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Mathematical modelling and numerical study of a Tunisian tunnel kiln used in brick industry

Nahed Soussi#1, Wassim Kriaa#2, Hatem Mhiri#3, Philippe BOURNOT *4

#UTTPI, National Engineering School of Monastir, Monastir, (Tunisia)
1nahed.soussi@yahoo.fr
2kriaawass@yahoo.fr
3hatem.mhiri@enim.rnu.tn

**IUSTI, UMR CNRS 6595, 5 Rue Enrico Fermi, Technopôle de Château-Gombert, 13013 Marseille, France*
4bournot@univmed.fr

***Abstract*— This work presents a numerical study of a tunnel kiln used in the brick manufacturing process. In a first step, we describe the studied tunnel kiln. In a second step, the mass, energy and species balance equations are modelled and solved using the finite difference method with a numerical code written in a programming language SCILAB in order to predict the distribution of air and brick temperature inside the kiln. The numerical evolution of air temperature was compared with plant data and good agreement between the results was reported.**

***Keywords*— tunnel kiln, numerical resolution, brick manufacturing, finite difference method, SCILAB**

I. INTRODUCTION

Several studies of tunnel kilns have been elaborated in the literature for ceramic [1] and brick [2-4] industries. The aim of these studies is to understand and improve thermal performance of the tunnel kiln in order to minimize energy consumption of this equipment [5].

Basing on heat and mass transfer between gas and the products circulating inside the tunnel kiln, mathematical modelling has been established [2-4].

A review of the literature indicates that not only theoretical works [6] are performed but also numerical and experimental studies of the tunnel kiln [7-9].

In this work, we modelled numerically the heat and mass transfer in a tunnel kiln. A numerical code was then elaborated in order to give a tool for further analysis of tunnel kilns.

II. DESCRIPTION OF THE TUNNEL KILN

The studied tunnel kiln is composed firstly of the pre-kiln zone which is heated with the air recovered from the cooling zone. This first zone is directly related to three other zones named: preheating, firing and cooling zones as shown in Fig.1.

The product being manufacturing during this work is the B12 type bricks which are moving in opposite direction with air inside the kiln. The bricks entering with a moisture content of about 4% are thermally prepared in the pre-kiln and preheating zones before reaching the firing zone containing gas burners which provide the sintering heat of bricks. Each 10 burners are associated in a group provided by natural gas and combustion air at ambient temperature (T_{amb}). Only 9 burner groups are functional in the present case.

In the last zone, bricks are cooled in two stages. In the fast cooling, ambient air is injected into the kiln. The final cooling is ensured by means of injection of cool air and extraction of hot air. The extracted air will be then recovered in the pre-kiln and the dryer. A part of air in the cooling zone is recovered to the firing zone.

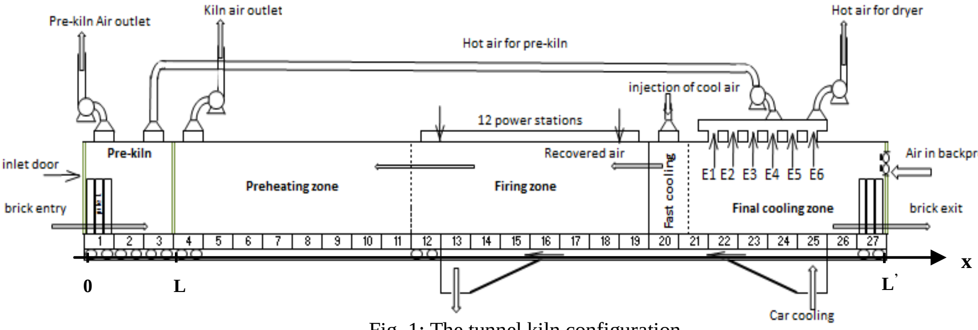

Fig. 1: The tunnel kiln configuration

For this case, 27 cars can be placed in the kiln and are pushed slowly through the kiln length, with approximately 10 min for each push.

III. THE NUMERICAL STUDY

The plant data collected from the real tunnel kiln are used for the numerical resolution of equations governing heat and mass transfer inside the kiln between bricks, air and walls.

