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Improving the curing cycle time through the numerical modeling of air flow in industrial continuous convection ovens

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Abstract

Drying, curing, baking are few of the manufacturing processes that require the use of impingement ovens. For the manufacturing of large batches typically continuous flow ovens are used that are part of an automated conveyor processing line. The retention time for a product to be treated in the oven usually drives the production efficiencies (i.e. energy usage or lead times). In many processing lines though, the ovens are not designed and run in the most efficient way, and as a result become the "bottleneck" process phase. In such ovens, usually the hot air is ejected from rows of nozzles perpendicularly to the moving product. In the most advanced designs the ovens are divided in zones, with each zone having different targeted operating temperature. The optimization of the manufacturing process is difficult to be experimentally determined due to several reasons: the length of the ovens and the complexity of the movement of the product in and out of the oven are the most challenging ones. The main objective of this paper thus is the development of a Computer Fluid Dynamics model for simulating the thermal - transfer efficiency of an existing hot-air convection oven used to produce continuous products. The model is used for the estimation of the maximum speed that the conveyor belt can be run, and further investigate possible improvements on the design of the oven for the reduction of the cycle time. The results can be useful during the overview of the actual production and manufacturing rules.

Keywords: Cycle time; CFD; continuous processing; ovens

1. Introduction

Manufacturing companies continuously try to improve their processes and operations to improve customer satisfaction and reduce production cost. One of the key performance measurements is the lead time and is correlated with both customer experience and cost. In discrete manufacturing, lead time can be improved through continuous improvement and investment in new more efficient equipment. In continuous manufacturing lines, however all processes are linked and the slowest process drives the lead time of the whole manufacturing lines. Usually the cost for replacing equipment is such that this cannot be considered. This is especially the case for products that require thermal treatment (such as curing) that require the use of long continuous ovens. The length of such ovens is decided based on the time that the product requires spending in a specific temperature setting. Obviously, the higher the speed of the line, the longer the oven needs to be for maintaining the temperature above the curing temperature. The performance, though can be increased if the efficiency of the oven is improved.

A variety of heat treatment chambers such as furnaces, kilns and ovens are widely used in different industries [1]. Among the numerous heat transfer technologies developed, thermal transfer from hot air nozzles within convection ovens are extensively used, including the glass temper, product

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coating, and baking various food products to name few. With arrays of hot impingement air nozzles perpendicular to the surface of targeted product, heat is transferred onto it [2]. A typical schematic of convection oven with impinging hot air jets is presented in Figure 1.

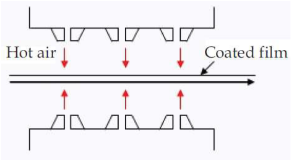

Fig. 1. Typical diagram of convection oven with impinging hot air jets.

Industrial ovens are often critical in the industrial production lines since they greatly affect the final product quality. However, several challenges exist due to the amount of energy consumed, the complex thermo-physical processes involved and the difficulties in monitoring the phenomena inside the oven [1]. The increase of energy price, the limitations posed to the lead time in the coating and converting industries [2], drive the pursue of higher efficiency of thermal transfer in the industrial ovens.

To reduce processing time and improve thermal efficiency of the oven, three basic approaches are employed to measure and forecast the performance of ovens, including experimental, theoretical and computational studies. The experimental approach involving full-scale experiments is always costly and time-consuming, providing however the most accurate results. However, monitoring the process and spot measuring the temperature inside the over pose many difficulties [3]. The theoretical method uses mathematical models. Initial attempt to calculate the detailed performance of furnaces date to the late 1970s [1]. This method though can be used only for simplified cases and complex phenomena in cannot be reproduced [4]. Computational approaches are based on the use of existing well established methods such as Computational Fluid Dynamics (CFD). CFD is based on the approximate solution of complex non-linear differential equations for simulating fluid flows. Heat and mass conduction, momentum transfer can be calculated for a variety of thermal problems. There are many remarkable benefits over experiments to fluid systems, such as reducing dramatically lead time and cost during design stage, assessing large and complex systems [3].

In the present paper, the efficiency of an existing oven is studied using CFD. The curing of the material requires the line to be run at a maximum speed, that limits the cycle time. By simulating the thermal - transfer efficiency of the oven, the maximum speed that the conveyor belt can be run can be estimated. Furthermore, possible improvements on the design of the oven for the reduction of the cycle time are investigated

2. Modelling

Forced convection ovens, that can be either indirect- or direct-fired and equipped with air impingement system have been used extensively in different industrial fields like paper dying, product coatings, glass tempering, electronic cooler and food productions like bread baking [5], [6].

