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MATHEMATICAL MODELING AND SIMULATION OF THE PREHEATING ZONE OF A TUNNEL KILN

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Abstract: Simulation of drying bricks in the preheating zone of a tunnel kiln was done by developing a one dimensional model describing the gas flow, heat transfer between gas and bricks and evaporation of bound water. Simulation results were compared to the previously measured plant data. Ambient air was fed into the preheating zone using two different profiles and vent locations to achieve desired gas temperature for high quality bricks. Temperature profiles obtained using both approaches agreed well with measurements. When no ambient air is fed, gas temperature was shown to reach 350°C at the preheating zone entrance which is not desired for the best quality product. Bound water in the bricks, which should be evaporated completely, approaches zero while reaching the 70% of the dimensionless length of the preheating zone.
Keywords: Tunnel kiln, Preheating zone simulation, Evaporation of bound water, Gas temperature profile.

TÜNEL FIRIN ÖN ISITMA BÖLGESİNİN MATEMATİKSEL MODELİ VE SİMÜLASYONU

Özet: Bu çalışmada tünel fırın ön ısıtma bölgesi simülasyonu için gaz akışı, tuğla-hava arasında gerçekleşen ısı transferi, tuğladaki bağlı suyun buharlaşmasını tanımlayan tek boyutlu model denklemleri çıkarıldı. Model denklemleri çözülerek proses değişkenlerinin (fırın iç gazının debi, sıcaklık ve nemi, tuğla yüzey sıcaklığı ve tuğlada ki bağlı su kesri) ön ısıtma bölgesi boyunca değişimi bulundu. Yüksek kaliteli tuğla üretiminde gerekli olan gaz sıcaklık profilini elde edebilmek için besleme nokta ve debileri farklı iki çevre havası profili önerildi. Sanayi tipi bir tünel fırından ölçülen sonuçlar ile simülasyon sonuçları karşılaştırıldığında önerilen çevre havası profillerinin uygulamada kullanılabileceği görüldü. Ön ısıtma bölgesi girişinde yaklaşık 200°C olması gereken gaz sıcaklığının çevre havası beslenmediği durumda 350°C'ye çıktığı görüldü. Boyutsuz ön ısıtma bölgesi uzunluğunun yaklaşık %70'inde tuğla bağlı suyunun buharlaştığı belirlendi.
Anahtar Kelimeler: Tünel fırın, Ön ısıtma bölgesi simülasyonu, Bağlı suyun buharlaşması, Gaz sıcaklık profili.

NOMENCLATURE

a	Heat transfer area per unit volume of bricks [m^2/m^3]
b	Half thickness of the bricks [m]
c_p	Heat capacity[J/kg °C]
D_e	Effective diffusivity within the pores of bricks [m^2/s]
D_{H2O}	Water vapor diffusion coefficient in air [m^2/s]
g	Blowing mass flux [kg/m^2s]
G	Superficial mass flux [kg/m^2s]
h	Convective heat transfer coefficient [J/m^2 s °C]
H	Absolute humidity [kg H_2O/kg dry air]
k	Thermal conductivity [W/m°C]
k_S	Reaction rate constant based on the unit surface [m/s]
$\bar{L}$	Dimensionless length [%]
L_s/A	Dry brick weight per mass transfer surface area of brick packages [kg/m^2]
MW	Molecular weight [k mol/kg]
R	Drying rate per unit surface area dry brick [kg H_2O/m^2s]
T	Temperature [°C]
t	Time [s]
v	Velocity [m/s]
w	Bound water content in the brick body [kg H_2O/kg brick]

Greek Letters

ΔH	Heating value [J/kg]
Δx	Axial length increment [m]
ρ	Density [kg/m^3]
λ	Latent heat of vaporization [J/kg]
ϕ	Void fraction of brick packages [-]

ε	Porosity [%]
τ	Tortuosity [-]