Taking account of some simplifying assumptions, the equations' model, for each kiln zone, are performed. A numerical code developed with the SCILAB program allows the resolution of the set equations associated to their boundary and injection conditions. The following assumptions were validated in Ref. [2-4].

A. Assumptions

- Steady state operation
- The flow circulating inside the kiln is air
- Counter current flow of hot air and brick loads
- Unidirectional problem (x)
- The thermo-physical proprieties of air are varying with temperature [10]
- Heat is transferred between bricks and hot air flow by convection.
- The radiative heat transfer occurs between exterior surfaces of brick loads and kiln interior walls.

B. Mass and Energy balance for air

1) In the pre-kiln and preheating zones

- Mass balance:

$$\dot{m}_a(x) = \dot{m}_a(x+\Delta x) + \dot{m}_b(x).(w(x) - w(x+\Delta x)) \qquad (1)$$

Where $\dot{m}_a$ and $\dot{m}_b$ represent the air and brick mass flux, respectively and w is the moisture content in the brick body. The last term of the equation (1) represent the water vapor released from bricks for the differential element Δx.

The evaporation of water from bricks is governed by the moisture diffusion equation mentioned by E. Mancuhan et al [2].

- Energy balance:

$$\left\{\begin{array}{c}\text{Heat}\\ \text{lost by}\\ \text{air}\end{array}\right\} = \left\{\begin{array}{c}\text{Heat transfer}\\ \text{by convection}\\ \text{between}\\ \text{bricks and air}\end{array}\right\} + \left\{\begin{array}{c}\text{Heat transfer}\\ \text{by convection}\\ \text{between walls}\\ \text{and air}\end{array}\right\} + \left\{\begin{array}{c}\text{Heat lost due to}\\ \text{evaporation and}\\ \text{taken by the}\\ \text{water vapor}\end{array}\right\}$$

$$-\frac{d(\dot{m}_a.c_{pa}.T_a)}{dx} = h.S_b(T_a - T_b) + h.S_w(T_a - T_w) + (c_{pH_2O}.(T_b - T_a) + L_{vH_2O}).\dot{m}_b.\frac{dw}{dx} \qquad (2)$$

Where:

c_{pa} and c_{pH_2O} are the heat capacity of air and water vapor.

S_b and S_w are the heat transfer area of bricks and walls with air.

T_a , T_b and T_w are the temperature of air, bricks and kiln interior walls.

L_{vH_2O} is the latent heat of vaporization.

h is the convective heat transfer coefficient.

2) In the firing zone

- Mass balance

$$\dot{m}_a(x) = \dot{m}_a(x+\Delta x) + \dot{m}_{GB}(x) \qquad (3)$$

$\dot{m}_{GB}$ is the sum of the natural gas ($\dot{m}_{a_{comb}}$) and combustion air ($\dot{m}_{GN}$) mass flux fed by each group of burner given by this expression:

$$\dot{m}_{GB} = C_{ft}.(\dot{m}_{GN} + \dot{m}_{a_{comb}}) \qquad (4)$$

Energy balance

$$\left\{\begin{array}{c}\text{Heat lost}\\ \text{or gained}\\ \text{by air}\end{array}\right\} = \left\{\begin{array}{c}\text{Heat transfer}\\ \text{by convection}\\ \text{between}\\ \text{bricks and air}\end{array}\right\} + \left\{\begin{array}{c}\text{Heat transfer}\\ \text{by convection}\\ \text{between walls}\\ \text{and air}\end{array}\right\} + \left\{\begin{array}{c}\text{Heat released}\\ \text{by}\\ \text{combustion of}\\ \text{natural gas}\end{array}\right\}$$

$$-\frac{d(\dot{m}_a.c_{pa}.T_a)}{dx} = h.S_b(T_b - T_a) + h.S_w(T_w - T_a) + Q_{comb} \qquad (5)$$

Q_{comb} is the heat released by the combustion of the natural gas given by this expression at burner locations:

$$Q_{comb} = C_{ft}.\dot{m}_{GN}.PCI + C_{ft}.\dot{m}_{a_{comb}}.c_{pa}.T_{amb} \qquad (6)$$

PCI is the heating value of natural gas.

