Pergamon

Applied Thermal Engineering Vol. 17, Nos. 8–10, pp. 921–933, 1997

PII: S1359-4311(97)00001-X
1359-4311/97 $17.00 + 0.00

IMPROVEMENT OF ENERGY EFFICIENCY IN GLASS-MELTING FURNACES, CEMENT KILNS AND BAKING OVENS

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Abstract—This paper is aimed at presenting the utilisation of dedicated modelling tools for the optimisation of a variety of thermal equipment for high-, medium- and low-temperature heat transfer processes. A combination of modelling with advanced extensive on-line measurements is proposed as an approach for the development of optimisation procedures able to be used in equipment design and operation. The industrially oriented utilisation of modelling is discussed considering the state-of-the-art and the application of existing codes capable of computing the three-dimensional characteristics of the aerodynamics, mixing, combustion (single- or multi-phase), pollutants formation and heat transfer of industrial combustion equipment. The present paper describes modelling tools for the optimisation of a glass-melting furnace, a ceramic tunnel kiln, a cement kiln and a baking oven. Significant reduction of energy consumption and low-cost abatement were achieved for these four industrial situations.

Keywords—Energy efficiency, operation and design optimisation, glass industry, ceramic industry, cement industry, baking industry.

INTRODUCTION

Efficient and clean production, in most energy-intensive systems, requires the use of furnaces/ovens/kilns and boilers able to yield products with reduced energy input, raw materials consumption, equipment degradation and liquid, gas, solid and thermal wastes.

High-temperature equipment, namely furnaces, are typically critical in the industrial production chain: mainly due to (i) the large amount of energy utilised; (ii) the relevance of technological processes occurring in that equipment for the final product quality; (iii) the significant part of the production time spent in these units; (iv) the important part of the plant pollution impact that is generated; (v) the involved thermo-physical processes that are complex; (vi) the difficulty to access and measure the phenomena inside these units.

First attempts to calculate the detailed performance of turbulent, reaction processes in furnaces and boilers date to the late 1970s. These models were mainly based on the pioneer research carried out in the late sixties and early seventies at Imperial College [1–3]. Several extensive reviews of mathematical models of furnaces and boilers have been presented in the literature. Jones and Whitelaw [4] presented a review on available models and measurements for turbulent combusting for combustors and furnaces. Smoot [5] reviewed coal-combustion models, also evaluating, classifying and identifying their potential. Viskanta and Mengüç [6] presented a review paper devoted to the radiation heat transfer in combustion systems. This paper reviews the fundamentals of radiation heat transfer and the progress of modelling in combustion systems. More recently, Rhine and Tucker [7] published a book describing a range of experimental and theoretical modelling techniques for gas-fired furnaces and boilers. A review on modelling of industrial furnaces was presented by Meunier [8].

A prediction method for three-dimensional reacting flows with a flux model for the thermal radiation was employed for the prediction of two industrial-type experimental furnaces [9]. A three-dimensional simulation of a glass furnace combustion chamber was presented by Gosman *et al.* [10] in which a more accurate and efficient technique for the handling of the thermal radiation was used (the 'Discrete Transfer' method, [11]). The developed prediction procedure was applied to a cross-fired glass furnace burning natural gas. That work was extended by Carvalho [12] to an oil-fired end-port glass furnace. Improved models for a gas-fired glass furnace have been presented [13–17].

Early works on modelling the three-dimensional flow heat transfer and combustion inside a utility boiler furnace burning pulverised coal were presented by Fiveland and Wessel [18]. Predictions of the three-dimensional flow in a utility boiler furnace burning pulverised coal were presented by Gorner and Zinser [19]. The combustion model was tested for a single enclosed flame and the predictions for three-dimensional furnace flow were validated with velocity data from an isothermal perspex model. More recently, several comprehensive three-dimensional modelling methods for pulverised coal combustion have been published in the literature [20–28]. Brewster *et al.* [29] presented a detailed review of comprehensive models of coal-fired combustors.

As reviewed above, prediction codes capable of computing the three-dimensional characteristics of the aerodynamics, mixing, combustion (single and multiphase), pollutants formation and thermal radiation of industrial furnaces exist. However, the prediction tools have been far from sufficiently employed in the quest for improved equipment design, operation and control. There would seem to be mainly three reasons for this: (i) general prediction techniques are highly sophisticated and their use demands a level of commitment which industry for the most part has so far not been prepared to make; (ii) lack of validation for full-scale industrial situations; (iii) general prediction methods are highly computer-time-consuming. In order to overcome these problems, methodologies should be developed to incorporate the available mathematical models in engineering tools for industrial applications in design, operation and control of furnaces and boilers.

The paper discusses industrial application of modelling tools in the optimisation of high-temperature equipment as a contribution towards the development of model-based knowledge systems capable of producing significant advances in the design and operation of furnaces, kilns and ovens. Four processes were selected, representing a broad range of situations where heat transfer plays a key role in the industrial operation: ceramic and glass-melting furnaces; cement kilns; and baking ovens.

The work has been performed under the framework of the INFLECT study—Improvement of Energy Efficiency in Glass-Melting Furnaces, Cement Kilns and Baking Ovens. The study involved 14 European partners among universities, research laboratories and industrial organisations: Instituto Superior Técnico (P), Imperial College of Science Technology and Medicine (UK). ATZ-EVUS (D), Faculté Polytechnique de Mons (B), Université Libre de Bruxelles (B), Centre for Renewable Energy Sources (GR), TNO Nutrition and Food Research (NL), TNO Institute Environmental and Energy Research (NL), Instituto da Energia (P), Institut National Belge du Verre (B), Adersa (F), TITAN Cement Company (GR), Tuki (H) and Technical University of Kosice (SK).