Subscripts

a	Air
b	Brick
g	Gas
H_2O	Water vapor
o	Outside
O_2	Oxygen
s	Wall

INTRODUCTION

A brick body composed of clay, sand and some additives contain high amount of water in order to satisfy the conditions required for shaping. This mixture is sent to a machine that presses it into the moulds. When green bricks come from molding, they contain between 20-30% moisture on dry basis. Before the preheating and firing processes in a tunnel kiln, most of water within the brick body is evaporated slowly in a tunnel dryer at temperatures varying from 30^{o}C to about 200^{o}C with a relative humidity changing from one end to the other of the tunnel dryer. Without a drying process, the water within the bricks turns to steam at the firing process and damages the bricks severely. Thus drying is required to reduce the water content to approximately 10-12% in the green bricks before the preheating and firing. The evaporation of free water from the green bricks depends on the temperature, humidity and velocity of the hot air used in dryer. The effect of drying conditions, such as air temperature (20, 30, 35 and 40^{o}C), relative humidity (30, 40, 50, 60, 70 and 80%) and velocity (1, 3 and 8 m/s) on the progress of the drying process of various building materials was investigated by (Moropoulou et al., 2005) to develop a drying model. The optimal values of the hot and outdoor air mass flow rate ratios, and optimum stack temperature at different conditions to avoid the condensation was determined by (Mançuhan, 2009) for drying of green bricks in a tunnel dryer. Different conditions in question were outdoor air temperatures (-5, 10, 20 and 30^{o}C), relative humidities (40, 60 and 80%), and hot air temperatures (180 and 200^{o}C).

Three different models to simulate one, two and three dimensional gas and refractory temperatures and composition profiles were developed by (Dugwell and Oakley, 1987, 1988, 1988) along the tunnel kiln. The results of the mathematical models were compared to the temperature profiles obtained from the plant measurements. The fuzzy-logic supervisory control of the tunnel kiln for brick and tile production were proposed by (Michael and Manesis, 2005). Aim of this proposed controller was to achieve desired temperature profile depending on the kind of process along the tunnel kiln. Heat transfer and fluid flow phenomena for different brick arrangements in tunnel kilns were investigated by (Abou-Ziyan, 2004) to propose correlations to calculate the pressure drops and convective heat transfer rates for different operating conditions. One dimensional simple method was proposed by (Halasz et al., 1988) for determining the energy optimal operation conditions of a tunnel kiln. It was reported that 5-8 % of the used energy has been saved**.** Works on the energy efficiency of the tunnel kiln brick making process and optimization of the fuels and air flow rates were done and it was reported that the energy requirement varies between 2040 and 3510 kJ/kg brick depending on the type of the fuels used (Mancuhan and Küçükada, 2006; Prasetsan et al., 1997). Model representing the phenomena of heat transfer and fluid flow was developed by (Kaya et al., 2008) to compute the optimal values of the blowing and suction air mass fluxes, superficial air mass flow rate, brick and air temperatures along the cooling zone of a tunnel kiln. Modeling and optimization were studied by (Kaya et al., 2009) for a tunnel kiln firing zone to find the optimal feed locations and mass fluxes of the pulverized coal and secondary air. The fuel consumption, the mass flow rate of primary air, cooling air and stack gas were determined by the model to provide the required gas temperature and oxygen concentration profiles along a tunnel kiln (Yu, 1994). Along the tunnel kiln, the bricks undergo treatments namely preheating, firing and cooling. Reducing the bound water content in the brick body is required from about 10% to 0% during the preheating zone. However, the proposed model which was improved by (Yu, 1994) did not include the bound water evaporation from the bricks in the preheating zone.

A review of the literature indicates that there are not sufficient data available for simulation of drying bricks in the preheating zone of a tunnel kiln. In this study, simulation of the preheating zone was done by developing one dimensional model equations describing the gas flow, heat transfer and evaporation of bound water. State variables were mass flux and feeding locations of the ambient air required for gradual heating, brick and gas temperatures, fraction of the bound water within the bricks and the humidity of the kiln gas. These variables were calculated by solving the developed model equations throughout the preheating zone. The data obtained around an existing tunnel kiln were compared to the simulation results. Those results were presented per unit mass of bricks produced and per unit kiln cross section area as a function of the dimensionless length.

TUNNEL KILN OPERATION

The operation of tunnel kiln involves the counter current flow of brick loads and air. Along the tunnel kiln, the bricks undergo treatments namely preheating, firing and cooling. The air and fuel are supplied into the tunnel kiln at several locations to satisfy the temperature profile necessary for evaporation of bound water, for combustion, for cooling to satisfy the desired temperature profile required for strength development. The locations of the air blowing and suction, and fuel supply along the tunnel kiln are depicted in Figure 1.

