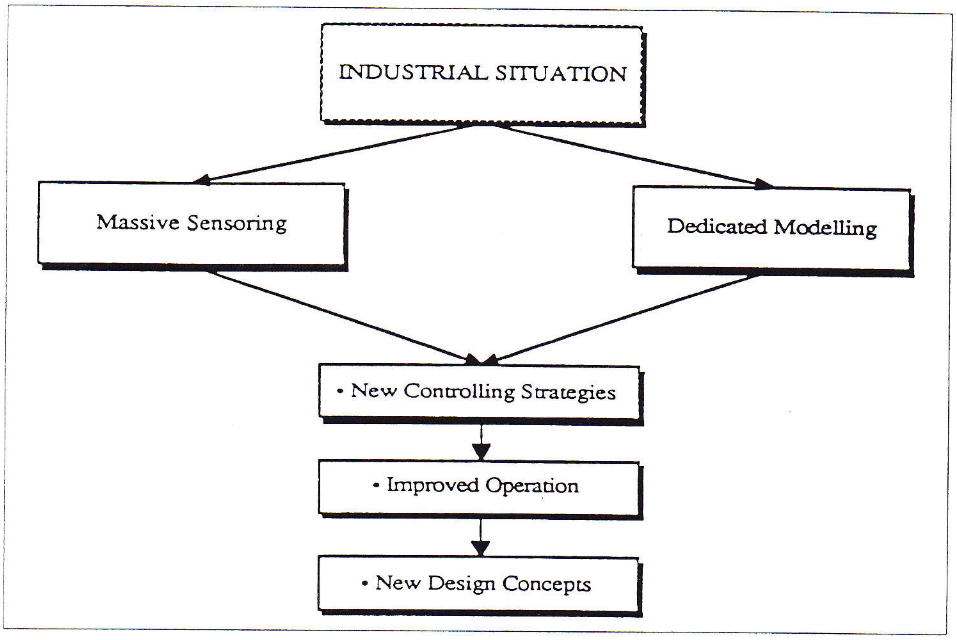

Figure 1. Considered response to the industrial needs.

Industrial Needs for Energy Saving

European industry is facing sustained pressure to improve its productivity and product quality together with strong constrains about pollutant emissions and energy consumption. Improvements in energy efficiency, product quality, pollution abatement in kilns and furnaces cannot be achieved without an effective physically-based knowledge and understanding of the relevant thermal phenomena. This approach have to consider specific aspects of the industrial process itself, its interactions with the heating chamber (electrically heated or by combustion) and heat transfer efficiency. Improvements in the workability and quality of the products (reducing the level of rejections and increasing the process efficiency) and production intensification constitutes an effective way for energy saving and pollution abatement. Also the furnace and kiln associated equipments are fundamental for energy saving and consequent abatement in pollutant emissions. The efficiency of the heat recovering systems cannot be neglected in this optimization effort.

Pollutant emissions abatement is possible through:

- improving the performance of the thermal process (allowing the reduction of energy requirements);
- acting on the combusting process in order to decrease the emission of pollutants generated by combustion as such as CO, NOx and some classes of particles.

Low-cost pollution abatement is therefore attainable.

A possible Approach

Mathematical modelling, based on computational fluid dynamics, and in particular 3-D modelling have to be explored as a powerful alternative to the empirical rules and global balance based static modelling. 3-D modelling provides, at reasonable cost, a way to access the spatial distributions of main fields inside combustion chamber, electric heating chambers, heat recovering devices and charge. This features allow an effective evaluation of the consequences of modifications in operating conditions and design, opening an wide range for optimization considering primary and secondary effects. However, the application of computational fluid dynamics techniques to full scale industrial equipments remains a topic far of to be closed since the physical description of the phenomena in the integrated system (heating chamber, heat recovering devices, process interaction with the furnace or kiln) remains far of to be satisfactory.

General modelling techniques for fluid flow and heat transfer predictions in furnaces and kilns are well established. Developments in should be aimed to explore advantages from a complete system representation.

A dedicated modelling approach is required in order to integrate, on the basis of well established general modelling know-how, specific characteristic of each studied system. Associated equipments and load have to be considered for practical effective application in process efficiency improvement. This integrated approach, present in the dedicated modelling conception, is the basic condition for a successful achievement of the proposed modelling based optimization effort.