APPLICATION 1—CERAMIC FURNACE OPTIMISATION

In continuous tunnel kilns for the ceramic industry (Fig. 1), the pieces of ware to be fired are piled on cars which are pushed intermittently through a long refractory-lined tunnel. During its residence in the kiln, the load successively passes through the following zones:

- The preheating zone, where the load is heated by combustion gases, coming from the firing zone and flowing counter-currently to the ware. In this zone, physical and hydration moisture is eliminated and organic matter, if any, is burnt out.
- The firing zone, which is the hottest part of the kiln. It is provided with wall- and/or roof-mounted burners being fired into the free space between adjacent ware settings. In the firing zone, high-temperature chemical transformations take place (e.g. decomposition of carbonates) and the ware is heated to the sintering temperature.

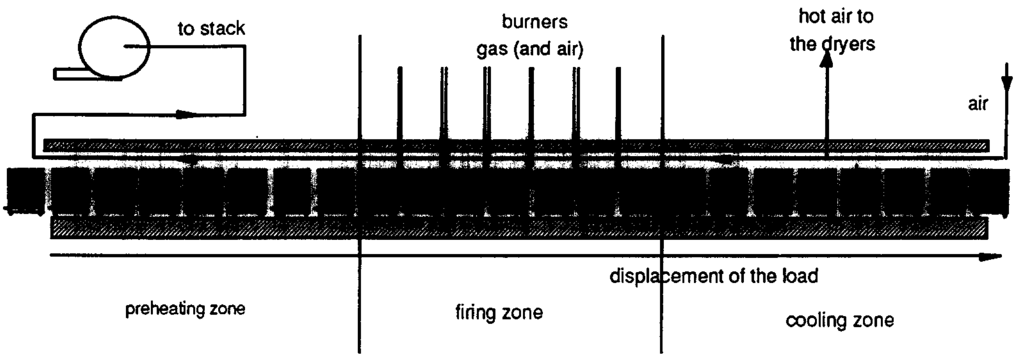

Fig. 1. Tunnel kiln for firing ceramics.

- The cooling zone, where the load is cooled down by preheating ambient air. To provide a precise control of the product temperature, the cooling zone is subdivided in one or more subsections, with cold-air injections and hot-air extraction at different locations along the length of the cooling zone. Parallel flow of the gases with respect to the load can occur in some subsections. The extracted hot air is usually sent to the dryers. Part of it can also be used as combustion air in the firing zone or for other heating purposes in the factory (e.g. space heating).

The large number of control parameters to be set and the fact that a change at a point has an effect on the whole temperature profile made it very difficult to find the optimal set-points of the kiln empirically. Numerical modelling was used to find these optimal operating conditions.

Mathematical modelling techniques have been applied to tunnel kilns for ceramics firing. Two models have been developed:

- A steady-state model, that solved the «direct problem»: it computed the ware and gas temperature profiles along the kiln, for given cooling air, extracted gas, in-leakage air, fuel and combustion air flow rates.
- A dynamic model, that took into account the transient behaviour as well as the control loops of the kiln. This model solved the «inverse problem», using the control structure and the temperature set-points as model input, it computed the injected air, extracted gas, and fuel flow rates required to meet the set-point values, as well as the resulting ware and gas temperature profiles.

Both models were based on a one-dimensional (1-D) approximation of the tunnel: the kiln was considered as a series of unit cells (Fig. 2) and the gas and ware temperature profiles were obtained

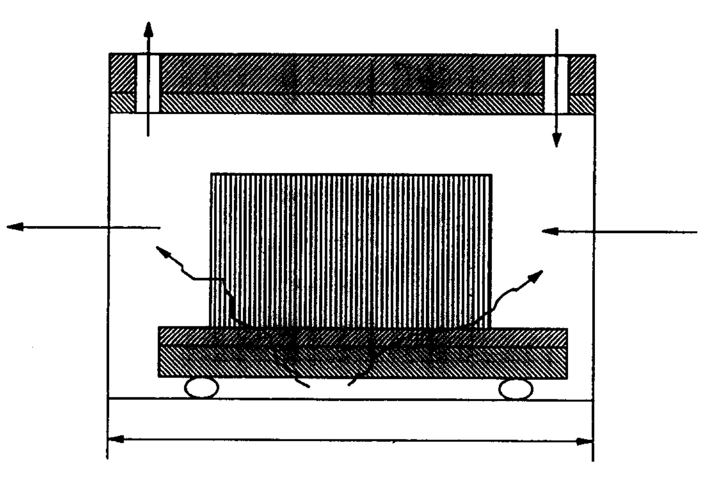

Fig. 2. Modelling of tunnel kilns—unit cell.

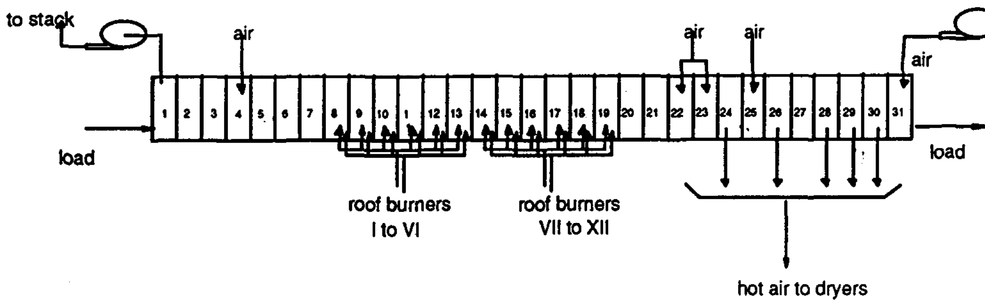

Fig. 3. Firing of heavy clay bricks—kiln flow diagram.