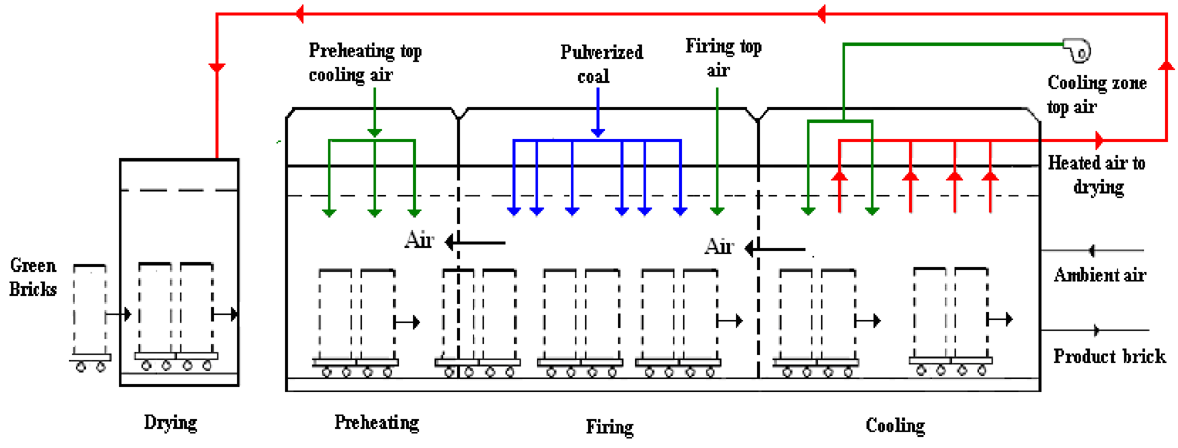

Figure 1. Schematic representation of the tunnel kiln.

Preheating of bricks is the first stage of the tunnel kiln where the bound water is evaporated due to contact of bricks and counter-current flow of hot kiln gas coming from the firing zone. Bricks coming from drying kiln with 10-12 % moisture content on dry basis are gradually heated from about 30°C to 600°C to evaporate the remaining water and to avoid cracking due to thermal shock. To avoid the thermal shock due to the sudden contact of bricks with hot gas coming from the firing zone, ambient air is supplied from the top of the kiln at several locations along the preheating zone. The gas leaving the preheating zone is sucked by fans and sent to the stack around 120-140°C. The stack gas contains the flue gases from the firing zone, air and some water vapor.

Brick packages move gradually from the preheating to the firing zone. During the firing period, the combustion of the admixed coal and sintering activate the formation of solid lattice within the brick. The hot air coming from the cooling zone is not sufficient to reach high temperatures for combustion of admixed coal particles and to activate strength development due to the bonding of clay particles. Therefore, the pulverized coal or natural gas and secondary air are fed through the holes from top of the kiln. The temperature of bricks increases gradually to about 1000°C by the combustion of the admixed coal within the bricks and pulverized coal.

The final step in the brick making process is to reach the desired temperature for the fired brick. Movement of brick loads and air in opposite directions along the kiln satisfies efficient cooling and shortens the cooling length as the temperature of the brick loads decreases. The cooling air is drawn from the exit of the tunnel kiln. Air circulation in the cooling zone is achieved by sucking of the hot kiln air to the drying kiln and blowing of the ambient air into the kiln at different locations. The hot bricks give off some of the heat to the cooling air while moving along the cooling zone so that the bricks cool down to the desired exit temperature. The purpose of the suction of the kiln air is to recover the heat content of the bricks. Similarly the ambient air is blown into the kiln to increase the heat transfer rate between the bricks and air.

In the cooling zone, the temperature of the bricks and wagons are reduced from about 1000°C to around 60°C.

MODEL OF THE PREHEATING ZONE

In attempting to develop an accurate simulation of the preheating zone of the tunnel kiln, the mathematical model should be developed by appropriate selection of simplifying assumptions.