Dedicated modelling allows an integrated representation of the furnaces and kilns with associated equipments as well as the consideration of physical interactions between the various sub-systems and associated phenomena. A powerful representation will be therefore obtained from this dedicated modelling philosophy. In spite of the physical differences between the several systems considered in the present proposal (kilns and ceramic/glass furnaces) significant experience and general know-how may be transferred from and to other application fields and industrial sectors.

The continuous development of new sensors, the enlargement of on-line sensoring capacities to traditionally non accessible variables and the application of recently developed techniques will allow massive sensoring of the analyzed equipments. An extensive characterization of the process will support and improve physical understanding of the phenomena, extended validation of modelling procedures, and open possibilities for the application of new operation and design concepts.

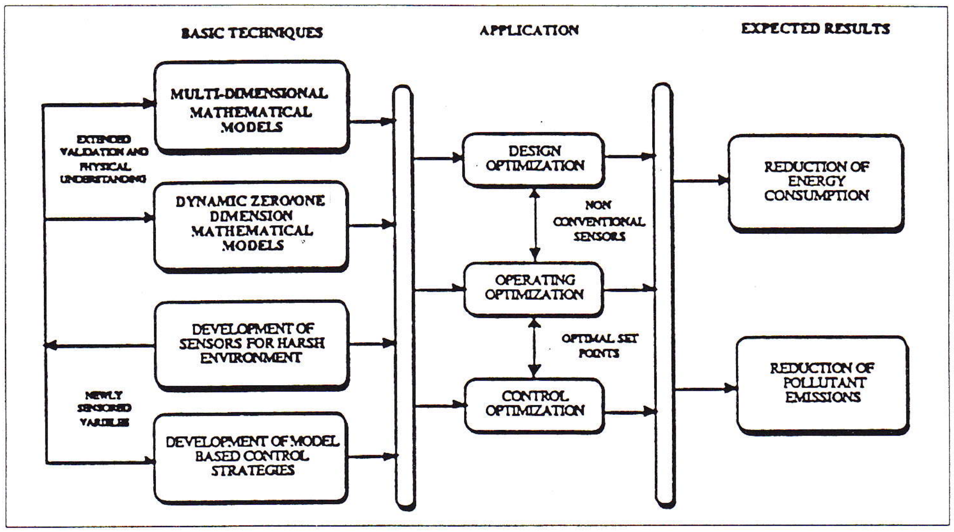

Figure 2. Expected achievements.

Objectives and Expected Achievements

Furnace operating conditions together with advanced control systems and improved conception are required to reduce energy consumption and decrease pollutant levels. Ceramic industries are responsible for an important part of the industrial energy consumption and pollutant emissions in EC countries. Advanced knowledge of the fluid flow and heat transfer processes in industrial furnaces, as shown in Table 1, is an essential basis to determine improved design and operation. Massive sensoring and dedicated modelling of the involved industrial equipment will permit the delivery of optimized control strategies and new design concepts for a improved energy efficiency in kilns, furnaces and ovens operation.

The main goal of these research efforts should be to develop knowledge and engineering tools able to assist the optimization of design, control and operation of glass/ceramic kilns and furnaces in order to allow improved energy efficiency and lowcost pollution abatement. This goal will be achieved through the use of sophisticated computational modelling, advanced massive sensoring and its application to enhanced model based control strategies, integrating newly sensored variables and knowledge based concepts, as well as novel design solutions.

Following the above referred approach the final objectives may be stated as follows:

- Development and application of advanced sensors in harsh environments allowing the access to nonconventional controllable variables and extensive characerization of the process.
- Development and validation of dedicated physically-based models of kilns and furnaces (comprising associated equipments and load) through the use of multidimensional and dynamical approaches. The modelling development may embody information obtained through the massive characterization of the equipment. Validation of the developed models have to be achieved through experimental characterization with advanced sensors considered in the previous objective. Continued development and validation of multidimensional physically-based mathematical models, together with zero/one dimensional dynamical models have to be undertaken in order to insure an innovative model basis.
- Study of more energy efficient design and operation concepts applying modelling facilities and embodying the new sensoring capacities (referred in objective 1). Lower cost pollutant abatement possibilities can be concurrently considered.

