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Energy Optimization of A Roof Tile Producing Tunnel Kiln by Examining the Kiln Car Physical Properties

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Abstract – Tunnel kilns are used for manufacturing coarse and fine ceramics like bricks, roof tiles and sanitary ware. Kiln cars which carry the ceramics through the tunnel kiln are considered to be one of the main contributors to energy loss. Depending upon the production capacity, a single kiln car can weigh up to 10 tonnes and there can be more than 20 kiln cars inside the tunnel kiln. In this paper, different physical properties of each layers of kiln car such as conductivity, density and specific heat capacity are analysed with the help of a mathematical model. The mathematical model developed for a generalized tunnel kiln which produces roof tiles, incorporates all modes of heat transfer taking place between the ceramic ware, gas and the kiln car. By examining the different physical properties of each layers of the kiln car, the physical properties of the first layer of kiln car is found to have an influence on energy saving.

Keywords: Energy optimization, Tunnel kiln, Kiln car, Ceramic, Roof tile, Ordinary differential equation

Nomenclature

Symbol

$\dot{Q}$	Heat flow rate, W
$\dot{M}$	Mass flow rate, kg/s
$\dot{H}$	Enthalpy flow rate, W
L	Length of the section where mass flow rate of gas is constant, m
c	Specific heat capacity, J/(kg·K)
T	Temperature, K
dx	Small section length, m
α	Overall heat transfer coefficient, W/(m^2·K)
A	Area, m^2
λ	Thermal Conductivity, W/(m·K)
L_i	Thickness of ith layer, m
NL	Numerical layer

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Conv	Convection
Cond	Conduction
Rad	Radiation
p	Heat capacity of gas at constant Pressure
1	1st numerical layer
i	ith numerical layer
n	nth numerical layer

1. Introduction

Tunnel kilns are ovens which have a length of more than 60 m, height of 3 m and a width of more than 4 m. The tunnel kiln is mainly used for the firing of bricks, roof tile, sanitary ware, etc. The temperature can reach more than 900 °C depending upon the required sintering temperature of the ceramics that is fired. The tunnel kiln has three zone namely, preheating, firing and cooling zone. The energy source of almost all the tunnel kilns are by combustion of fossil fuels. Therefore, the goal to be carbon neutral and the increase in the natural gas prices [1], have made it important to understand the energy losses from the tunnel kiln and make the required changes. There are many reasons for energy loss through the tunnel kiln like, heat loss through the walls of the kiln, cold air (false air) entering into the tunnel kiln and the thermal mass of kiln cars and kiln furniture which are heated and cooled as it moves through the tunnel kiln. According to Agrafioits and Tsoutsos [2], reducing the thermal mass of the kiln car is a way to reduce the energy loss from the tunnel kiln.

Oba et.al [3] had done three dimensional finite volume thermal analysis on a tunnel kiln producing roof tiles. Because of the computational time and cost, it is difficult for that method to be used for studying the influence of different materials on the kiln car for saving energy. Nicolau and Dadam [4] did numerical thermal analysis of a tunnel kiln producing tiles. Their paper depicted many figures showing the temperature distribution of the ware along the kiln length as well as the two-dimensional temperature distribution in the cooling zone but not the kiln car. The temperature distribution of the ceramic ware along the tunnel kiln is called the firing curve and it is used as the criteria for quality control.

Kiln car is made up of different thermal insulations and refractory materials along with the support structure. In this paper the kiln car is considered to be made up of five different layers of thermal insulation and refractory materials. The aim of the paper is to show the influence of different physical properties of individual layer on the firing curve and thereby determining which physical properties and layer has the potential for saving energy.