Typically, a forced convection oven is separated into independently controllable heating. The main components of the heater zones include an electrical burner that warm the air, a fan that transfer the heated air, and the air nozzles which deliver the airflow over the surface of the product and transfer energy [8]. Figure 2 shows a typical schematic diagram of a forced convection oven [5]. Tunnel (or continuous conveyor) ovens in which the products are transported through a heat transfer zone continuously are widely applied to improve the production efficiency [7].

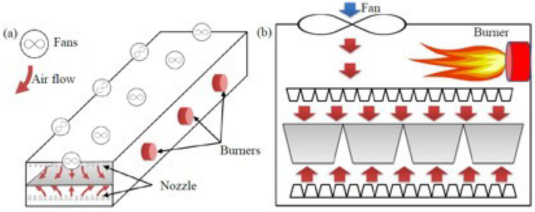

Fig. 2. Schematic diagram of a production oven [5]

Air impinging jet technology which is applied in widespread industries such as drying process or food production has been investigated thoroughly [9]. The basic heat transfer mechanism is convection due to the flow of hot air along the product surface [10]. This technique has many advantages in applications. For example, when baking planus bread, the higher velocity of the hot air can help to reduce temperature and baking time [11]. The application of jet impingement can also increase the coefficient which reflects the efficiency of thermal-transfer between the surface of product and the oven atmosphere as additional control [9]. The flow patterns followed by impinging hot air jets have three regions: free flow field; impingement, stagnation flow and radial flow areas, as shown in Fig. 3 [2].

Factors like nozzle geometry (in which round or slot ones has been studied most extensively), orientation of the nozzle, Reynolds number and the distance between nozzle and surface of the product have great effect on the heating efficiency, as they directly affect thermal-transfer coefficient and flow patterns [10].

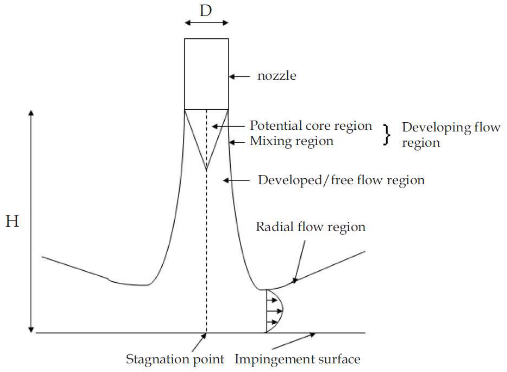

Fig. 3. Flow patterns in a hot air impingement jet

For the modeling of the existing oven, several steps should be followed. Firstly, data including both geometrical dimensions and operating parameters are collected as the input for the model. Secondly, the geometry of oven needs to be designed in a CAD software based on gathered data, and then imported to a meshing software to conduct the meshing work. Thirdly, numerical modelling (mathematics model, materials, and boundary conditions) is carried out in a CFD software. Then the results are analyzed and validated by comparing with experimental data, and, if possible, the model should be modified until the results are identical to the real situation. Finally, optimization of the model by varying some input parameters such as temperature to achieve maximum speed of the conveyor belt is carried out. Using the model developed, proposals for improvement of the existing oven can be suggested. The methodology of the numerical modelling is shown in Figure 4.