- Steady state operation.
- The variation of the temperatures and air flow rates in the vertical direction was not taken into account.
- Heat is transferred between the gas and bricks predominantly by convection.
- There is no temperature gradient within the bricks i.e. temperature is uniform.
- Heat content of kiln cars is very close to the heat content of the brick loads. Therefore, the kiln cars were considered as brick loads while solving the model equation.
- The kiln roof is made up of two separate walls between which the roof cooling air flows. The purpose of roof cooling air is to recover the heat loss from the roof. Then the hot roof cooling air is sent to the stack to avoid the risk of condensation. It does not intervene with the air flowing through the brick loads.
- Brick body is homogenous,
- Initial bound water content was uniform within the brick body,
- Shrinkage of brick body was negligible,
- The combustion of the volatiles coming from the admixed coal within the brick body is neglected.

Heat Transfer

Heat is transferred between the gas and bricks by convection. Temperature difference between the bricks and gas is the driving force for heat transfer. In the real kiln, the gas temperature at about 730°C coming from the firing zone is decreased gradually to about 200°C by blowing a certain amount of ambient air through the vents at three different locations to avoid the thermal shock due to high temperature gas flow, Fig. 1.

Model equations were derived for a differential length increment, Δx, along the preheating zone of the tunnel kiln as shown in Fig. 2. Superficial mass flux of gas for each Δx interval enables us to investigate the trend of gas mass flux, temperature profiles of brick and gas, absolute humidity of the kiln gas along the preheating zone. The mass flux of gas coming from the firing to preheating zone, $G_g(\bar{L})$ the blowing ambient air mass flux, $g_a(x)$ are the manipulated variables. Both determine the profile of the superficial gas mass flux, $G_g(x)$, within the preheating zone. The mass balance for gas around the differential element is given as:

$$G_g(x) = G_g(x+\Delta x) + g_a(x+\Delta x) - G_b\left(w(x+\Delta x) - w(x)\right) \quad (1)$$

In this equation the term to the left of the equation represents the gas mass flux leaving the differential element of Δx. Meanwhile the first, second and third terms to the left of the equation represent the gas mass flux entering, the ambient air sucked into and water vapor released from bricks for the differential element of Δx, respectively.

The temperature of the gas decreases as it flows from the preheating zone exit side to the entrance side. The differential energy balance for the gaseous phase can be written as follows:

$$\frac{d\left(G_g\, c_{pg}\, T_g\right)}{dx} = h_b\, a_b\left(T_g - T_b\right) + h_s\, a_s\left(T_g - T_s\right) + T_o\, c_{pa}\frac{dg_a}{dx} \quad (2)$$
$$+\left(c_{p\,H_2O}\left(T_b - T_g\right) + \lambda\right) G_b\frac{dw}{dx}$$

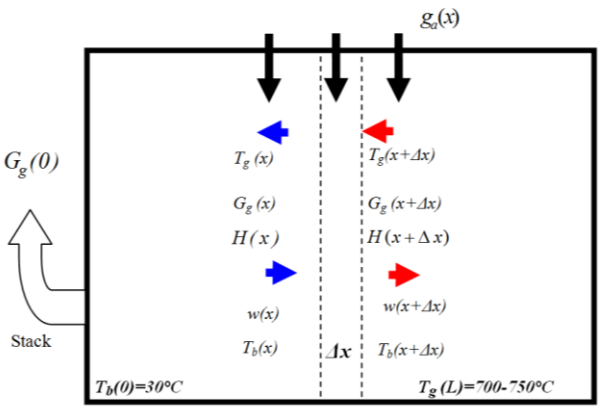

Figure 2. Differential length element and state variables used in the model equations.

The left-hand side term of the Eq. (2) represents heat lost by gas. The first term on the right-hand side of the Eq. (2) represents heat transfer by convection between bricks and gas while the second term represents heat transfer by convection between gas and wall. The third term acts a source term due to suction of ambient air into the kiln. The last term to the right of the Eq. (2) represents the heat lost due to evaporation and the heat taken by the evaporated bound water.

The differential heat balance for bricks is given by Eq. (3). The term to the right of Eq. (3) represents the convective heat transfer from gas to brick.

$$G_b c_b \frac{dT_b(x)}{dx} = h\, a_b\left(T_g - T_b\right) \quad (3)$$

The gas and brick inlet temperatures are 750°C and 30°C, respectively. These values which are the inlet conditions are used for solving the above given model equations.

$$T_g(\bar{L}) = 750^oC;\ \ T_b(0) = 30^oC \quad (4)$$

In the above equation, $\bar{L}$, represents the brick exit side where the gas is introduced into the preheating zone of the tunnel kiln due to suction of the stack fans.

