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Thermal performance augmentation in the cooling zone of brick tunnel kiln with two types of guide vanes

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ABSTRACT

The energy consumption in bricks and ceramics industry is of great importance. Therefore, the present work introduces an augmentation technique to improve the thermal performance during the cooling process in bricks tunnel kiln. A test rig by scale 1:4 has been designed and fabricated to simulate the cooling zone of tunnel kiln. Two types of guide vanes (side wall (SV) and U-shape (UV)) have been designed with attack angles (θ= 120º, 135º, and 150º) in flow direction. Seven different settings within Reynolds number range of 13,609 ≤ *Re* ≤ 27,634 are tested in a suction-type tunnel kiln. Effect of brick setting arrangement, Reynolds number, guide vane type, and attack angle on the thermal performance is studied. The results reveal that the UV guide vanes influence the thermal performance more than SV guide vanes. The maximum enhancement in heat transfer rate to pumping power ratio (Q_{avg}/PP) is about 25 for setting 7 in absence of vanes and 23 for (UV) with attack angles 150° and 135° at *Re* = 14,000. The present study introduces two correlations for average Nusselt number. Settings 4 and 1 provide a moderate production time with highest productivity while setting 2 has lowest productivity with small production time.

1. Introduction

Tunnel kilns are of great importance in manufacturing ceramics and bricks. They are composed of a collection of attached opposite directed heat exchangers with the solids on the kiln car that move counter-current with the air flow. There are three main temperature zones in the kiln; preheating, firing, and cooling zone. Tunnel kilns are long structure kilns in which the green products are heated up in the preheating zone, and then to the sintering temperature which is different from one product to another. After that the product goes through the cooling zone, where it is cooled down to a temperature near the ambient temperature [1]. Fig. 1 shows a schematic representation of temperature profile along the tunnel kiln.

Energy conservation management pushed many researchers to consider the thermal trouble inside the tunnel kilns to reduce the intensive energy consumption. A worthy mathematical, numerical and optimization studies have been performed on tunnel kilns. These studies included many aspects on the separate zones or on the whole kiln such as; temperature profile, fuel distribution, flow field, and heat transfer. Boming [2] established a dynamic model for tunnel kiln. The results showed that the model could describe the process and could help in kiln design. Tehzeeb et al. [3] used the computational fluid dynamics to simulate the temperature profile in bricks tunnel kiln.

Dugwell and Oakley [4] studied the heat transfer process along the kiln. The brick column was represented as a solid block. Therefore, the actual hydrodynamic pattern around the bricks was ignored in their study. Riedel [5] concluded that convection is the key factor for tunnel kiln. Number of features such as setting pattern and kiln roof was suggested to promote cross convection. Almeida et al. [6] provided a mathematical and numerical study to dry hollow bricks in a tunnel dryer. Refaey and Specht [7] presented three-dimensional analysis to simulate the burning of Sanitaryware products. The effect of nozzle axial velocity and nozzles arrangement was presented. The results revealed that the radial velocity produced by the burner and/or nozzles was essential to increase the heat transfer. Mancuhan et al. [8] developed one-dimensional model for the preheating zone of the tunnel kiln. The model described the following; gas flow, heat transfer between bricks and gases, and water evaporation. Ambient air was fed into the preheating zone by two different profiles and vent locations. The results revealed that the gas temperature reached 350 °C at the entrance of the preheating zone when there was no air fed.

Kaya et al. [9] developed a mathematical model to compute the mass flow rate of air and temperature profile along the cooling zone of tunnel kiln. The results revealed that, to minimize the pressure drop, the kiln cooling zone should be composed of four regions, two of them with a suction flow and the others of blowing type. Nicolau and Dadam

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Nomenclature

A	Brick length, mm
A_b	Brick surface area, m^2
A_w	Wet area, m^2, $A_w = A_{b,w} + A_{d,w}$
$A_{b,w}$	Bricks wet area, m^2
$A_{d,w}$	Duct wet area, m^2
B	Brick width, mm
C	Brick height, mm
C_p	Specific heat, J/kg.K
D	Diameter, m
D_h	Hydraulic diameter, m, $D_h = \frac{4V_f}{A_w}$
F	Friction factor
G	Gap between cover plate and top layer
H	Tunnel height
h	Convective heat transfer coefficient, $W/m^2.K$
I	Electric current, Amp
K	Fluid thermal conductivity, W/m.K
L	Length of brick setting, mm
M	Mass flux, $kg/s.m^2$
Nu	Nusselt number
P	Pressure, Pa
Q	Heat transfer rate, W, $Q_{input} = V_i I \cos\varnothing$
Q_{input}	Input heat from variac, W
S	Spacing between columns, m
U	Superficial velocity, m/s
U	Interstitial velocity, m/s, $U = \frac{u}{\varepsilon}$
Re	Reynolds number
$T_{a,b}$	Air bulk temperature, K
$T_{s,i}$	Local brick surface temperature, K
V_b	Bricks volume, m^3
V_d	Duct volume, m^3
V_f	Volume of flow, m^3, $V_f = V_d - V_b$
V_i	Voltage drop, Volt