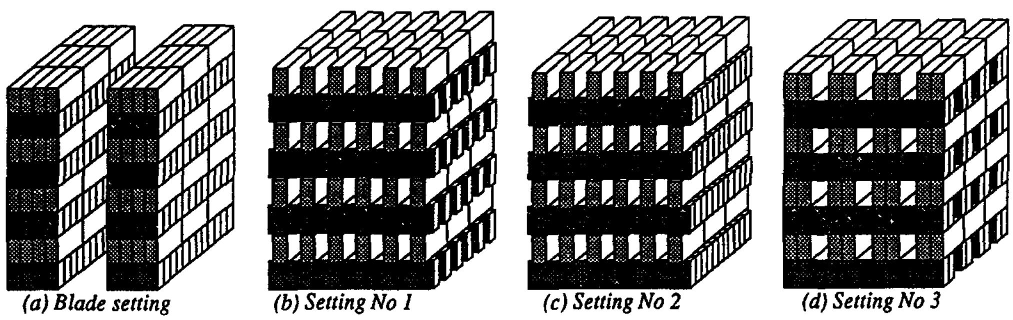

Fig. 4. Typical brick setting geometry.

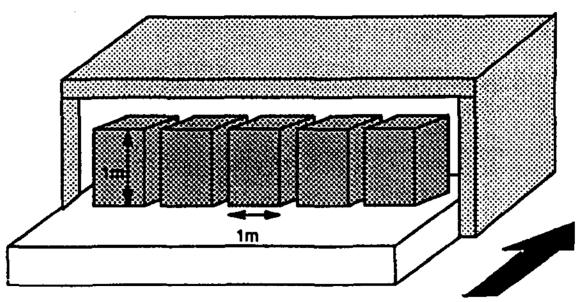

Fig. 5. Firing of bricks—geometry of the brick stacks.

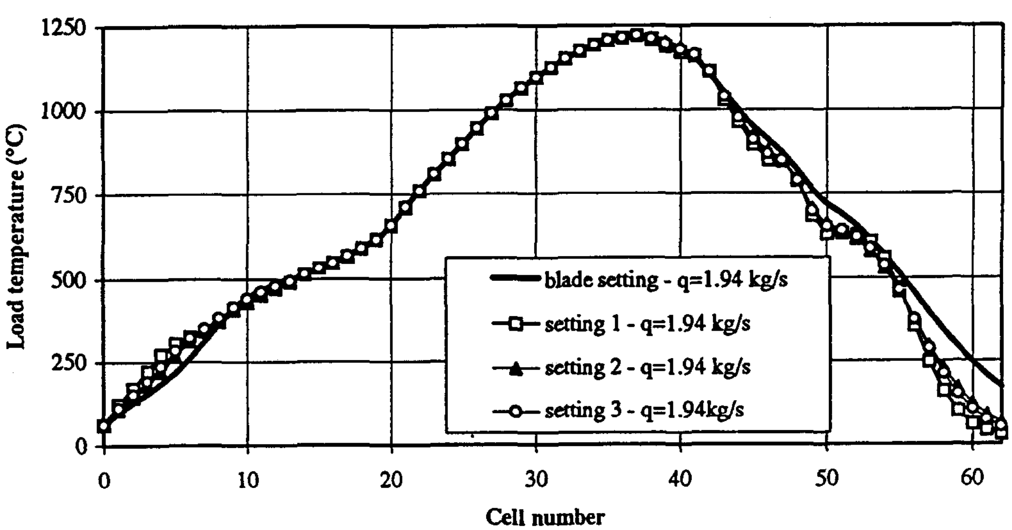

Fig. 6. Firing of bricks—effect of ware setting geometry on load temperature profile (°C).

Table 1. Operating conditions for oxy-fuel and air-fuel alternative furnaces

Model input parameter	Applied value
Load surface	28.0 m^2
Number of oxy-fuel burners	6
Number of air-fuel burners	3
Burners relative location—oxy-fuel	frontal or staggered
Burners relative location—air-fuel	regenerative end-port
Type of fuel	Algerian natural gas
Fuel flow rate—oxy-fuel	0.0397 kg/s
Fuel flow rate—air-fuel	0.0653 kg/s
Oxygen/fuel mass fraction—oxy-fuel	3.2 kgO_2/kg/fuel
Oxygen/fuel mass fraction—air-fuel	19.0 kgO_2/kg/fuel
Oxygen inlet temperature	310 K
Air inlet temperature	1558 K
Fuel inlet temperature	310 K
Outside temperature	298 K
Walls and crown emissivity	0.6
Walls and crown heat transfer rate	0.710 W/(Km^2)

by writing out cell mass and energy balances. Details of these models may be found in Meunier *et al.* [30].

The models have been validated against available measurements obtained on a tunnel kiln for the firing of building bricks in the heavy clay bricks industry. The flow diagram of the kiln is represented in Fig. 3. In all cases, a satisfactory agreement between measured and computed load temperature profiles could be obtained.

The dynamic model has been used to optimise kiln operation. As an example, the effect of the ware setting geometry on the performance of the kiln was analysed. As far as heat transfer is concerned the widely used blade setting is not very efficient: it has a low porosity (about 0.30), and a low specific heat transfer surface (0.00524 m^2/kg ware). The thickness of the ware is large (200 mm) and this leads to significant temperature gradients inside the ware and large firing times. Figure 4 shows brick setting geometries used in the ceramic industry and analysed in the present work.