2. Tunnel Kiln And Kiln Car

Each industrial tunnel kiln is constructed to handle specific production requirement and hence have different kinds of kiln car. To get an overall idea of what the influence of a parameter on the firing curve, a generalized tunnel kiln was designed and the details of this kiln are used to simulate the firing curve and studied in this paper. Figure 1 shows the schematic of the tunnel kiln with different zone along with their respective length and also the different kinds of inlets and outlets for air, natural gas (fuel) and exhaust gas. The tunnel kiln has a total length of 102 m, inner width of 3.9 m and a height of 1.08 m. The wall and roof of the kiln has a total thickness of 1 m which is consisting of 0.5 m insulation and 0.5 m brick. The residence time of a kiln car inside the tunnel kiln is 16 hours and 28 minutes is the push time i.e. the time interval for feeding the tunnel kiln with a kiln car that has unburned ceramic ware. In Figure 2, the ideal firing curve (Solid Ideal) is constructed using the heating/cooling rate and the residence time of the roof tile in each zone and these informations are shown on the ideal firing curve. The simulated firing curve (Solid Simulated) is obtained using the values of mass flowrates and temperatures which are given in Table 1 [5].

Along the length of the tunnel kiln there are 34 kiln cars, each with a length of 3 m and a width of 3.7 m and a height of 0.68 m. The kiln car is considered to be consisting of 5 individual layers with same specific heat capacity and the other properties of each layers are described in Table 2. The kiln car represents a heavy standard kiln car and has a mass of more than 10 tonnes. Each kiln car carries a total of 560 roof tiles along with the cassette and the mass of the roof tiles and cassettes per kiln car are 3.5 tonnes and 4.4 tonnes respectively. There are four stacks of roof tiles on the kiln car and each stack has 14 rows and 10 columns of roof tiles and cassettes.

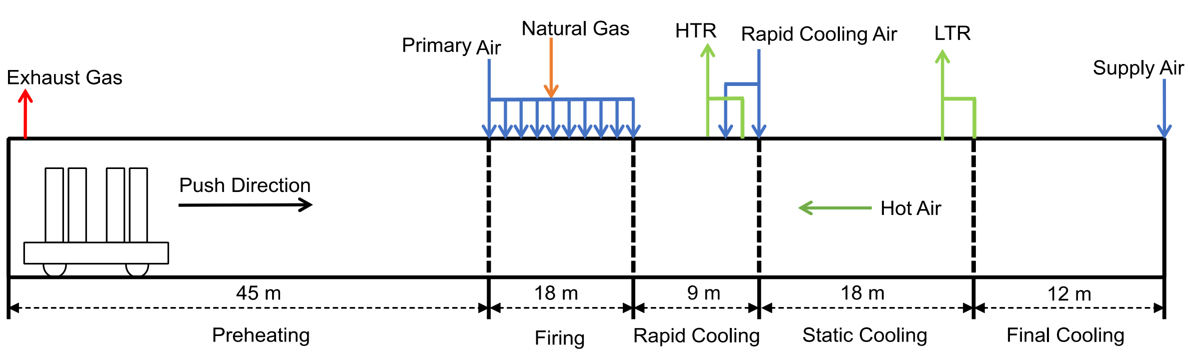

Figure 1: Schematic of the tunnel kiln

Table 1: Mass flowrates and temperatures of inlets and outlets

Name of the inlet or outlet	Mass flowrate (kg/s)	Temperature (°C)
Roof tile	2.08	100
Furniture	2.6	100
Supply Air	7.35	30
Low Temperature Recovery (LTR)	3.93	200
Rapid Cooling Air	1.27	25
High Temperature Recovery (HTR)	0.21	500
Natural Gas	0.08	15
Primary Air	1.21	35
Exhaust Gas	5.77	235