Research Priorities

Dedicated modelling, massive sensoring, improved operation and new design concepts will result from the following research priorities:

- Development and validation of dedicated mathematical models in the following directions:
  - integration of specific aspects of the industrial processes;
  - study of alternative fuels (solid fuels, emulsions) and advanced burners;
  - study of the interactions between the furnace and upstream/downstream equipments (preheaters, regenerators, recuperators, controlled cooling devices, dryers).
- Refinement of the developed computational models in order to adapt them for an easy application to the test of new geometries and to the study of operating conditions and control actuators setpoints.
- Development of new sensors for innovative process evaluation:
  - direct access to nonconventional controllable variables as pollutant emissions level, product quality indexes:
  - extensive characterization of the process occurring in harsh environments;

Required Developments in the Current Technological State

The above referred priorities require research efforts in the following topics:

- Continued development of multi-dimensional mathematical models, enlarging the knowledge about the physical processes and enabling its optimization.
- Development of dynamical global balance models enabling the study of improved control regulation parameters.

- Characterization of Near Burner Region:
  - continuation of efforts in the characterization studies in the dense, near burners regions in order to improve knowledge concerning sprays-formation, droplet combustion etc..
  - integration of near burner region models with combustion chamber modelling;
  - implementation of advanced turbulence modelling, NO_X formation and dissociation modelling and cenospheres generation and transport.
- Development of new sensors, in order to:
  - obtain enhanced experimental sensoring techniques enabling more accurate characterization of the furnace thermal state for an improved understanding of the physical phenomena and model results validation;
  - extend the set of parameters which can be sensored allowing the study of new control strategies and on-line optimization of set-points (namely reliable on-line measurements of NO_X and O_2 under harsh conditions and gas composition through artificial vision access to furnace enclosure), load conditioning, flame shape;
- Extensive characterization of furnaces and kilns operating conditions, yielding:
  - extensive data from industrial and laboratory situations for dedicated modelling validation;
  - experimental measurement in industrial and laboratory situations, through advanced sensoring techniques, of nonconventional variables allowing improved characterization of the process.
  - installation of sensors in furnace harsh environment under real industrial operating conditions.

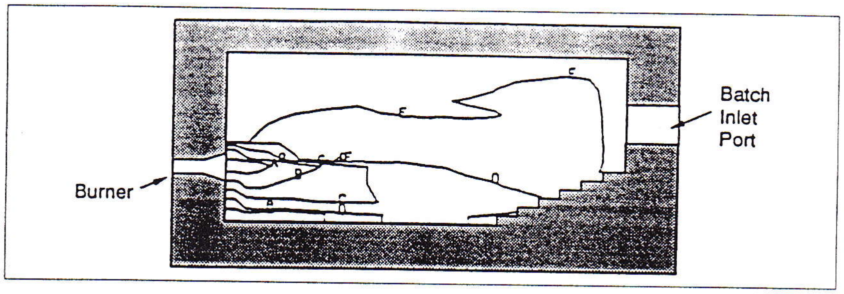

Figure 3. Prediction of temperature field inside a smelting kiln obtained through a three-dimensional procedure in which fluid flow, combustion and heat transfer are solved (A = 3000 K; B = 2200 K; C = 1900 K; D = 1700 K; E = 1650 K;)

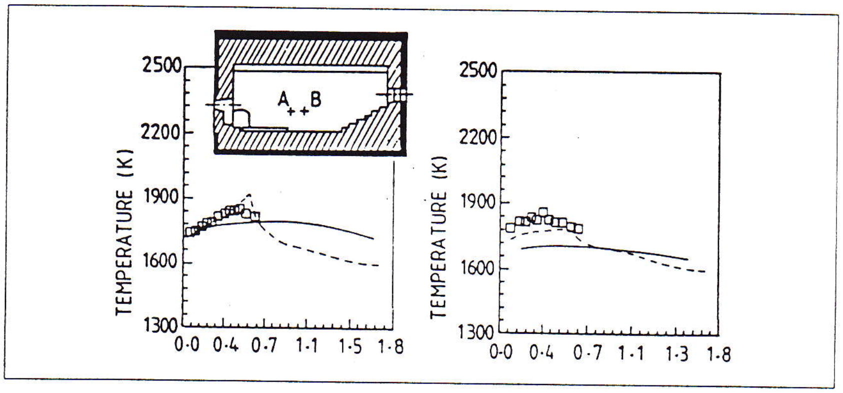

Figure 5. Comparison between predictions of the phenomena in a smelting kiln obtained throiugh three-dimensional procedures with measurements (° Measurements, CARVALHO et al., 1988; -- Computational Results, CARVALHO et al., 1987; -- Computational Results, CARVALHO et al., 1989).