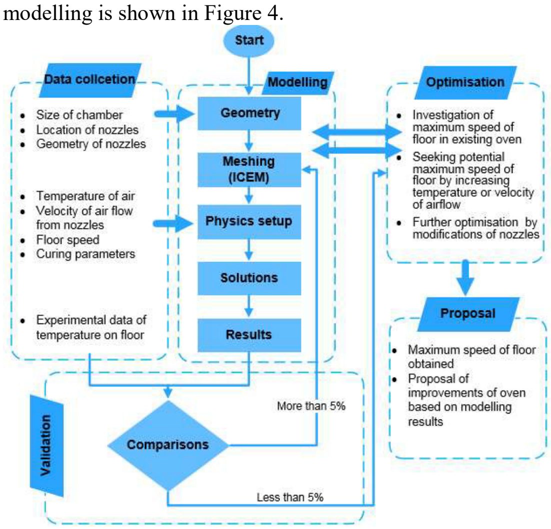

Fig. 4. Methodology for numerical modelling

3. Model implementation

The CFD meshes were developed in ANSYS ICEM CFD (Version 16.2). Several different meshing configurations had to be tested to select the one with the best balance between accuracy and accuracy within the available computational budget. Tetrahedral mesh was generated in fluid domain with different sizes in different surfaces, for example, at the inlet where the air flow is violent, the mesh size was set finer, while at the near outlet domain, the mesh size can be coarser. Near the wall, surface of floor, boundary layer inflation was generated to enable enough resolution in domains where thermal and momentum gradients are dominant. Since the final product that is cured inside the oven is based on Plasticized (Flexible) Polyvinyl Chloride (PVC-P) material, relevant material properties were selected. For the calculation of the temperature distribution on the final product, the one-equation turbulence model of Spalart–Allmaras was used, with the compressible density-based solver with explicit formulation; the Flux type was set as Roe-FDS. The Green-Gauss Cell Based gradient was applied. The process was considered as a steady state because the floor is moving through the oven at constant speed. The convection oven exhibits symmetry, thus only half of the oven was modelled. Furthermore, the fluid domain between side-door and chamber was removed because only the air flow and thermal transfer between arrays of nozzles and product were investigated. The velocities of the air flow from nozzles vary along the length of the oven, thus no simplification along the length was applied. The inlets (nozzles), outlets (side exhaust duct, and the entrance and exit of floor) are distributed in X, Y, Z coordinate system, thus a 3-D full scale model was developed.

A schematic of half of the oven is shown in Figure 5. Three heating zones are included with each zone being 4000 mm in length. In zone 1, two types of air inlets (V-nozzles and slots which are located on top platform) are used. In zone 2 and 3 only V-nozzles are used with spacing of 220mm. There are 50 arrays of the V-nozzles on the top of surface and 54 arrays on the lower plate. Among the lower nozzle-matrix, 15 square support bars with spacing of 920mm are introduced to support the moving product. The product under consideration is a laminate 2mm in thickness, situated at the middle of the cavity inside the oven, moving through the oven from the entrance in zone 1 to exit in zone 3 at constant speed.

The fluid domain within the studied oven is presented in Figure 6. For decreasing the cells number, the fluid domain between side-door and chamber are neglected. Furthermore, the support bars were removed from the model. The exits of the nozzles are set as velocity-inlet, and the front surface is set as symmetry, the back surface and the two end surfaces are defined pressure-outlet, the top and downside surface are outside wall. The SRF (Single moving reference frame) was applied to simulate the product moving through the oven.

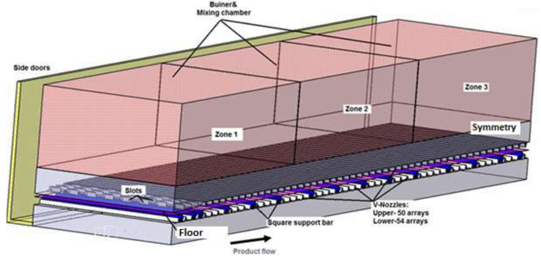

Fig. 5. Schematic diagram of the studied oven.

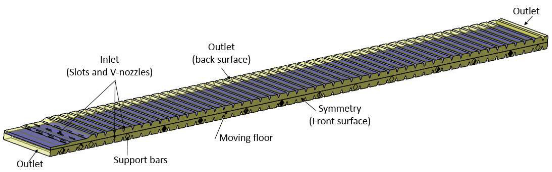

Fig. 6. CFD Fluid domain.

The air flow system on the vertical cross-section of the oven is shown in Figure 7. The cold air is heated by gas burner and then flows down to the mixing chamber by a fan. When the mixed air reaches required uniform temperature, it is separated to two parts, one going to the upper nozzles directly and the other is transferred to the lower nozzles by a connecting duct. The upper and lower nozzle-matrixes distribute the heated air which generates hot air streams perpendicularly to the surfaces of the product. Finally, the exhaust air escapes from the side exhaust duct, and at the entrance and exit of floor. The velocities of the airflow inlet measured from workshop are shown table 1. The nozzles used are shown in figure 8.