The porous settings are placed on the tunnel cars in several piles or stacks (Fig. 5), the width of which is limited by the stacking machines (about 1 m). The length and the height of the piles are kept equal to the length and width of the reference blade setting.

For higher porosity settings, the mass of ware on every car is smaller and the pushing time has to be reduced in order to keep a constant production rate. For example, the new value of the pushing time is 45.1 min for setting No. 1 (instead of 90 min in the reference case). The flow rates of the cooling air and of the extracted hot air are maintained identical to the values of the reference case. In order to obtain the same firing curve for the ware, the combustion air and fuel gas flow rates are controlled by using the mean temperature of the ware as set-point temperatures, in the cells where air and fuel are injected.

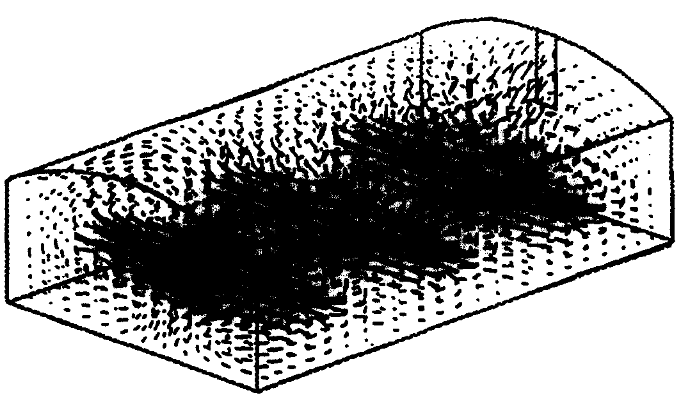

Fig. 7. Predicted flow pattern inside the studied oxy-fuel furnace (marker particles followed during 0.2 s).

Table 2. Comparison of oxy-fuel and air-fuel glass-melting furnaces performance

Type of furnace	Specific NO_x emission ($kgNO_x/TJ$)	Mean efficiency (W_{fuel}/W_{load})
oxy-fuel	5.82 (ref. case)	0.56 (ref. case)
air-fuel	300	0.34

Table 3. Influence of combustion chamber aspect ratio on the furnace performance

Aspect ratio (width/length)	Specific NO_x emission ($kgNO_x/TJ$)	Efficiency (W_{fuel}/W_{Load})
1.00	5.61	0.57
1.16	5.82	0.56
1.32	7.21	0.54

Table 4. Influence of combustion chamber height on the furnace performance

Chamber height (m)	Specific NO_x emission ($kgNO_x/TJ$)	Efficiency (W_{fuel}/W_{load})
1.00	5.61	0.57
1.16	5.82	0.56
1.32	7.21	0.54

Table 5. Influence of distance between burners and melt on the furnace performance

Burner height (m)	Specific NO_x emission ($kgNO_x/TJ$)	Efficiency (W_{fuel}/W_{load})
0.23	6.69	0.57
0.37	5.82	0.56
0.51	5.69	0.54

Table 6. Influence of the burner arrangement on the furnace performance

Burner arrangement	Specific NO_x emission ($kgNO_x/TJ$)	Efficiency (W_{fuel}/W_{Load})
Staggered	3.89	0.57
Frontal	5.82	0.56

The effect of using a higher porosity setting has been simulated with the dynamic model. For the different setting geometry, the gas-side heat transfer coefficient has been calculated by using an experimental correlation for blade settings [30].

The ware temperature profiles computed for the four ware setting geometry are represented in Fig. 6. The differences can be explained as follows:

- The smaller thickness of the ware in porous settings gives faster chemical reactions and the ware temperature is higher than in the reference case in the first six cells.
- In the cooling zone, the larger heat transfer area of the porous settings leads to faster cooling and lower temperatures of the ware.

The computed values can be explained as follows:

- Gas extraction: if the porosity of the load increases, cooling is more efficient, i.e. more heat is extracted from the ware, and the extraction temperatures are higher.
- Flue gases–stack: for low porosity settings, high gas temperatures are required in preheating zone to keep the same firing curve of the load, hence the sensible energy loss in the flue gases increases.
- Heat storage in the load: cooling being more intensive for porous settings, this energy loss decreases when the porosity increases.
- Heat storage in the car: for porous settings, the pushing time is shorter to keep the same production rate. The mass «flow rate» associated with each car getting in the kiln will thus increase. Moreover, in the cooling section, the gas temperatures are higher. Hence, the energy stored in the cars at the kiln outlet end is higher for more porous settings.
- Heat losses through the walls and the cars: as the ambient temperature and the wall heat loss coefficients are assumed to be constant, the determinant factor will be the temperature of the gases. The major part of the heat losses occurs in the firing section. In this zone, the gas temperatures are higher for low porous settings and, hence, the heat losses increase.

APPLICATION 2—MODELLING ASSISTED DESIGN OF AN OXY-FUEL GLASS FURNACE

The cost of oxygen has to be balanced by the gain in energy efficiency of the oxy-fuel furnace. Therefore, the optimisation of the heat transfer process is a design priority in this kind of furnaces. The industrial implementation of 100% oxy-fuel furnaces requires the use of sophisticated engineering design tools able to handle the particular features of these furnaces and the complexity of the involved phenomena.