Evaporation of Bound Water in the Bricks

Drying is the removal of small amounts of water as vapor from the solid material using hot air. External conditions such as temperature, humidity and velocity of the drying air are the main parameters controlling drying operation and affect the product quality. During diffusion-type drying, the resistance to mass transfer of water vapor from the surface is usually very small, and the diffusion in the solid controls the rate of drying. This type of diffusion is often characteristics of relatively slow drying in non-granular materials such as wood, foods and in the later stages of drying of bound water in clay (Geankoplis, 2003).

The drying rate per dry brick surface area can be defined as (Geankoplis, 2003):

$$R = -\frac{L_S}{A}\frac{dw}{dt} = \frac{\pi^2 D_e}{4b^2}\frac{L_S}{A}w \quad (5)$$

Eq. (5) states that when internal diffusion controls, the rate of drying R, is directly proportional to the bound water content of bricks, w, and the moisture diffusivity, D_e. At the same time, the rate of drying is inversely proportional to the thickness of brick slab, b. In this study, drying surface area per unit mass of bricks A/L_s, was assumed to be 0.192 m^2/kg.

Equation (6) was used to calculate the drying rate per volume of brick:

$$-G_b\frac{dw}{dx} = -\frac{(1-\phi)a_b L_S}{A}\frac{dw}{dt} = \frac{(1-\phi)a_b\,\pi^2 D_e}{4b^2}\frac{L_S}{A}w \quad (6)$$

where a_b represents the brick surface area per unit surface area of the kiln or it can also be used as the brick volume per unit volume of the kiln. The term ϕ

represents the volume of voids per volume of tunnel kiln or the surface area of the voids per unit surface area of the tunnel kiln. The value of ϕ varies between 0.4 and 0.57 depending on the geometry of the bricks produced. In this work an average value of 0.49 was used. In the below equation D_{H2O} is the diffusion coefficient of water vapor in air. The effective diffusivity D_e, within the pores of bricks can be given using the following relation (Geankoplis, 2003):

$$D_e = \frac{\varepsilon\, D_{H_2O}}{\tau} \quad (7)$$

where ε and τ represent the porosity and tortuosity of the bricks, respectively. Previous investigations of clay brick samples showed great variability in their physical and micro structural parameters. Range of total porosity and tortuosity were in the 19-43% and 1.6-3.9, respectively (Raimondo et al., 2009). The porosity of bricks was taken to be 0.32 and the dependence of the tortuosity on the porosity can be given as follows,

$$\tau = \frac{1}{\varepsilon^{0.41}} \quad (8)$$

At the bricks inlet side where the preheating zone starts, the initial bound water content of bricks is given as initial condition:

$$w(0) = 0.12\, kg\, H_2O / kg\, brick \quad (9)$$

As the bricks move along the preheating zone the humidity of the gas flowing in the opposite direction starts to increase for any differential length element, Δx, due to evaporation of the bound water. The following water vapor balance is written for a differential length increment Δx in order to compute the humidity of the gas leaving at any length x in the opposite direction to the brick flow. This is given by Eq. (10) to predict the gas humidity leaving the Δx differential increment.

$$\left\{\begin{matrix} Moisture\ content \\ entering\ at\ point\ x \\ with\ the\ bricks \end{matrix}\right\} + \left\{\begin{matrix} Humidity\ entering \\ at\ point\ x+\Delta x \\ with\ the\ gas \end{matrix}\right\} + \left\{\begin{matrix} Humidity\ entering \\ at\ point\ x+\Delta x \\ with\ the\ ambient\ air \end{matrix}\right\} = \left\{\begin{matrix} Moisture\ content \\ leaving\ at\ point\ x+\Delta x \\ with\ the\ bricks \end{matrix}\right\} + \left\{\begin{matrix} Humidity\ leaving \\ at\ point\ x \\ with\ the\ gas \end{matrix}\right\}$$

$$G_b\, w(x) + \left[G_g H\right]_{x+\Delta x} + g_a(x+\Delta x) H_o = G_b w(x+\Delta x) + \left[G_g H\right]_x \quad (10)$$