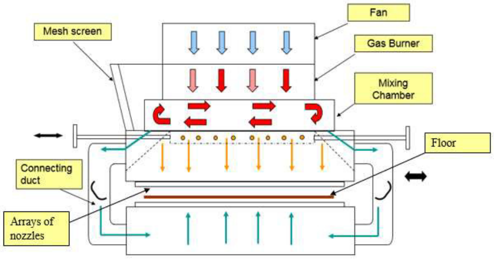

Fig. 7. Schematic diagram of the studied oven.

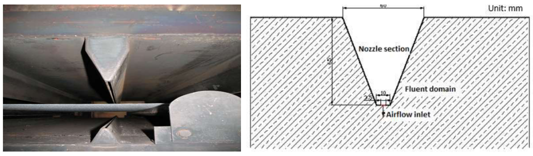

Fig. 8. Schematic diagram of the studied oven.

Table 1. Airflow velocity at the nozzle outlets (in m/s)

Distance from oven entrance (in m)	Zone 1		Zone 2		Zone 3	
	0-2	2-4	4-6	6-8	8-10	10-12
Upper nozzle	4	8	12	16	20	4
Lower nozzle	2	4	8	8	8	4

3.1. Model validation

For the curing of the product, the product needs to be heat up to 170°C and maintain this temperature for 60 seconds. For the verification of the developed model, the full scale model was solved and the temperature distribution on the product was estimated. Furthermore, using a thermos-camera, the surface temperature of the product at various distances from the entrance of the oven was measured.

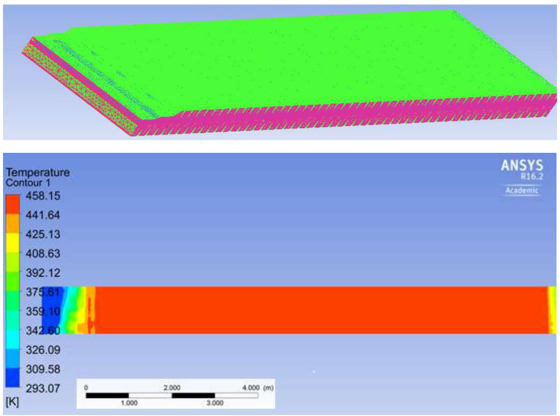

Fig. 9. Full scale model (top) and temperature distribution (bottom).

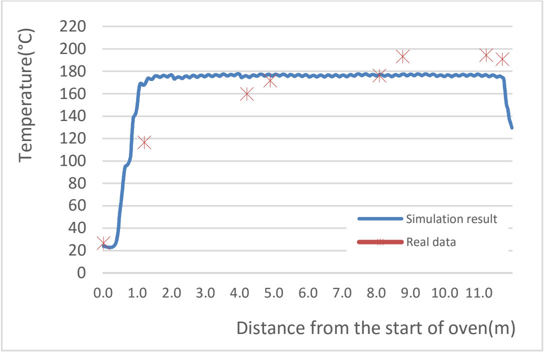

Fig. 10. Comparison of the product temperature between simulation result and experimental data.

The mesh of full scale oven is shown in figure 9. The number of cells is approximately 20 million. The model was submitted to Astral system in Cranfield University and run for about 3 days in order to produce the temperature distribution.

The simulation results were compared to the experimental measurements (figure 10). The model can simulate the temperature profile with acceptable accuracy. The deviations can be accounted to the measurement technique used and the limited access to the inside of the oven.

4. Results

4.1. Effect of the line speed on the temperature distribution

In order to validate the physical settings of the moving product in the CFD software, a 10-nozzle model was carried out at 5m/s of airflow inlet, changing the product speed from 0.15m/s to 0.6m/s. The temperature distribution at different line velocities are shown in Figure 11. Figure 12 shows the comparison of temperature distribution along the length of oven at different floor speeds 0.15m/s, 0.3m/s, 0.6m/s.

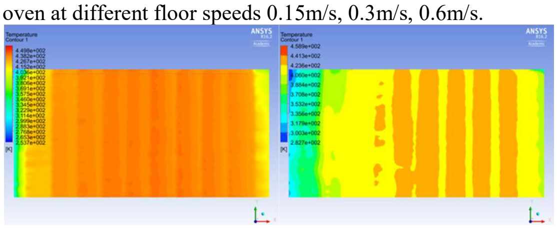

Fig. 11. Temperature distribution under inlet: 5m/s, line speed: 0.15 m/s (left) and 0.30 m/s (rigtht).