A comprehensive 3-D model able to simulate turbulent fluid flow, heat transfer, combustion and pollutants formation has been developed to assist oxy-fuel furnace design. This model is based on the solution of conservation equations 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 thermal fluid behaviour was predicted by solving the governing partial differential equations set in its steady-state time-averaged form using the finite difference/finite volume method. The domain is represented by a numerical non-orthogonal non-staggered grid. The turbulent behaviour of the flow inside the combustion chamber has been modelled using the well-established k–ε model. The combustion model is based on the ideal fast single-step reaction between the fuel and the oxidant. A statistical approach was followed to handle the turbulent fluctuations. A probability density function was defined based on the knowledge of the mixture fraction and its variance, g, for which a transport equation is solved. This probability density function is applied to calculate the time-averaged value of the following variables: chemical species concentration; soot formation/oxidation rates; radiative properties of the gas media; thermo-physical properties as temperature, density and specific heat. In the present model, a transport equation for the soot mass concentration was solved which includes as source/sink terms the formation/oxidation rates. For the NO_x formation–oxidation–transport process, the Zeldovich mechanism assuming local chemical equilibrium was adopted. A transport equation for the thermal NO mass fraction was solved. The 'discrete transfer' radiation prediction procedure was applied to model the radiative heat transfer process inside the combustion chamber enclosure.

The three-dimensional model was applied to the prediction of the behaviour of oxy-fuel and air-fuel glass-melting furnaces. The main working conditions are described in Table 1. Figure 7 shows the three-dimensional velocity field for the oxy-fuel case. The flow inside the combustion chamber presents a very complex pattern. The main features of this flow can only be calculated by a completely 3-D model using a curvilinear grid. Details of this model may be found in Carvalho and Nogueira [31].

Table 1 presents the working conditions of oxy-fuel and air-fuel cases with the same pull rate. In Table 2 the performance of both systems is compared. In Tables 3–6 the performance of the oxy-fuel case is compared for the different design parameters from the point of view of thermal

Table 7. Test cases—TITAN cement kiln

Runs	Parameter to be modified	Comparison with the base case
1.	Base case	
2.	Coal:petcoke = 70:30	(80:20 in base case)
3.	Coal:petcoke = 75:25	(80:20 in base case)
4.	Coal:petcoke = 85:15	(80:20 in base case)
5.	Coal: pet coke = 90:10	(80:20 in base case)
6.	Ash in coal = 10%	(13.5% in base case)
7.	Ash in coal = 12%	(13.5% in base case)
8.	Ash in coal = 14%	(13.5% in base case)
9.	Ash in coal = 20%	(13.5% in base case)
10.	Excess air (secondary air) = 35%	(30% in base case)
11.	Excess air (secondary air) = 40%	(30% in base case)
12.	Excess air (secondary air) = 25%	(30% in base case)
13.	Excess air (secondary air) = 20%	(30% in base case)
14.	H_2O in feeding fuel = 1.0%	(1.6% in base case)
15.	H_2O in feeding fuel = 1.2%	(1.6% in base case)
16.	H_2O in feeding fuel = 1.4%	(1.6% in base case)
17.	H_2O in feeding fuel = 1.8%	(1.6% in base case)
18.	H_2O in feeding fuel = 2.0%	(1.6% in base case)
19.	Swirl angle = 45	(56 in base case)
20.	Swirl angle = 50	(56 in base case)
21.	Swirl angle = 60	(56 in base case)
22.	Swirl angle = 65	(56 in base case)

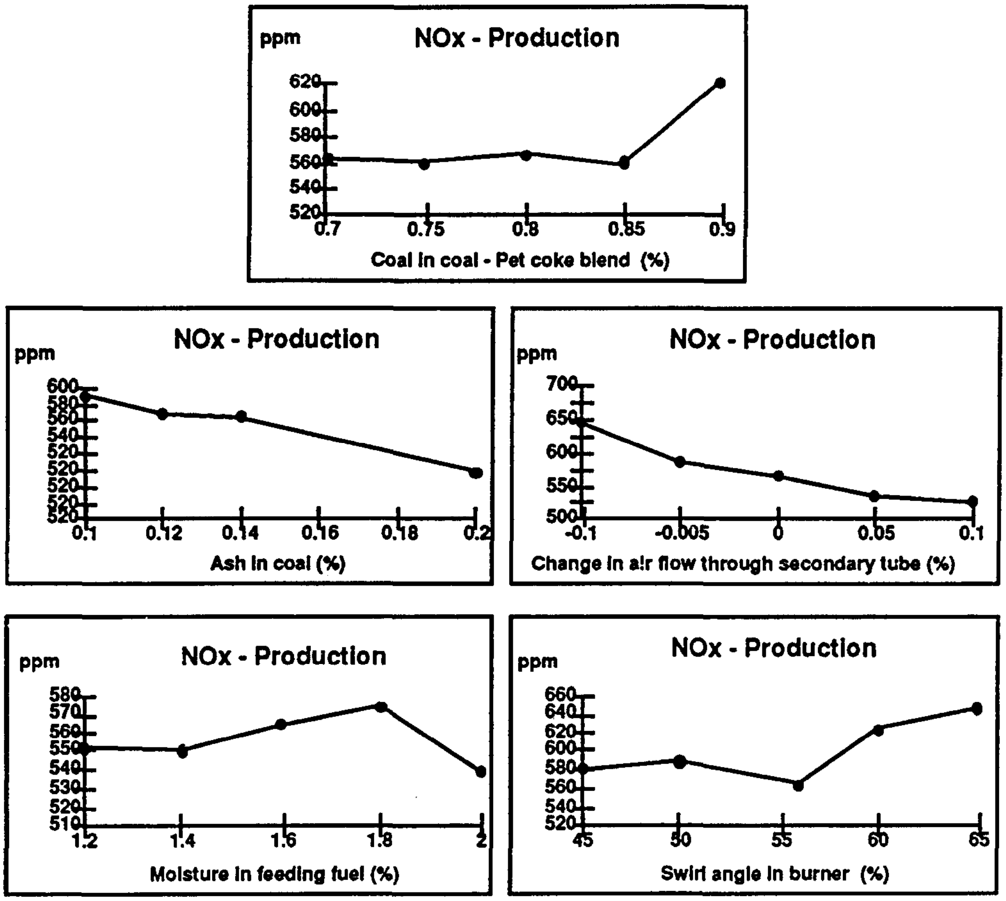

Fig. 8. NO_x production in a cement kiln.