- Recommendations for more efficient operation of furnaces and kilns, including:
  - conception of new control strategies based on modelling application and on the above referred allowance for nonconventional on-line measurements;
  - test of improved model based regulation techniques.
  - search of more efficient operating conditions and low-cost pollution abatement possibilities and process intensification through acting on set-points definition and regulation parameters.
  - search of process optimization possibilities by acting on set-points definition and regulation parameters.
- Recommendations for more efficient design of furnaces and kilns, including:
  - development of model based concepts for design;
  - studies, applying dedicated modelling tools, of the influence on the furnace, kiln or oven efficiency of a group of selected main geometrical parameters.
  - search of more efficient operating conditions and low-cost pollution abatement possibilities and process identification by acting on geometrical variables.
- Study of new control strategies based on modelling and nonconventional sensoring, in order to:
  - obtain control strategies able to embody physically based information yield by computational modelling allowing multi-inputmulti-output control;
  - obtain control strategies able to embody information from new on-line sensors;
  - develop direct control of efficiency, quality and emissions;
  - develop a strategy for on-line optimization, as part of a knowledge based system, with information available from multi-dimensional models of the

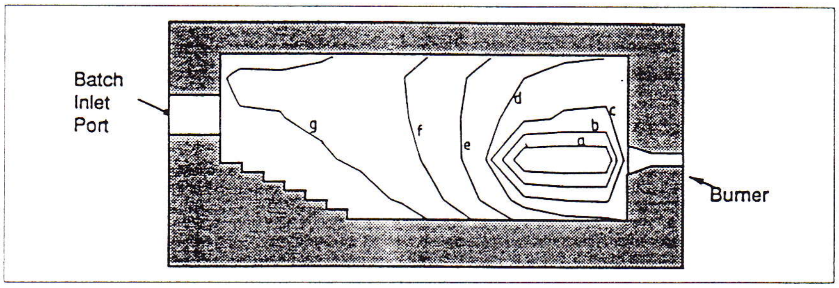

Figure 4. Prediction of temperature field inside a smelting kiln obtained through a simplified three-dimensional procedure in which radiative heat transfer is solved (A = 2400 K; B = 2200 K; C = 2000 K; D = 1900 K; E = 1800 K; F = 1700 K; G = 1600 K;)

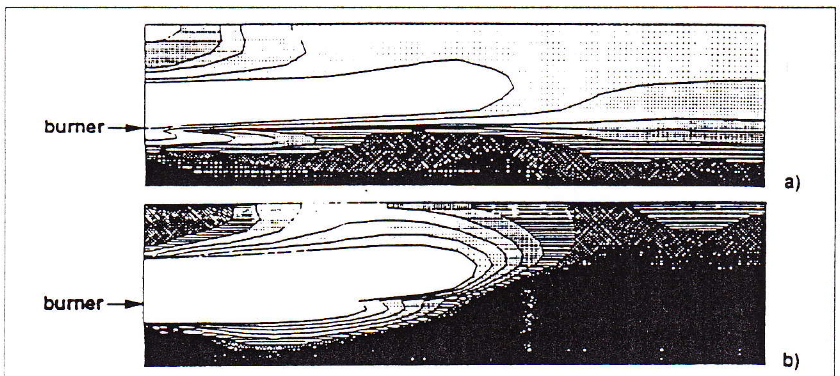

Figure 6. Prediction of NO_x and SO_2 mass fraction field inside a furnace through a three-dimensional procedure in which fluid flow, heat transfer and chemical reactions are solved.

furnace environment, to control of efficiency, quality and emissions.