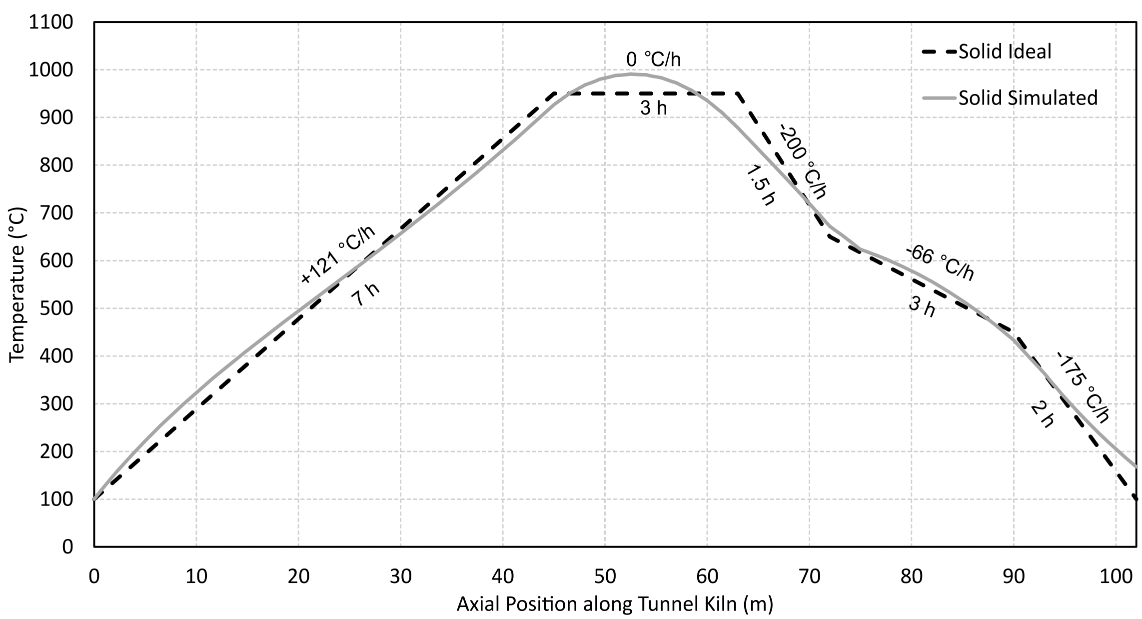

Figure 2: Firing Curve

Table 2: Different Material Layers of kiln car

Layer	Thickness (m)	Conductivity (W/(m·K))	Density (kg/m^3)
First	0.17	1.5	1550
Second	0.15	0.25	400
Third	0.06	0.18	64
Fourth	0.1	0.4	2013
Fifth	0.2	0.8	2200

3. Heat Transfer Mechanism And Mathematical Equations

Figure 3 illustrates the heat transfer mechanisms taking place in the preheating zone of the tunnel kiln. The ware and the furniture on the kiln car move in the opposite direction to the gas. The ware and the furniture together are designated as 'Solid'. In the preheating zone, the gas is at a higher temperature than the kiln car and the solid. Hence, heat from the gas is transferred to the solid and the kiln car. The gas exchanges heat through convection '$\dot{Q}_{Conv,\ Gas\rightarrow Solid}$' due to the velocity of the gas through the gaps between the roof tiles and cassette and also as radiation '$\dot{Q}_{Rad,\ Gas\rightarrow Solid}$' because of the presence of water vapour and carbon dioxide. The gas exchanges heat as convection '$\dot{Q}_{Conv,\ Gas\rightarrow 1}$' and radiation '$\dot{Q}_{Rad,\ Gas\rightarrow 1}$' to the kiln car also. The inside wall of the tunnel kiln is assumed to be the gas temperature and this results in heat transfer through the wall as conduction '$\dot{Q}_{Cond,\ Wall}$'and then to the outside air as natural convection '$\dot{Q}_{Conv,\ Wall\rightarrow Air}$' and radiation '$\dot{Q}_{Rad,\ Wall\rightarrow Air}$'. The solid radiates '$\dot{Q}_{Rad,\ Solid\rightarrow 1}$' heat to the kiln car by solid to solid radiation and the heat which the kiln car receives from gas and solid is conducted to the inside of the car '$\dot{Q}_{Cond,\ KC}$'.