The absolute humidity of kiln gas coming from the firing to preheating zone was assumed to be equal to the absolute humidity of the ambient air at 60% relative humidity and 20°C. Therefore, one of the inlet conditions to solve the model equations is as follows:

$$H(\bar{L}) = 0.008\, kg\, H_2O / kg\, dryair \quad (11)$$

There are five state variables such as gas and brick temperatures, gas mass flux, kiln gas humidity and the bound water fraction within the brick body illustrated as $T_g(x)$,$T_b(x)$,$G_g(x)$, $H(x)$ and $w(x)$, respectively (Figure 2). There are manipulated or input variables such as ambient air mass flux profile, the initial fraction of bound water within the brick body, the kiln gas inlet humidity and the mass flux of the kiln gas coming from the firing zone. These manipulated variables are shown as $g_a(x)$, $w(0)$, $H(\bar{L})$ and $G_g(\bar{L})$, respectively.

The thermo-physical properties of brick, air, water and water vapor were obtained by fitting linear equations to the data obtained from (Holman, 2001). The model equations should be solved simultaneously to find the temperature profiles for kiln gas and bricks by using the numerical methods for a given set of ambient air mass flux blown into the kiln from the top. Using the shooting method the iterative computations were done until a satisfactory convergence is obtained (Rao, 2002). The solution was realized by solving the set of equations for N interconnected cells using Excel solver.

ANALYSIS OF THE EXISTING TUNNEL KILN DATA

The validity of the model is tested by comparing the computed results of the model to the plant data. The plant data have been collected from an existing tunnel kiln. The following parameters were monitored for this aim:

- Physical dimensions of tunnel kiln, physical dimensions and properties of brick loads, load rate of kiln cars and ambient air blowing holes.
- Ambient air and stack gas mass fluxes.
- Initial fraction of the bound water within the brick body.
- Kiln temperature measurements along the tunnel kiln and stack gas temperature measurement.

The overall mass and energy balances were computed around the preheating zone by using data collected from the existing tunnel kiln and the results were given in Table 1. The total ratio of ambient air added is 0.96 kg air/kg brick. The gas mass flux ratio varies lengthwise and increases from 1.13 to 2.09 kg gas/kg

Table 1. Mass and energy balances around the preheating zone for existing tunnel kiln.

	Mass flow rate ratio (kg/kg brick)		Temperatures (°C)		Heat flow rate ratio (kJ/kg brick)	
	In	Out	In	Out	In	Out
Gas coming from the firing zone	1.130		750		1271.4	
Ambient air	0.960		20		19.3	
Evaporation of bound water	0.120	0.120	30	100	15.0	322.9
Bricks	1.043	1.043	30	550	26.2	479.7
Kiln cars	1.083	1.083	30	250	27.2	226.4
Roof cooling air	0.800	-	100	-	80.4	-
Hot gas leaving through stack		2.89		130		521.2
Total Balance	**5.136**	**5.136**			**1439.5**	**1550.2**

brick. Roof cooling air mass flux ratio, 0.8 kg air/kg brick, is mixed with mass flux ratio of the kiln gas, 2.09 kg gas/kg brick before the stack. Then the total mass flux ratio of roof cooling air and kiln gas, 2.89 kg gas/kg brick, leaves through the stack of the tunnel kiln

At the entrance of the preheating zone, kiln cars have a heat content of 27.2 kJ/kg brick while the brick loads have 26.2 kJ/kg brick. Therefore, kiln cars can be considered as brick loads in the solution of the model equations. In order to consider the thermal effect of kiln cars, the computations were done for a brick flow rate of 2.126 kg brick/m^2 s as basis.

In Table 1, gas temperature from firing to preheating zone was calculated to be 750°C by computing overall mass and energy balance. But, the measured gas temperature is about 736°C at the entrance of the preheating zone. This is a value below the temperature of gas, 750°C, computed by using values from existing tunnel kiln. Stack gas temperature sucked from the preheating zone was measured to be between 130 and 140°C. The energy balance showed a difference of 110.7 kJ/kg brick. This may be due to the neglected effect of the combustion of volatiles coming from the admixed coal within the bricks.

SIMULATION RESULTS AND DISCUSSIONS

In the tunnel kiln brick making process, the temperature of the gas coming from the firing zone should decrease from 750°C to approximately 200°C to avoid the conditions causing the formation of cracks at the entrance of the preheating zone (Michael and Manesis, 2005). The sudden increase in the brick temperature is avoided by feeding ambient air with different mass flux through the vents at different locations along the preheating zone. Feeding of the ambient air affects the mass flux of the kiln gas, brick and gas temperatures, and the kiln gas humidity as well.