efficiency and combustion-generated pollutants. From the comparison shown in Table 2, the following effect may be observed: the NO_x emission from 100% oxy-fuel melting is strongly reduced when compared with a conventional air-fuel melting furnace and the heat transfer efficiency is strongly improved for 100% oxy-fuel melting furnaces. The design of 100% oxy-fuel furnaces is clearly a multi-variable problem—a 100% oxy-fuel furnace presents a higher degree of freedom as far as design parameters are concerned.

APPLICATION 3—CEMENT KILNS OPTIMISATION

The reduction of pollutant emissions generated from cement plants and the efficient use of energy can be realised if the flow as well as the heat transfer characteristics prevailing inside the rotary cement kiln are known in advance, so that effective control is realised. However, the cement production is a process that cannot be interrupted but requires continuous monitoring and control. These tasks may be accomplished on a low-cost basis, using mathematical models for numerically simulating the flow and temperature fields inside the rotary cement kiln.

A mathematical model incorporating a set of advanced mathematical models was developed and used for simulating the performance of the rotary kiln of the cement factory TITAN, under various operating conditions. Details of the code may be found in Koras and Tzitidis [32]. The used code handles the combustion of gas and/or coal in three-dimensional domain. The simulation of the aerodynamics as well as the combustion and radiation processes are embodied in the solution procedure via the appropriate conservation equations. The solved group of equations is as follows: the gas phase equations; the particulate phase equations; the radiation model and the combustion model. The gas phase equations include the continuity equation as well as the transport equations of momentum and scalar quantities. The turbulence is modelled using the k–ε turbulence model.

This work is concerned with the simulation of the aerodynamics, combustion and pollutants formation in a cement kiln fired with pulverised coal installed at a TITAN cement plant. In order to study the optimised operating conditions for a cement kiln, the modelling procedure described above was used. A number of runs were performed for different operating conditions which include (a) various fuel compositions with different concentrations of moisture, ash and petcoke; (b) various quantities of excess air and (c) various values of swirl angle. The test runs are given in Table 7.

The influence of these operating conditions in the NO_x production is presented in Fig. 8. Although TITAN runs the cement rotary kiln on a ratio of coal rate to petcoke rate equal to 80:20, sometimes mainly due to variations of the coal or the petcoke prices this ratio is modified. Test cases 2–5 deal with this situation in which the ratio of the coal rate to the pet coke rate is varied. The total NO_x production at the exit of the kiln is rather constant (about 560 ppm) for the base case and the test cases 2–4. In test case 5 (90:10) the total NO_x production at the exit is higher (about 615 ppm) due to higher nitrogen concentration in the coal than in the petcoke.

The concentration of the ash in the feeding fuel varies due to the composition of the coal. Also, sometimes when the produced clinker is dusty, the kiln operators use fuel rich in ash in order to produce coarser clinker. The test cases 6–9 show the variation of NO_x distributions with the concentration of ash in the coal. The NO_x production at the exit gets lower as the ash concentration in the coal gets higher, since the temperature distribution is lower.

The quantity of the total air, entered in the kiln, is adjusted to fit the quantity of the produced clinker. The lower the clinker production, the higher the entered air. This quantity of the air is adjusted by means of the regulation of the quantity of the air entered through the secondary tube. In such a case both the temperature and the NO_x distributions are strongly affected.