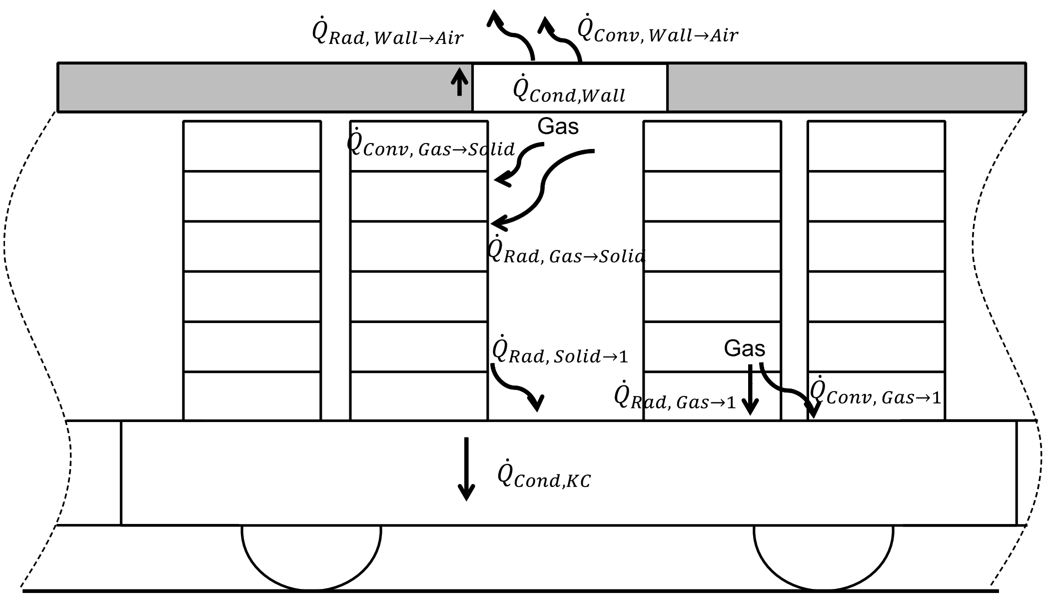

Figure 3: Heat transfer mechanism in preheating zone

In a tunnel kiln, the movement of the ware on the kiln car is opposite to the gas, hence the tunnel kiln can be considered as a counter current heat exchanger. The core mathematical equations for generating the temperature profile of the fluids in a heat exchanger is applied to the tunnel kiln. The ordinary differential equations are developed from the fact that the change in enthalpy of the fluid at an infinitesimally small section along the length of the heat exchanger is equal to the amount of heat transferred from one fluid to other. A single ordinary differential equation for the kiln car cannot represent the interaction with the gas and the solid because the kiln car is made up of different layers of material. So, the kiln car is divided into different numerical layers as shown in Figure 4 and ordinary differential equation for each layer is generated which represent the conduction of heat through kiln car. The heat transfer from the gas and the solid to the kiln car are designated as '$\dot{Q}_{mode,\ Gas\rightarrow 1}$' and '$\dot{Q}_{mode,\ Solid\rightarrow 1}$', mode represents convection or radiation. 1 is used to represent the kiln car's first numerical layer. The equations given in Table 3 are the ordinary differential equations which are solved numerically using MATLAB ordinary differential equation solver. The number of ordinary differential equations depends on the number of numerical layers of the kiln car plus the equations for the gas and solid. In this paper, each material layer of the kiln car is divided into 35 numerical layers after a grid independence study. A total of 177 differential equations are solved as an initial value problem, from the entrance of the kiln to the exit, that is from left to right. The inlet temperature of the solid and the numerical layers are fixed as 100°C. An assumed outlet temperature of the gas is used to begin the solution process then with the help of linear regression the outlet temperature of the gas is varied such that the inlet temperature of the gas calculated by the solver should be equal to the actual inlet temperature of gas as 30 °C.