Previously calculated gas mass flux at the inlet of preheating zone and the measured mass flux of ambient air fed were 1.13 kg air/kg brick and 0.96 kg air/kg brick, respectively for the existing tunnel kiln (Kaya et al., 2009). This gas mass flux of 1.13 kg/m^{2}s coming from the firing zone stays constant for a while along the dimensionless length varying from 100% to 60% since there is no ambient air fed into the preheating zone along this interval. As shown in Fig. 3, passing through the 60% of the dimensionless length towards the entrance of the preheating zone in the opposite direction to the brick flow, there is a gradual increase in the gas mass flux as the ambient air of 0.96 kg air/kg brick is fed from the top. Thus, the gas mass flux ratio varies lengthwise and increases from 1.13 to 2.09 kg gas/kg brick. Ambient air addition is done to prevent the sudden contact of brick with kiln gas flowing at very high temperature. This operation is very important to avoid the risk of thermal shock.

Two different profiles for the ambient air fed from top of the kiln were shown in Fig 3. First one is the equallydistributed mass flux of ambient air fed at different locations between 0% and 35% of the dimensionless length. The other is proposed mass flux profile of ambient air between the 0% and 60% of the dimensionless length. The purpose of using two different profiles is to see their effect on the gas temperature profiles along the preheating zone. Thus, one can decide on the method to be used to control the vents located at the top of the kiln to let the ambient air flow into the kiln for desired temperature profile along the preheating zone.

As bricks and gas move in opposite directions the brick entrance corresponds to the gas exit. As soon as the gas from the firing zone enters the preheating zone and moves towards the entrance of the preheating zone (0% of the dimensionless length), the gas temperature starts to decrease because of the contact with the bricks at lower temperatures. While temperature of the bricks

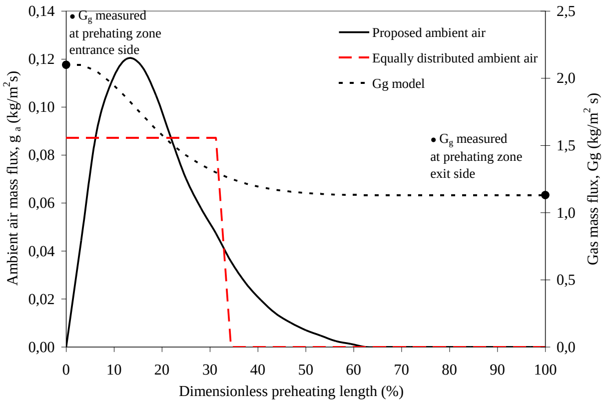

Figure 3. Ambient air mass flux profiles together with gas mass flux along the preheating zone.

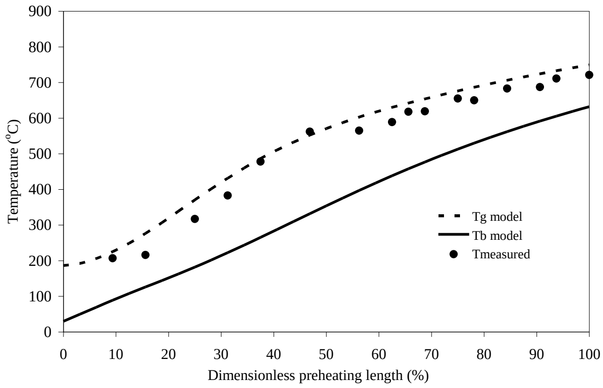

Figure 4. Comparison of the measured temperatures to the computed gas and brick temperatures.

coming from the entrance of preheating zone at 30°C increases to approximately 630°C, temperature of the gas coming from the firing zone at 750°C decreases to approximately 200°C (Fig. 4). Because of the ambient air sucked into the kiln, a steeper decrease of gas temperature occurs between the 0% and 60% of the dimensionless length compared to the rest of the kiln. Temperature data collected along the preheating zone of the investigated tunnel kiln is compared to the kiln gas and brick temperatures predicted by model equations. These comparisons are shown in Fig. 4.