Basis for a dedicated modelling approach

Advances in computer power allied to advances in computational fluid dynamics science, in the understanding of radiative heat transfer phenomena, and chemical reactions turned possible to couple the fluid flow equations for heat and mass transfer and chemical reaction rates and to obtain a detailed picture than hitherto of the phenomena occurring in combustion chambers. This can improve design of conventional equipment and, more important, might simulate innovate ideas for radically new designs of equipment.

Abou Ellail et. al. (1978) described a prediction method for three-dimensional reacting flows where a flux model for the thermal radiation, was employed. The prediction procedure was applied to two industrial-type experimental furnaces from the French national gas corporation, „Gaz de France“, in Toulouse and from the International Flame Research Foundation, IFRF, in The Netherlands. The fuel in both instances was natural gas.

A three-dimensional simulation of a combustion chamber was presented by Gosman et. al. (1980) in which a more accurate and efficient technique for the handling of the thermal radiation was used - the „Discrete Transfer“ method of Lockwood and Shah (1980). The developed prediction procedure was applied to a cross-fired glass furnace burning U.K. North Sea natural gas.

Semião (1986) has applied a three-dimensional prediction procedure to a ceramic glass smelting-kiln with oxygen-rich burning conditions. Carvalho et. al. (1987) have extended that work and used a two-dimensional axisymmetric model to simulate the burner region, providing with these results the inlet conditions for the three-dimensional calculations of the combustion chamber. The results were extensively validated with experimental data acquired in the furnace (Carvalho et. al., 1988). This model is based in the numerical solution of governing transport equations for momentum, mass, energy and species concentration besides a discrete transfer approach to solve the radiative heat transfer. Results obtained with this model are presented in figure 3. The model was used to optimize the furnace operating conditions and, for example, the results have shown an 18 % improvement in energy efficiency when oxygen enrichment is applied. An energy balance based procedure as been applied to real time modelling of glass ceramic furnaces embodying simplifications of the above referred 3-D modelling procedures (Carvalho et. al., 1989). Results obtained with this model are presented in figure 4. Comparison between both models and experimental results is presented in figure 5. These developments and results have been obtained under the scope of a research project led by the Instituto Superior Técnico (Technical University of Lisbon) in the Non-Nuclear Energy R&D Programme (Energy Conservation) entitled „Improved Design for Glass Smelting Kilns“- EN3E-0153-P.

Similarly, a modelling procedure for the calculation of 3-D fluid flow and heat transfer phenomena in a industrial furnace, considering by an integrated approach the combustion chamber (turbulent flow, thermal radiation, pollutants formation) and load (laminar buoyancy-driven glass-melt flow), has been recently developed (Carvalho et al., 1992). The NO_X and SO_2 concentration fields calculated by this procedure are presented in figure 6 in a plane crossing one of burners as an example of the model applicability.

Recent mathematical modelling significant applications to ceramic furnaces are reported in Meunier (1991).

The flexibility of the codes family above referred can be clearly demonstrated by applications of similar three-dimensional codes to calculate the flow in industrial boilers. Robinson (1985) has presented a three-dimensional model tor a large tangentially-tired furnace of the type used in power-station boilers. In this work a six-flux model was used for the evaluation of radiative heat transfer. The model was strictly applicable only to gaseous- fulled furnaces. Abbas and Lockwood (1986) described the application of a fully three-dimensional mathematical model to the combustors of two large power station boilers: one front wall-fired and other corner-tired. Predictions of the aerodynamics of the flow were compared with experimental data obtained in cold models and combustion and radiation heat transfer characteristics were calculated tor the corner-fired case using the „Discrete Transfer“ method. The results were in fairly good agreement with the model data, suggesting that the flow in a full-scale plant can be predicted with current models with a reasonable accuracy.

However, in spite of the progress made during the last decade in the computer solution of complex panial different equations, and the modelling of turbulence, combustion and heat transfer phenomena, it is probably fair to say that no furnace design engineer is yet making any real use of a general modem computational technique to assist his work. There would seem to be four principal reasons for this:

- in the early days of their development, the methods were insufficiently developed to represent a substantial improvement on existing design procedures as primitive as these were.
- prediction techniques have emerged, which could considerably assist the furnace design engineer, they are highly sophisticated and their use demands a level of commitment, which industry for the most pan, has so far not been prepared to make.
- lack of validation for the full scale furnace. Most models published in the literature have been validated at laboratorial and semi-industrial scale. Such efforts are not without value but it is now recognized that its worth is very limited, because tor the most pan the many complex processes occuring in combustion chambers scale in different ways.
- the general prediction methods are highly computer time consuming, because furnace and boilers geometries tend to feature much geometrical detail and because extremely complex fluid mechanical, chemical and heat transfer processes require to be simulated.