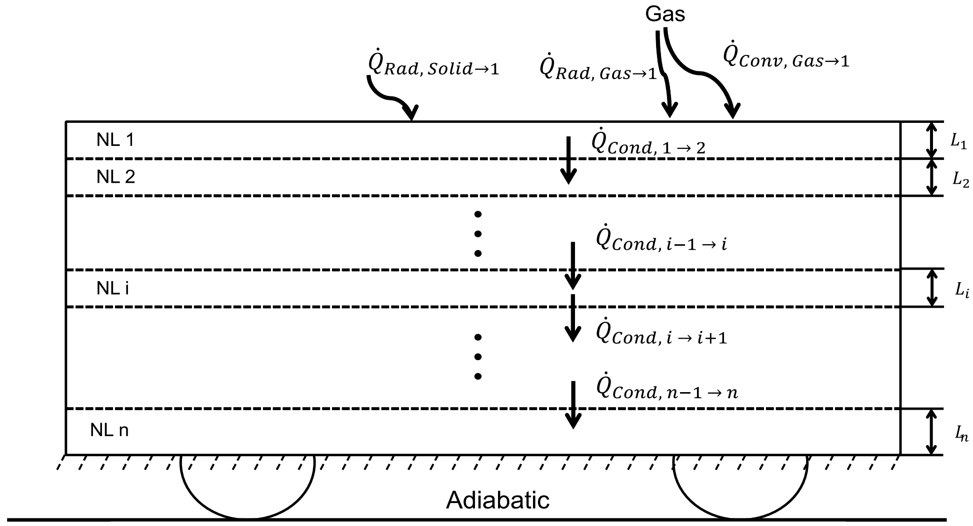

Figure 4: Numerical layers inside the kiln car

Table 3: Ordinary differential equations for temperature profiles

Gas	$\frac{dT_{Gas}}{dx} = -\frac{1}{\dot{M}_{Gas}c_{pGas}}\cdot\left[-\alpha_{Gas\rightarrow Solid}\frac{A_{Solid}}{L}(T_{Gas}-T_{Solid}) - \alpha_{Gas\rightarrow 1}\frac{A_{KC}}{L}(T_{Gas}-T_1) - 2\alpha_{Gas\rightarrow Air}\frac{A_{Wall}}{L}(T_{Gas}-T_{Air})\right]$

Solid	$$\frac{dT_{Solid}}{dx} = \frac{1}{\dot{M}_{Solid} c_{Solid}} \cdot \left[\alpha_{Gas\rightarrow Solid} \frac{A_{Solid}}{L}(T_{Gas} - T_{Solid}) - \alpha_{Solid\rightarrow 1} \frac{A_{KC}}{L}(T_{Solid} - T_1)\right]$$
Layer 1	$$\frac{dT_1}{dx} = \frac{1}{\dot{M}_1 c_1} \cdot \left[\alpha_{Gas\rightarrow 1} \frac{A_{KC}}{L}(T_{Gas} - T_1) + \alpha_{Solid\rightarrow 1} \frac{A_{KC}}{L}(T_{Solid} - T_1) - \frac{Width_{KC} \cdot (T_1 - T_2)}{(\frac{L_1}{2 \cdot \lambda_1} + \frac{L_2}{2 \cdot \lambda_2})}\right]$$
Layer i	$$\frac{dT_i}{dx} = \frac{Width_{KC}}{\dot{M}_i c_i} \cdot \left[\frac{(T_{i-1} - T_i)}{(\frac{L_{i-1}}{2 \cdot \lambda_{i-1}} + \frac{L_i}{2 \cdot \lambda_i})} - \frac{(T_i - T_{i+1})}{(\frac{L_i}{2 \cdot \lambda_i} + \frac{L_{i+1}}{2 \cdot \lambda_{i+1}})}\right]$$
Layer n	$$\frac{dT_n}{dx} = \frac{Width_{KC}}{\dot{M}_n c_n} \cdot \left[\frac{(T_{n-1} - T_n)}{(\frac{L_{n-1}}{2 \cdot \lambda_{n-1}} + \frac{L_n}{2 \cdot \lambda_n})}\right]$$

