is empty the radiation contribution to the rollers is much higher determining a larger temperature value. Furthermore, the rollers demonstrate to have the largest thermal inertia with respect to the hot air flow and the ceramic material.

A second numerical analysis of the transient behavior of the kiln is investigated focusing on the empty kiln operations, i.e. transient profile #2 in Figure 12. The temperature set points for the burners in the different modules are firstly operated at the 50% of the nominal values until steady state regime is reached. Afterword, the nominal temperature set points are adopted until regime conditions are met again; finally, the shutdown phase is subdivided into two transient periods, i.e. a stand-by phase at 50% of the temperature set points followed by a complete shutdown of the burners until the kiln is cooled down to ambient temperature. The ceramic product is not considered for this analysis and the kiln operation is analyzed during production gaps. Figure 13 b) shows the transient profile of the air temperature in the upper chamber of module # 10. It can be noticed that the cool down transient of the kiln results larger than the warm up phase by several times.

4. CONCLUSIONS

In this paper the 0D/1D model of an entire ceramic kiln is constructed and employed to simulate the performance of an entire ceramic kiln under actual operating conditions. Each component of the real kiln is accurately simulated and particular attention is devoted to predict the heat transfer phenomena that take place in the system. The numerical results have been validated against experimental measurements carried out on the real facility and the prediction resulted in good agreement with the measurements. The numerical model was then adopted for investigating different strategies that can be used to enhance the energy efficiency of the kiln. First, the exploitation of the exhausts from a gas turbine for enhancing the heat exchange in the pre-heating section of a ceramic kiln were investigated. The effects of the exhausts injection into the kiln were evaluated in terms of both the heat absorbed by the tiles due to the increased convection phenomena and the reduction of the kiln natural gas consumption.

The use of the exhausts from the CHP turbine unit resulted in a lower natural gas fuel consumption of approximately 0.35 % of the entire kiln fuel requirements. Furthermore, the cooling temperature profile of the tiles in the final section of the kiln was investigated and the operating conditions of the kiln for a new cooling profile were determined. A smoother temperature gradient in the fast cooling section was obtained in order and the relating fans' speeds, valves' positions and burners' temperature set points were determined. Finally, the dynamic behavior of the kiln under unforeseen events were investigated and the characteristic time for the kiln warm-up and cool-down were calculated for different temperature set points of the firing modules.

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REFERENCES

[1] Agrafiotis C, Tsoutsos T. (2001). Energy saving technologies in the European ceramic sector: a systematic review. Applied Thermal Engineering. 21: 1231-1249. https://doi.org/10.1016/S1359-4311(01)00006-0

[2] Kaya S, Mançuhan E, Küçükada K. (2009). Modelling and optimization of the firing zone of a tunnel kiln to predict the optimal feed locations and mass fluxes of the fuel and secondary air. Applied Energy 86: 325-332. https://doi.org/10.1016/j.apenergy.2008.04.018

[3] Mezquita A, Boix J, Monfort E, Mallol G. (2014). Energy saving in ceramic tile kilns: Cooling gas heat recovery. Applied Thermal Engineering 65: 102-110. https://doi.org/10.1016/j.applthermaleng.2014.01.002

[4] Jiang X, He B, Liu Q, Wang D, Xu J, Xie W. (2017). A CFD analysis of gas plume stratification in confined space. Journal of Modelling, Measurement and Control B 86(2): 557-568. https://doi.org/10.18280/mmc_b.860217

[5] Milani M, Montorsi L, Paltrinieri F, Stefani M. (2014). Experimental and numerical analysis of the combustor for a cogeneration system based on the aluminum/water reaction. Energy Conversion and Management 87: 1291-1296. https://doi.org/10.1016/j.enconman.2014.03.027

[6] Bottazzi D, Farina S, Milani M, Montorsi L. (2012). A numerical approach for the analysis of the coffee roasting process. Journal of Food Engineering 112(3): 243-252. https://doi.org/10.1016/j.jfoodeng.2012.04.009

[7] Nuñez Vega AM, Sturm B, Hofacker W. (2016). Simulation of the convective drying process with automatic control of surface temperature. J. Food Eng. 170: 16-23. https://doi.org/10.1016/j.jfoodeng.2015.08.033

[8] M Milani, L Montorsi, M Stefani. (2014). An integrated approach to energy recovery from biomass and waste: Anaerobic digestion-gasification-water treatment, Int. Journal of Waste Management and Research 32(7): 615-625. https://doi.org/10.1177/0734242X14538307

[9] LMS AMESim User Manual, 2016 Siemens Industry Software NV.

[10] Milani M, Montorsi L, Stefani M, Saponelli R, Lizzano M. (2017). Numerical analysis of an entire ceramic kiln under actual operating conditions for the energy efficiency improvement. Journal of Environmental Management 203: 1026-1037. https://doi.org/10.1016/j.jenvman.2017.03.076