Dedicated modelling approach aims to respond to the second and fourth reasons. A careful modelling representation of the actual furnace-kiln system, and a correct exploitation of the specif aspects of each process will allow the set up of faster modelling implementations and a significant reduction of the lead time needed to train the industrial user to have useful results. Massive sensoring will allow a correct validation of dedicated modelling codes against industrial data. Prediction codes capable of computing the three-dimensional characteristics of actual equipment to improved furnace and kiln design, control and operation optimization will therefore be available.

Basis for a massive sensoring approach

In recent years, novel sensors have been developed for withstanding harsh environmental conditions occurring in process industry such as glass-melting furnaces and ceramic furnaces. For the application to high temperature environments new cooling devices allow the application of temperature sensitive sensors under these conditions. Research work in functional tests for different working conditions, taking into account high temperature, aggressive media and radiation as well as distortion causes by additional sources of heat production, has been carried out in the past. These new developed sensors and additional sensors to be developed for direct access to non conventional controllable variables have shown new possibilities for process control in industry.

The role of European joint research projects

The development and use of dedicated modelling for combustion chambers, heating chambers, load, preheaters and other associated equipment of kilns and furnaces, together with the implementation of on-line sensors will provide detailed knowledge of the very complex phenomena occurring in those industrial equipments. The approach proposed for this optimization task will allow the study of a very large range of Parameters enabling the set-up of nonconventional design solutions, new control strategies and improved operating concepts. The proposed approach may allow energy saving for example in the magnitude of 10%- 20% for the batch melting industries and can be expected simultaneously low-cost reduction of environmental damages, better product quality and longer life cycle of the equipment.

In the current joint European research project, under the JOULE programme of DGXII of the CEC, „Energy Saving and Pollution Abatement in Glas-Making Furnaces, Cement Kilns and Baking Ovens“ JOUE-0051-C (SMA), modelling procedures have been developed and validated enabling its use for a variety of furnaces, kilns and ovens. This project involves research groups from Instituto Superior Técnico (Technical University of Lisbon); Imperial College of Science, Technology & Medicine; University of Erlangen- Nuernberg; TNO Institute of Environment and Energy Technology, TNO Flour & Bread Institute; ADERSA, Institut National du Verre; Faculté Polytechnique de Mons; Centre of Renewable Energy Sources.

In the following sections several aspects which the involved research groups intent to continue exploring will be focussed.

Modelling of ceramic furnaces, Associated Equipment and load

The stabilization and optimization of the temperature profile in tunnel continuous kilns is a basic requirement to improve the product quality and to make possible the extension of this equipment applicability for more quality demanding process. Low energy consumption is theoretically possible and is often claimed for this type of furnace. The process in batch furnaces is traditionally optimized in order to respect a suitable temperature being the energy consumption aspect often neglected. The knowledge of the temperature and fluxes spatial distribution inside the furnace enclosure allows the combination of both aspects; energy saving with respect by the temperature profile constraints. At the end of the „Energy Saving and Pollution Abatement in Glass-Making Furnaces, Cement Kilns and Baking Ovens" JOUE-0051-C (SMA) project, a mathematical model able to calculate the flow and the heat transfer in furnace combustion chambers containing packing of pieces of a batch melting furnaces will be available. This model will be used as a basis for the following developments.

- Study of the Interaction of the furnace operation with dryers. Owing to the transient nature of the batch process, interaction with the dryers should be studied in order to reduce the overall energy consumption.
- Detailed modelling of flow inside the furnace chamber particularly inside the stacking accounting for bypass flows and transverse flow due to natural convection. A simplified model of these phenomena must be developed for its inclusion in an overall model of the furnace.
- Overall modelling of a tunnel kiln allowing calculation of relevant parameters for energy consumption and pollutant emissions calculation.
- Development of dynamic model of the tunnel furnace system.