4. Results

4.1 Influence of the physical properties

The influence of the physical properties like conductivity, density and specific heat capacity of individual layers on the temperature profile of the solid is discussed in this section. Figure 5a, Figure 5b and Figure 5c shows the temperature profile of the solid when the conductivity, density and specific heat capacity of each layer is individually reduced to 20% of the reference case (Figure 2 Solid simulated case) respectively. The highest temperature attained by the solid increases to be more than 1150 °C when the conductivity, density or the specific heat capacity of the first layer decreased to 20% of the reference case as can be inferred from Figure 5. The other layers do not influence the solid temperature profile which can be seen in Figure 5 where the simulated solid temperature remains similar to the reference case.

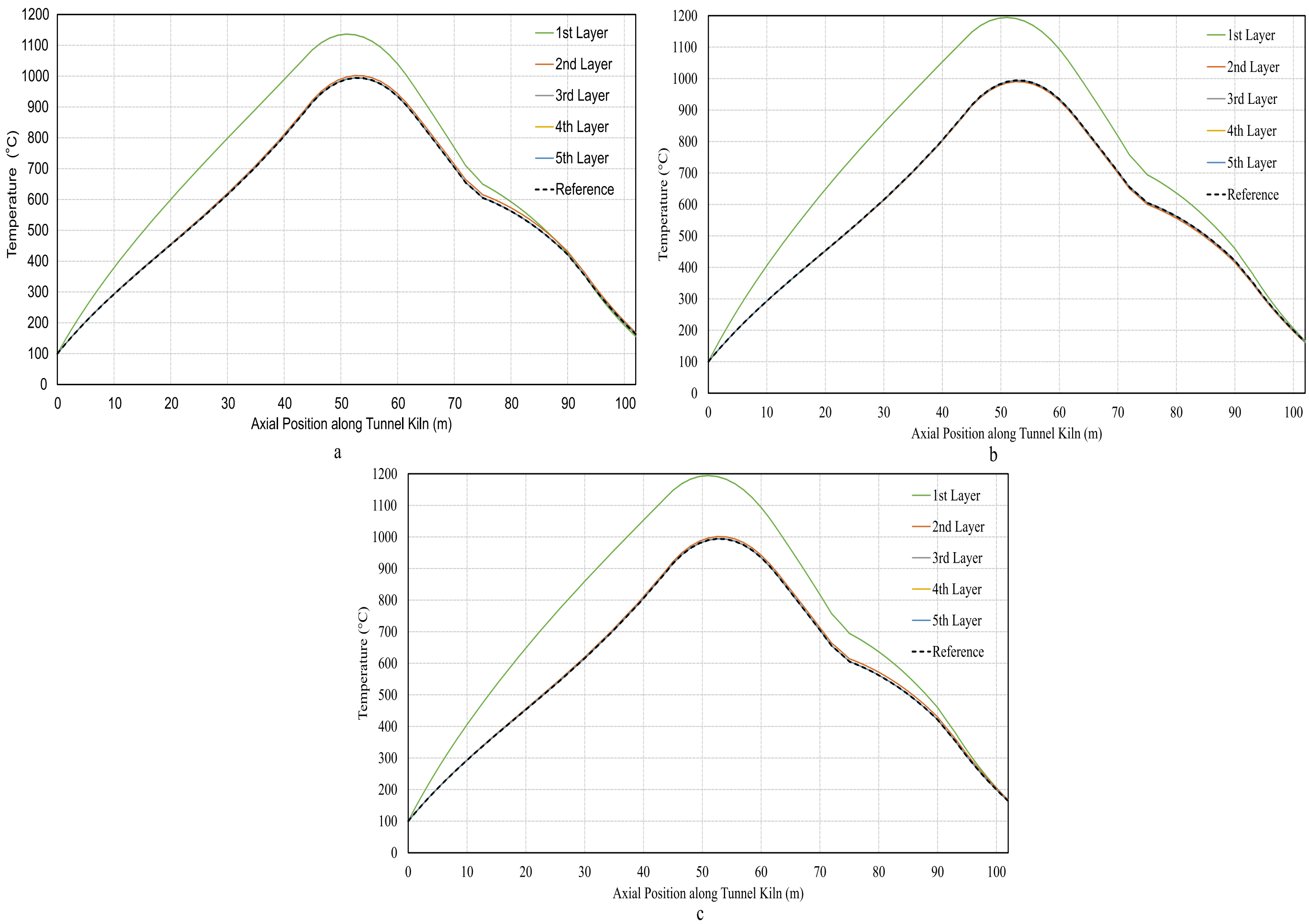

Figure 5: Solid Temperature profile along the tunnel kiln when the physical properties of individual layers are changed to 20% a) Conductivity b) Density c) Specific heat capacity

4.2 Energy saving

The solid temperature profile obtained by changing the conductivity, density and specific heat capacity of the first layer to 20% do not represent the firing curve to get the desired product quality. As given in Table 4 the mass flowrates of the fuel, primary air and supply air are to be changed to get the reference firing curve. The combustion of natural gas is with an air excess number of 1.2 and hence the percentage change of mass flowrate of the natural gas and the primary air are the same.

Table 4: Variation in the mass flowrates of different inlets in percentage

Case	Natural Gas	Primary Air	Supply Air
Conductivity	-17	-17	-4
Density	-25	-25	-4
Specific Heat Capacity	-24	-24	0

5. CONCLUSIONS