3) In the cooling zone

- Mass balance

$$\dot{m}_a(x) = \dot{m}_a(x+\Delta x) + \dot{m}_a^{i,e} \qquad (7)$$

$\dot{m}_a^{i,e}$ is the mass flux of air injected or extracted from the cooling zone.

- Energy balance

$$\left\{\begin{array}{c}\text{Heat}\\ \text{gained}\\ \text{by air}\end{array}\right\} = \left\{\begin{array}{c}\text{Heat transfer}\\ \text{by convection}\\ \text{between}\\ \text{bricks and air}\end{array}\right\} + \left\{\begin{array}{c}\text{Heat transfer}\\ \text{by convection}\\ \text{between walls}\\ \text{and air}\end{array}\right\} + \left\{\begin{array}{c}\text{Heat due to}\\ \text{extraction or}\\ \text{injection of air}\\ \text{inside the kiln}\end{array}\right\}$$

$$-\frac{d(\dot{m}_a.c_{pa}.T_a)}{dx} = h.S_b(T_b - T_a) + h.S_w(T_w - T_a) + Q_a^{i,e} \qquad (8)$$

$Q_a^{i,e}$ is equal to: For extraction: $Q_a^e = \dot{m}_{a,e}.c_{pa}.T_a$

For injection: $Q_a^i = \dot{m}_{a,i}.c_{pa}.T_a$

$\dot{m}_{a,e}$ and $\dot{m}_{a,i}$ are respectively, the extracted and injected mass flux.

C. Mass and energy balance for bricks

- Mass balance

When bricks still contain moisture, brick mass balance is given by this equation:

$$\dot{m}_b(x+\Delta x) = \dot{m}_b(x) - \dot{m}_b(x).(w(x) - w(x+\Delta x)) \qquad (9)$$

When all moisture content is evaporated Eq. (9) becomes:

$$\dot{m}_b(x+\Delta x) = \dot{m}_b(x) \qquad (10)$$

- Energy balance

$$\left\{\begin{array}{c}\text{Heat}\\ \text{gained}\\ \text{by}\\ \text{bricks}\end{array}\right\} = \left\{\begin{array}{c}\text{Heat transfer}\\ \text{by convection}\\ \text{between}\\ \text{bricks and air}\end{array}\right\} + \left\{\begin{array}{c}\text{Heat transferred}\\ \text{to kiln interior}\\ \text{walls by}\\ \text{radiation}\end{array}\right\}$$

$$\dot{m}_b.c_{pb}\frac{d(T_b)}{dx} = h.S_b(T_a - T_b) - Q_r \qquad (11)$$

$$Q_r = \frac{\sigma}{\frac{1}{\varepsilon_b} + \frac{S_{eb}}{S_w}.(\frac{1}{\varepsilon_w} - 1)} S_{eb}.(T_b^4 - T_w^4) \qquad (12)$$

ε_b and ε_w are the emissivity of bricks and walls.

D. Heat loss

The heat lost through kiln walls to the environment is given as follows:

$$K.S_w.(T_w - T_{amb}) = h.S_w(T_a - T_w) + Q_r \qquad (13)$$

K is the global heat transfer coefficient.

E. Numerical method

The equations (1-13) associated to their injection and boundary conditions were discretized with the finite difference method.

F. Boundary and injection conditions

The boundary and injection conditions are given as follows:

$$T_b(0) = 30°C \qquad (14)$$

$$w(0) = 0.04\,kg_{H_2O}/kg_{bricks} \qquad (15)$$

$$T_a(L) = 160°C \qquad (16)$$

$$T_b(L) = 53°C \qquad (17)$$

$$w(L) = 0.028\,kg_{H_2O}/kg_{bricks} \qquad (18)$$

$$T_a(L') = 30°C \qquad (19)$$

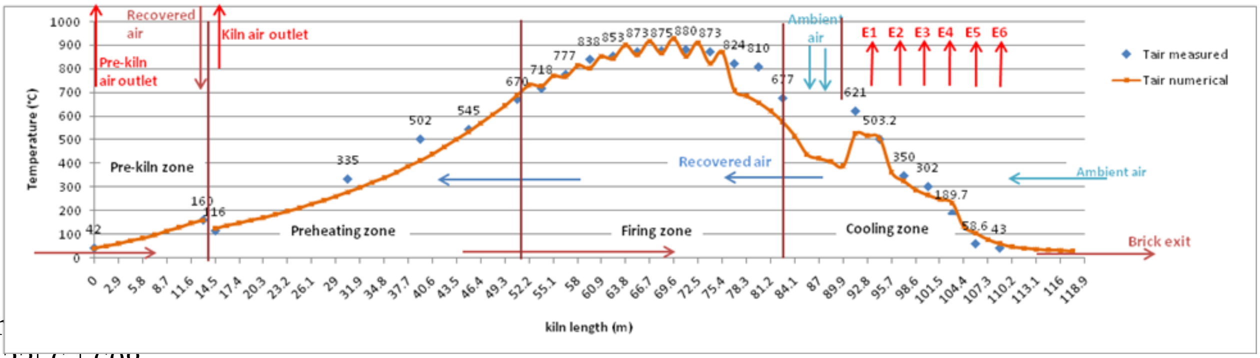

Fig. 2: The evolution of measured and numerical air temperature along the kiln length

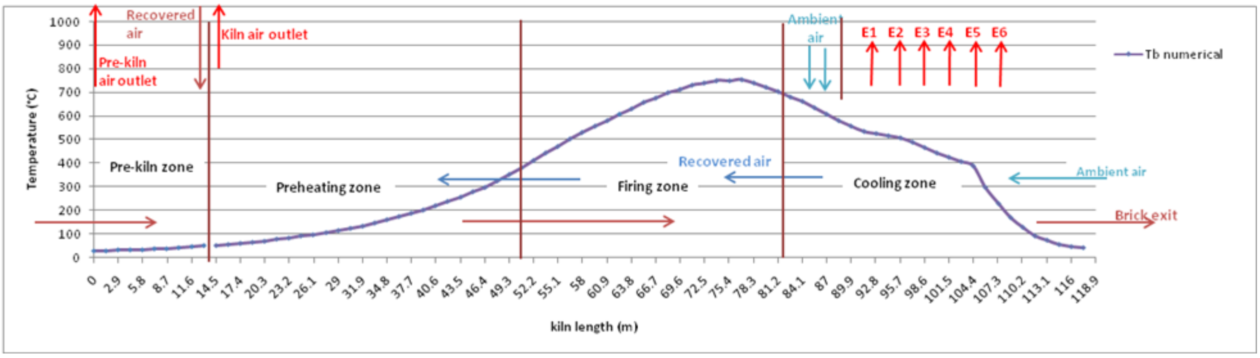

Fig. 3: The evolution of numerical brick temperature along the kiln length

IV. RESULTS AND DISCUSSION

The numerical distribution of air temperature and measured air temperature profile inside the kiln are plotted in Fig. 2. This result shows that numerical air temperature has the same profile of measured temperature. Some gap between the curves is noted due to experimental errors.

The numerical resolution allows obtaining the brick temperature distribution inside the kiln presented in Fig. 3. At their entry in the kiln, the temperature of bricks increases by contact with hot air circulating in counter-current. The brick temperature increases up to its highest value in the firing zone containing gas burners. In the last zone, bricks leaving the firing zone give their heat to air injected at ambient temperature. In fact, brick temperature decrease to 41°C. This value is very closer to brick temperature measured experimentally of about 45°C.

From these results, it is reported that the elaborated numerical code represents an interesting tool to predict temperature evolution inside the kiln.

V. CONCLUSIONS

In the present work, we have established a mathematical modelling of heat and mass transfer inside a Tunisian tunnel kiln for the brick industry in order to determine the temperature evolution along the kiln length.

The following conclusions may be taken from this study

- The validity of the numerical method was confirmed by the comparison between numerical and experimental results of air temperature distribution inside the kiln.
- The present mathematical modelling and numerical method can serve as an interesting tool for detailed analysis of tunnel kilns.

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