In Fig.5, gas temperature profiles can be seen for different mass fluxes of ambient air fed from the top of the kiln along the preheating zone. When no ambient air is fed, gas temperature is around 350°C at the preheating zone entrance. This is not desired value of gas temperature profile for bricks to achieve the best quality product. For both ambient air mass flux profiles, the trends of the predicted gas temperatures agree well with temperatures measured along the preheating zone. Therefore, two different ambient air mass flux profiles can be proposed to produce highest quality product and safe operation. The gas temperature profile depends on two factors. The first factor is the location and the number of vents through which ambient air is sucked into the kiln. The second factor is the method of control (manual or automatic) which is used to adjust mass flux of ambient air. The approaches presented here are not limited to brick production but can be extended to various ceramic ware productions using different ambient air mass fluxes and different locations of vents.

As a result of the evaporation of bound water in the bricks, absolute humidity of the kiln gas increases gradually from 0.008kg H_2O/kg dry air to 0.065kg H_2O/kg dry air along the preheating zone as shown in Fig. 6. It can be seen that the bound water percentage in the bricks, $w(0)$=0.12 kg H_2O/kg brick, decreases gradually and approaches zero while reaching the 70% of the dimensionless length of the preheating zone. Bound water should be evaporated completely in the preheating zone. Otherwise, there may be damage due to thermal shock and decrease in the efficiency of the firing zone.

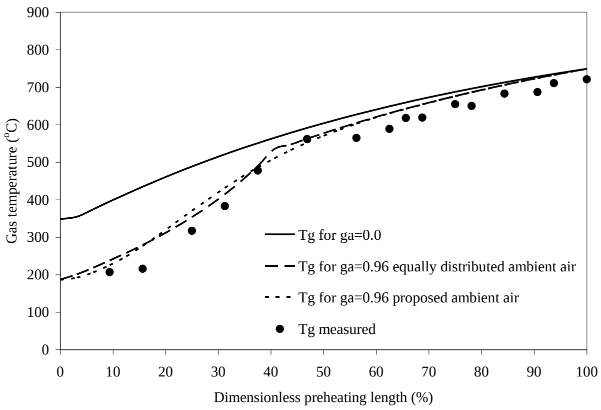

Figure 5. Variation of kiln gas temperature profiles as a function of different mass fluxes of ambient air.

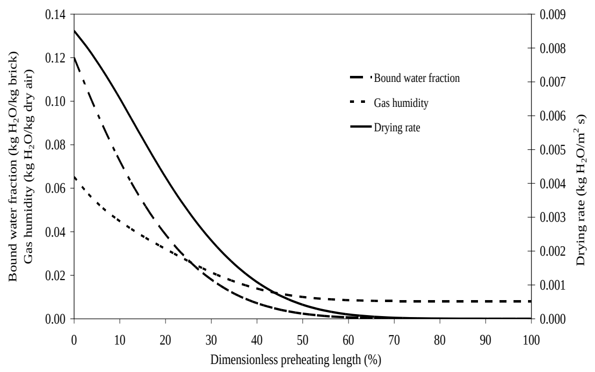

Figure 6. Bound water content in the bricks, humidity of gas, drying rate along the preheating zone.

CONCLUSIONS

Simulation of drying bricks in the preheating zone of a tunnel kiln was done by developing one dimensional model equations describing the gas flow, heat transfer between gas and bricks and evaporation of bound water. The simulation results were compared to the plant data and it was found that:

- Ambient air of 0.96 kg air/kg brick can be fed into the preheating zone using two different profiles and locations to achieve desired gas temperature for high quality bricks. First one is the equally distributed mass flux of ambient air between the 0% and 35% of the dimensionless preheating length. The other one is the proposed mass flux profile of ambient air between the 0% and 60% of the dimensionless length. Temperature profiles obtained using both approaches agreed well with measurements. Consequently, these approaches can both be employed to dry bricks effectively.

- Kiln gas temperature profile does not change significantly with the number of vents increased to generate a smooth distribution of ambient air mass flux. However, it is of extreme importance to supply ambient air into the kiln in order to avoid temperature of gas to reach 350°C at the very entrance of the kiln.
- Bound water in the bricks should be evaporated completely along the preheating zone to increase the efficiency of the firing zone. It decreases gradually and approaches zero while reaching the 70% of the dimensionless length of the preheating zone.

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