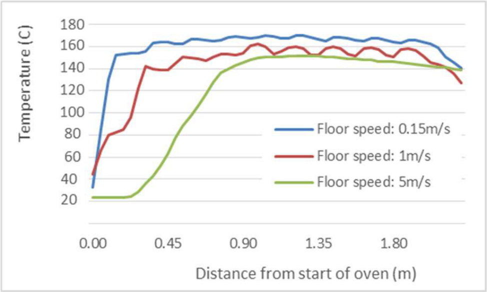

Fig. 12. Line speed effect comparison on product temperature

4.2. Effect of velocity of airflow inlet on the temperature distribution

The effect of different velocitys of airflow inlet on the temperature distribution was also analyzed. Figure 13 show the different temperature distributions of floor for various inlet temperatures. As it is expected, ejecting hot air at higher velocities result in higher temperature on the product.

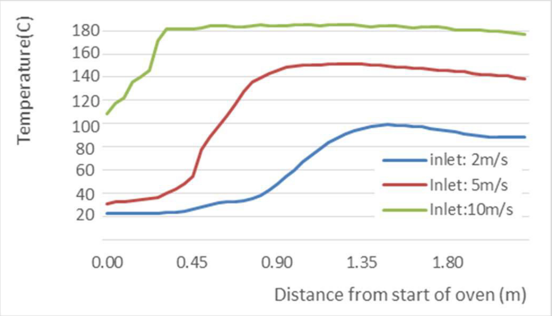

Fig. 13. Comparison at different velocities of outlet on the product temperature.

4.3. Line speed optimization

As already explained, for the curing of the product, it is required that the product temperature exceeds 170°C for at least 60 seconds (figure 14). Therefore, the line speed needs to be selected accordingly. Since the oven has a length of 12 m, the distance from the entry of the oven where the product need to be at the critical temperature to stay at least 60 seconds before exiting the oven can be easily calculated using the following equation:

$$L = L_{oven} - v_{line}.t_{exp} \quad (1)$$

Where v_{line} indicates the line speed, t_{exp} is the exposure time for the curing of the product and L_{oven} is the length of the oven. Since the line is currently working with a nominal speed of 0.15 m/s, using equation (1) it can be concluded that the product needs to be heated to the critical temperature within 3 m. Table 2 indicates thus the length L as a function of the line speed. It is obvious that the maximum line speed is less than 0.2 m/s, and any attempt to increase the speed would require either the expansion of the oven, or the use of plastics that can be cured at higher temperature and thus in less time. However, CFD analysis can be used to increase the efficiency of the heating and thus allow the increase of the line speed. This can be achieved, through several different modifications, such as changes on the nozzle geometry as to increase the amount of heat air ejected onto the product surface, increasing the velocity of the air jet and increasing the temperature of the hot air.

Table 1. Airflow velocity at the nozzle outlets (in m/s)

Line speed (m/s)	0.15	0.16	0.17	0.18	0.19	0.20
Length L	3	2.4	1.8	1.2	0.6	0

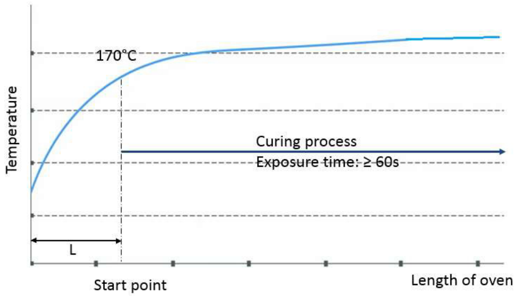

Fig. 14. Temperature distribution under inlet: 5m/s, line speed: 0.15 m/s (left) and 0.30 m/s (rigtht).

Since the goal is to reduce the length L, the model is focused in the entrance of the oven, and thus there is not the need for solving the whole oven, reducing thus the computation time. Afterwards the maximum line speed with the existing setup was investigated. The results of this investigation are shown in figure 15. When line speed was increased to 0.16m/s, the temperature went up to 173.11°C after 0.96m, which met requirement of curing process (Table 2: 2.4m), but when the speed of floor was increased to 0.17m/s, the temperature reached the required temperature at 1.91m, which does not meet the requirement (table 2: 1.8m), so the maximum line speed with the existing oven setup is 0.16m/s.