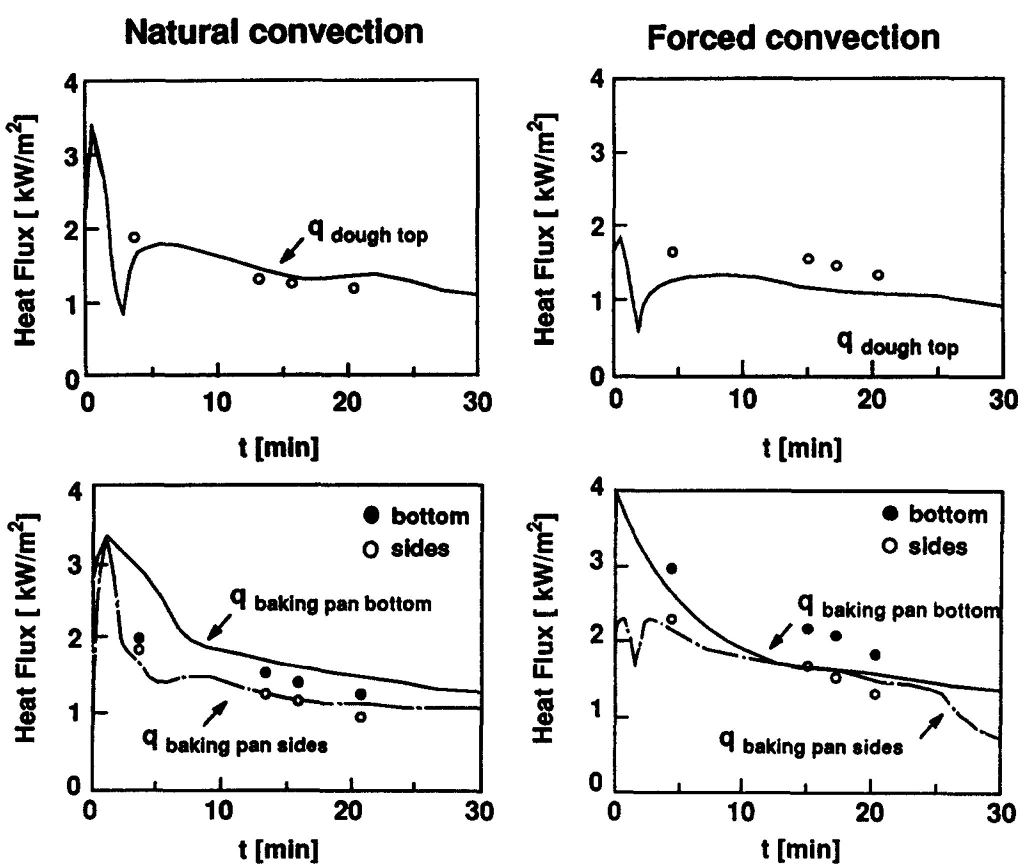

Fig. 9. Total heat fluxes to the bread.

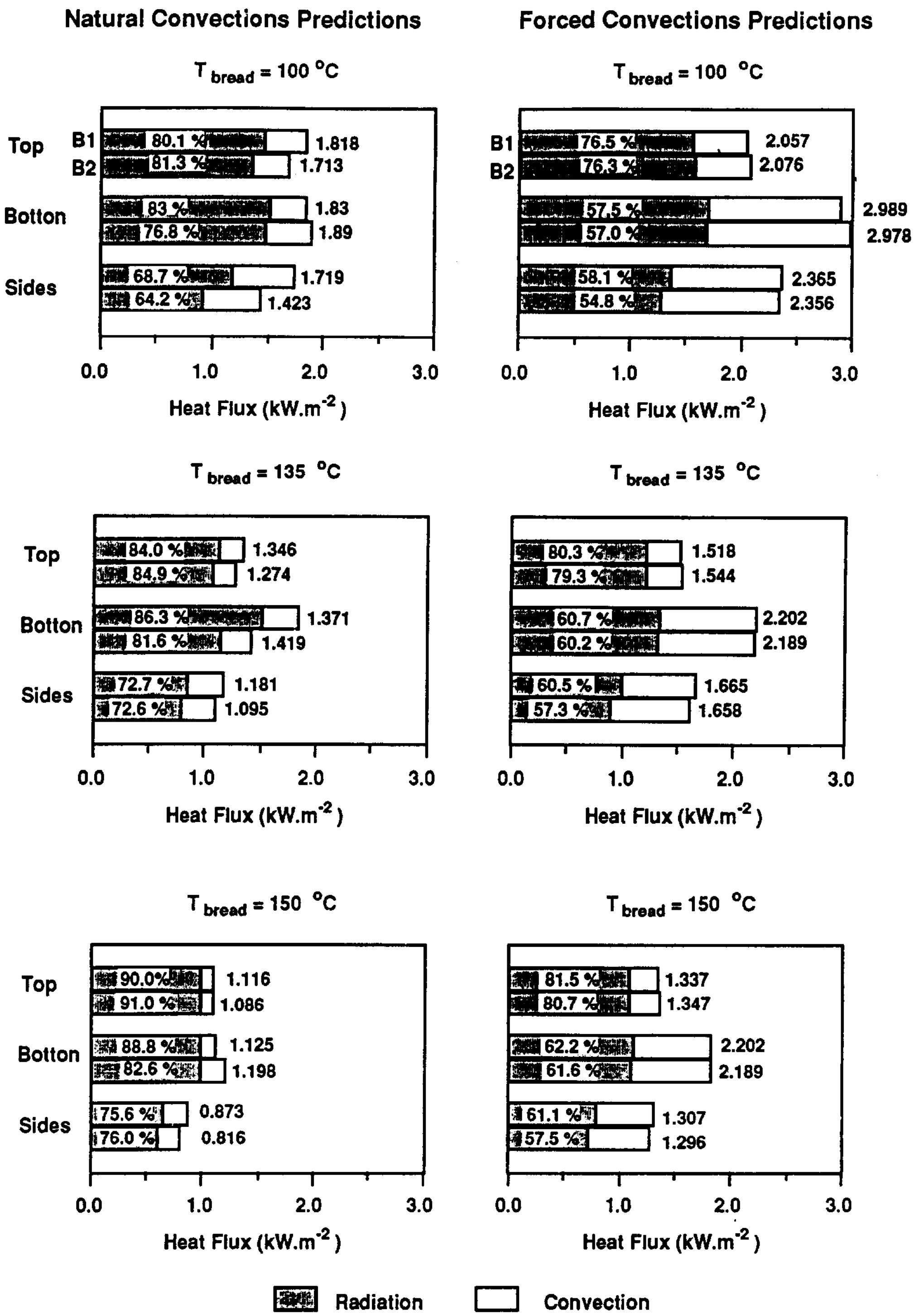

Fig. 10. Heat fluxes to the bread.