Greek letters

θ	Attack angle
ε	Void fraction, $\varepsilon = V_f/V_d$
ρ	Density, kg/m^3
ρ_s	Setting density $= V_b/V_d$
ω	Uncertainty
η	Performance criteria
ν	Kinematic viscosity, m^2/s

Subscript

avg	average
i	Local value
mv	Middle with vanes
w,nv	Wall with no vanes

Abbreviations

LM	Longitudinal middle
LW	Longitudinal wall
PP	Pumping power
SV	Side wall guide vanes
TM	Transversal middle
TW	Transversal wall
UV	U-shape guide vanes

[10] presented three-dimensional numerical study to show the temperature distribution through load, gas, and walls. In addition, an experimental thermal analysis of a tunnel kiln was presented. Naccache et al. [11] numerically investigated heat transfer and fluid flow of combustion gases inside a tunnel kiln. The numerical results were compared with experimental results from literature. The results showed that natural gas can be used in tunnel kiln instead of sawdust.

Essenhigh [12] performed an analysis of the energy equation to determine the relation between input and output energies. Santos [13] provided a numerical formulation to get the thermal behavior of a tunnel kiln. A good agreement was obtained between the numerical and experimental results of sawdust as a fuel. In addition, other simulations were performed by using natural gas as a fuel in this kind of kiln. Refaey et al. [1&14] developed one-dimensional mathematical model by using MATLAB program to predict temperature profile along tunnel kiln. Furthermore, the influence of fuel distribution along the firing zone was studied. Dugwell and Oakley [15] built up a laboratory model of a tunnel kiln. The results presented a correlation to calculate convective heat transfer rates for the firing of refractory. Roth [16] described the influence of combined heating & power system (CHPS), the number of CHPS modules, and the structure of the needed purchased-power component on the economic efficiency. Recently, Soussi et al. [17] optimized the recovered air mass flow from the cooling zone to the firing zone to reduce the natural gas consumption during the manufacturing of hollow bricks in a Tunisian tunnel kiln. The results showed that the existence of an optimal value of the recovered air mass flow that could reduce the actual daily consumption of the natural gas up to 4.6%. Durakovic and Delalic [18] established a mathematical model to analyze and check the stationary temperature field in brick and kiln.

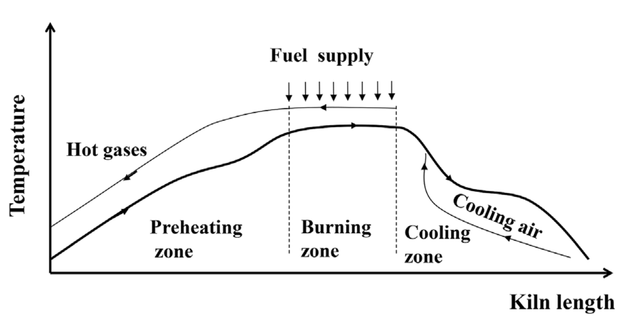

Fig. 1. Schematic diagram of temperature distribution along tunnel kiln [1].

Other researchers made experimental investigations on tunnel kilns. Karaush et al. [19] studied the heat absorption from the ceramic kiln radiating walls experimentally. They concluded that there was an optimal spacing between the ceramic pieces and there was no increase in the heat absorption rate if this space increased. Abou-Ziyan [20] experimentally studied the thermal performance in the cooling zone for six different brick settings. The results showed that the setting arrangement affects the pressure drop and convective heat transfer coefficient. Correlations for the friction factor and Nusselt number were presented. Ros-Dosdá et al. [21] provided a study of the environmental life cycle assessment of different Porcelain stoneware tile to identify the hotspots and choose the Environmental Product Declaration (EPD) program.

Recently, Refaey et al. [22] presented an augmentation technique using guide vanes with different attack angles attached to the kiln side walls. The heat transfer and the pressure drop for ten different brick settings were experimentally investigated. The results were obtained for a wide range of Reynolds number from 11,867 to 25,821. The results revealed that both of convective heat transfer and pressure drop were strongly depend on the brick settings arrangement. The attack angle has a great influence on the average Nusselt number. The results revealed that a maximum enhancement of about 94.5% was obtained for