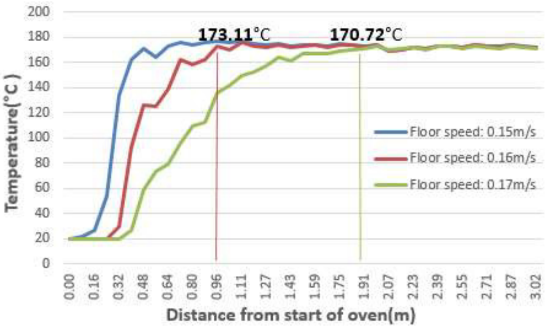

Fig. 15. Comparison at different velocities of outlet on the product temperature.

As indicated, one of the possible solutions for increasing the speed of the line is to increase the temperature velocity of airflow. When the temperature of hot air was increased to 200°C, the product was heat up to required temperature at 1.11m which is within 1.8m, which means the maximum speed of floor was achieved up to 0.17m/s. Similarly, if the airflow inlet velocity is increased by 2m/s, the product reaches the critical temperature within 0.64m, allowing for a line speed of 0.17m/s.

Finally, a simple modification of the nozzle geometry was considered. The structure of modified nozzles was designed by shortening the height of nozzles by 10mm as shown in Figure 16.

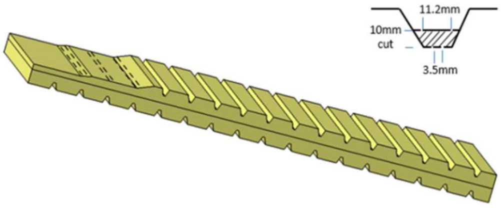

Fig. 16. Structure of modified nozzles.

The results show that the thermal efficiency with shortened V-nozzles was improved a lot compared to existing V-nozzles, (figure 17), because when the height of V-nozzle was shortened, the width of airflow inlet at the nozzle increased from 3.5mm to 11.2mm, which allowed more amount of hot air distributed to the surface of floor, causing the temperature to climb up quickly.

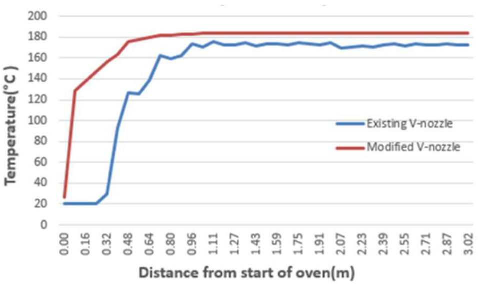

Fig. 17. Study on effect on the product temperature by modification of nozzle

4.4. Cycle time improvement

Within manufacturing, cycle time is defined as the average successive time between completions of successive units. It is a measure of Throughput (units per time), which is the reciprocal of Cycle Time. Since the production is continuous and not in discrete products, the cycle time needs to be related to the production of a set length of product, in this case a meter of length of product. In the production line presented in the present paper, as has been already mentioned, the cycle time is driven by the amount of time the product must be retained at the elevated curing temperature. Therefore, based on the CFD findings, the improvement in cycle time for the various improvements is shown in fig. 18.

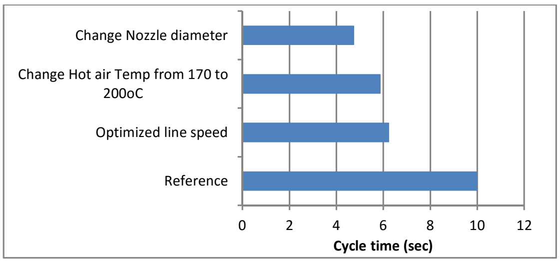

Fig. 18. Cycle time (time for manufacturing a meter of product) improvement as a function of different improvements.

As can be seen, by simple optimizing the speed of the production, the cycle time of the process can improve by 37.5%. If the temperature of the hot air is increased by 30ºC, then the cycle time can be improved by 41% and if the nozzles' geometry is modified (a change that requires some minor investment), the cycle time is improved by 53%.

5. Conclusions

In the present study, a CFD model was developed to investigate the thermal-transfer efficiency of the existing hot - air convection ovens in a continuous production lines. The maximum speed of the line given the capabilities of the existing oven was calculated. The increase of the line speed was investigated by varying the temperature, velocity of airflow, and modifications of nozzles.

Through simple modifications the line speed can be increased, allowing the reduction of cycle time.

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Disclaimer

All results have been multiplied by a factor X for commercial confidentiality reasons.

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