The first layer on the kiln car is found out to be important to save energy and the material for the first layer should have low conductivity, low density and low specific heat capacity. On top of the mentioned characteristics, the material should have the proper thermo-mechanical stability to resist the deformations that can be caused due to the heating and cooling in the tunnel kiln. To support the weight of the ware and the furniture on the kiln car in addition to the support structure of the kiln car, the first layer of the kiln car cannot be made entirely of mineral wool. But mineral wool as an additional top layer is used as a temporary solution to reduce energy consumption of the tunnel kiln.

References

[1] BBC,(2022, Jan 20 "Why are gas prices so high and what is happening to fuel bills?," [Online]. Available: https://www.bbc.co.uk/news/business-58090533.

[2] C. Agrafiotis and T. Tsoutsos, "Energy saving technologies in the European ceramic sector: A systematic review," *Applied Thermal Engineering*, vol. 21, no. 12, pp. 1231–1249, 2001, doi: 10.1016/S1359-4311(01)00006-0.

[3] R. Oba, T. S. Possamai, and V. P. Nicolau, "Thermal analysis of a tunnel kiln used to produce roof tiles," *Applied Thermal Engineering*, vol. 63, no. 1, pp. 59–65, 2014, doi: 10.1016/j.applthermaleng.2013.10.063.

[4] V. De Paulo Nicolau and A. P. Dadam, "Numerical and experimental thermal analysis of a tunnel kiln used in ceramic production," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 31, no. 4, pp. 297–304, 2009, doi: 10.1590/s1678-58782009000400003.

[5] D. M. Alex, T. Redemann, and E. Specht, "Development of Process Model for the Manufacturing of Sanitary Ware in Tunnel Kiln," in *12TH EUROPEAN CONFERENCE ON INDUSTRIAL FURNACES AND BOILERS*, 2020,, [Online]. Available: https://infub.pt/geral/paginas.aspx?cod=138.