This effect is shown on one hand in the test cases 10 and 11 in which the above air rate is increased by 5 and 10%, respectively, and on the other hand in the test cases 12 and 13, in which the air rate is decreased by 5 and 10%, respectively. The increase of air rate causes reduction of the temperature level and therefore an increase of the fuel consumption in order to keep constant the heat transfer rate to the load. This is the primary cause a decrease in NO_x formation.

The fuel drying process depends on the temperature of the flue gases, which is not always constant. This means that the composition of the feeding fuel in moisture varies. The test cases 14–18 deal with the moisture variation in the feeding fuel. It is worth noting differences are encountered for the NO_x distributions. The increase of the feeding fuel moisture results in an increase of the hydrogen and therefore of the HCN and fuel-NO. However, if the moisture concentration is higher than 1.8%, the local temperature at a distance of about 40 m away from the burner exit is reduced and the fuel-NO formation is prevented.

The relative position of the burner tubes sometimes changes, therefore causing a change of the swirl angle. The test cases 19–22 show the dependence of the NO_x distributions on the variation of the swirl angle. The swirl angle of 56° (base case) results in a lower NO_x production.

Although uncertainties exist in the modelling of both the NO_x and the aerodynamics/combustion, this work has shown that realistic NO_x predictions are obtainable even in the near burner region.

APPLICATION 4—BAKING OVENS OPTIMISATION

For many years, the design and control of baking ovens fully relied on the use of empirical models, correlating overall performance with simple global parameters, such as chamber volume, temperature of the heating elements, inlet air conditions, etc. A much more powerful approach is that based on the numerical solutions of the averaged forms of the partial differential conservation equations for momentum, mass, chemical species and energy. A better knowledge of the physical phenomena occurring during the baking process may significantly contribute to the improvement of the design and control of a wide range of baking industry equipment.

Mathematical models for the baking chamber for the dough and for the crust have been developed. These models take into account the heat and mass transfer phenomena occurring inside an electrically heated baking oven in and to the dough, during the baking process. Heat transfer to the dough by free or forced convection and radiation can be predicted, as well as the atmosphere quality inside the baking chamber. For the heat transport inside the dough, heat diffusion and evaporation–condensation of water are considered in addition to mass, volume and physical structure evolution during the process. A specific model was developed for the prediction of the crust thickness as a function of operating conditions. Details of the model may be found in Carvalho and Martins [33].

The present work was applied for the prediction of the mean flow and heat transfer to the bread in a laboratory baking oven. Experimental work has been performed in this installation [34], where measured heat fluxes to the bread are presented. Six loaves of bread were baked simultaneously and due to the symmetry of the geometry only a quarter of the whole chamber was considered.

Total heat fluxes to the bread are presented in Fig. 9. Lines refer to experimental measurements and dots represent numerical predictions. The differences between experimental measurements and numerical predictions are smaller than 15%. For the forced convection case, total fluxes to the bottom and top surfaces of the bread are slightly overestimated. This is due to the need to use a simplified shape for the bread and the heating elements.

Based on the developed mathematical modelling tools, an example of the optimisation of the design and operation of baking ovens was performed.

The influence of baking operating conditions on the heat flux to the bread were investigated. Two conditions were considered: free convection operation and forced convection with $v_{air} = 0.6$ m/s. For each one of the considered cases, the total heat flux for the bottom, top and side surfaces of the bread, as well as its convection and radiation components, are calculated for a loaf at the center of the baking chamber (B1) and a loaf near one of the walls (see Fig. 10).

It was confirmed that radiation is the most important heat transfer mode for the baking process. As expected, the importance of radiation heat transfer increases when only natural convection is considered. Forced convection results show that with a uniform temperature distribution on the heating elements, total heat fluxes to the different bread surfaces are not well distributed. Actually, differences of almost 50% were achieved between bottom and top heat fluxes, which is not a good working condition for an industrial baking oven. This is an interesting result which confirms that some improvements could be done to enhance the performance of this baking chamber.

Actually an optimised temperature profile on the heating elements can be obtained in order to improve the heat flux distribution on the charge, however, this optimised temperature distribution will also depend on the bread distribution. A more effective approach could be used to define control strategies based on the following up of the heat flux instead of the more conventional strategies which are based on temperature measurements.

CONCLUSIONS

The utilisation of dedicated modelling tools for the optimisation of a variety of thermal equipment for high- medium- and low-temperature heat transfer processes has been presented. The equipment considered (ceramic and glass-melting furnaces, cement kilns and baking ovens) covered a broad range of situations where heat transfer plays a key role in the industrial operation. The approach consisted of the combination of modelling tools with advanced extensive on-line measurements for the development of optimisation procedures to be used in design and operation for energy saving and pollution abatement in industry. This was successfully accomplished in each one of the reported industrial cases. The authors believe that these achievements are a contribution for the pollution abatement strategies for industries that are intensive users of energy.

Acknowledgements—The present work was financed by the JOULE (R and D) programme under contract project JOU2-CT92-0107 entitled 'Improvement of Energy Efficiency in Glass-Melting Furnaces, Cement Kilns and Baking Ovens' (JOULE Programme, DG XII). The authors would also like to acknowledge the helpful discussions and suggestions of Dr P. Pilavachi. A very special acknowledgement is due to Prof. Hector Meunier, Prof. Frederik Lockwood, Dipl.-Ing. G. Dimaczek, Prof. Samuel Wajk, Dr Andreas Koras, Dr Ubo de Vries, Ir A. van Duuren, Eng. Nelson Martins, Ir Michel Brichard, Dr J. Papon, Dr Dimitri Hadjicostantis, Dr T. Kapros and Prof. V. Vitek for their valuable contribution to the preparation of this paper.

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