Modelling of Ceramic Glass Melting furnaces Associated Equipment and load

Ceramic glass-melting furnaces often burns heavy-fuel-oil (HFO). A model of the near burner region of combusting HFO spray has been developed, under the scope of the „Energy Saving and Pollution Abatement in Glass-Making Furnaces, Cement Kilns and Baking Ovens" JOUE-0051-C (SMA) project. This development will allow the coupling with the above referred three-dimensional glass melting model ensuring a strongly physically based description of the combustion chamber.

Massive Sensoring of Ceramic Glass Furnace Systems

Improvements achieved by numerical modelling used in control strategies and furnace design optimization will lead to more energy efficiency and higher product quality in glass/ceramic furnaces. The numerical codes developed in the „Energy Saving and Pollution Abatement in Glass-Making Furnaces, Cement Kilns and Baking Ovens" JOUE-0051-C (SMA) project have been validated by experimental data in real furnaces.

However variations in fuel rate and batch load must be documented and compared to the results obtained by simulating the process with new control strategies. Experimental results to be obtained by the involved research groups will include video observation; temperature sensors; gas analysis in the furnace. Variations of the governing process parameters will be reported and their influence to the production process evaluated. Based on these results, a combination of accurate sensor systems, withstanding the harsh environmental conditions, will be developed to be applied for on-line monitoring the industrial process, by measuring the evaluated key-parameters, allowing an effective process control to obtain maximum product quality with less energy consumption.

New Control Strategies and Design Concepts for Ceramics Furnace Systems

The research efforts to be developed by the involved groups will consider the: development of the modelling action of the batch and continuous furnace operation interaction with dryers; study of improved design of batch furnaces; study of improved design of continuous furnaces; study of control strategies and operating conditions for energy saving and pollutant abatement in batch furnaces; study of control strategies and operating conditions for energy saving and pollutant abatement in continuous furnaces; study of control strategies directed for energy saving in batch furnaces.

New Control Strategies and Design Concepts for Ceramic Glass Furnace Systems

The stability and optimization of glass melting process is a basic requirement for product quality and workability (with indirect gains on energy consumption and pollutant emissions), furnace thermal efficiency and pollutant abatement. Also the optimized specification of main design parameters is essential. This aspect requires the application of integrated models able to simulate the whole system.

Model based knowledge, will be applied to study of energy efficient operating conditions of glass furnaces low-cost pollutant abatement controlling and operating techniques. Novel design concepts directed for these two objectives will be evaluated using those modelling capacities in this domain the involved research groups will conduct parametric studies of the influence of the fundamental design and operating parameters in thermal efficiency and pollutant emissions.

Conclusions

The developments suggested and outlined in the present paper will allow significant gains in energy efficiency of the considered process. From the use of 3-D numerical modelling, and dynamical modelling important improvements in the reduction of combustion generated pollutant emissions, increase of fuel efficiency and product quality may be attained. The generality of the employed and developed modelling and sensoring techniques ensure a wide range for their application involving a large number of industrial situations, in a dedicated modelling approach.

Software houses, able to be involved with numerical modelling solution of the 3-D enclosures may participate in the application of the developed modelling procedures in to other industrial cases. Specialists in industrial automation systems have to be committed to the integration of the developes concepts into the existing specific control, actuators and sensors systems. New sensors, able to operate under harsh environments, are of unquestionable interest for the optimization of industrial furnaces.

The development of novel operating, controlling and design concepts based on the application of physically based modelling and nonconventional variables measurements may open new possibilities for energy saving and lower cost pollutant reduction. Manufacturers, certainly, will be able to embody and promote such developments.

An expected near future marketing of the developments to be achieved under the presently discussed objectives scope will contribute for a continued development of the furnaces kilns and ovens European technology and manufacturing industry competitiveness. This marketing will naturally be dependent of the manufacturers of control systems, sensors and thermal equipments as such as furnaces and kilns.

Summarizing, the reduction of pollutant emissions and energy consumption, will certainly constitute an essential target in the furnace conception and operation. The development of low pollutant concepting and operating techniques, namely based in 3D computational dedicated modelling, will certainly be one of the priority areas requiring strategic industrial research in the next years.

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