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A systematic approach to numerical analysis and validation for industrial oven design and optimization

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A R T I C L E   I N F O

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A B S T R A C T

The findings of this research not only provide valuable insights into industrial oven design but also demonstrate the broader importance of adopting systematic approaches and incorporating numerical analysis techniques to achieve clean energy goals. By leveraging such approaches across various industrial sectors, we can pave the way for a greener future, where energy efficiency, environmental sustainability, and economic growth can harmoniously coexist. In today's rapidly evolving world, where the need for sustainable practices and clean energy solutions is more critical than ever, research plays a pivotal role in driving innovation and addressing environmental challenges. The study presented in this article aligns with this overarching goal by focusing on the optimization of industrial oven design, aiming to achieve energy efficiency and high-quality product outcomes. Efficient oven design and optimization hold significant implications for energy conservation, reducing greenhouse gas emissions, and minimizing environmental footprints. By precisely controlling heat distribution and velocity within industrial ovens, such as the one investigated in this study, resource consumption can be minimized, resulting in reduced energy usage and improved operational efficiency. Moreover, the enhanced uniformity in temperature and airflow distribution ensures optimal product quality, reducing waste and promoting sustainable production practices. A systematic approach to numerical analysis and validation for industrial oven design and optimization is developed. Computational fluid dynamics (CFD) and the Taguchi design of experiment methods were employed to determine the influential design variables. The 3D CFD model was then compared with experimental results to validate its accuracy. An experimental oven design was developed based on optimal signal-to-noise (S/N) ratios, and the numerical findings were corroborated through experimental measurements, demonstrating a strong agreement. The proposed approach, encompassing the design, manufacturing, and analysis stages, can be applied to diverse industrial oven designs. Using the Taguchi method, the optimal configuration for the industrial oven was determined with the following parameters: four fans (A), spaced 240 mm apart (B), and positioned at a height of 250 mm (C). This configuration was found to provide the best balance of airflow distribution and heat transfer, ensuring uniform cooking throughout the chamber.

Endüstriyel fırın tasarımı ve optimizasyonuna yönelik sayısal analiz ve doğrulamaya sistematik bir yaklaşım

M A K A L E   B İ L G İ S İ

Anahtar Kelimeler:
Taguchi DOE
Deney tasarımı
Ortogonal diziler
Hesaplamalı akışkanlar dinamiği (HAD)
Optimizasyon

Ö Z E T

Bu araştırmanın bulguları yalnızca endüstriyel fırın tasarımına dair değerli bilgiler sağlamakla kalmıyor, aynı zamanda temiz enerji hedeflerine ulaşmak için sistematik yaklaşımları benimsemenin ve sayısal analiz tekniklerini birleştirmenin büyük önemini de gösteriyor. Çeşitli endüstriyel sektörlerde bu tür yaklaşımlardan yararlanarak enerji verimliliğinin, çevresel sürdürülebilirliğin ve ekonomik büyümenin uyumlu bir şekilde bir arada var olabileceği daha yeşil bir geleceğin yolu açılabilir. Verimli fırın tasarımı ve en iyileştirilmesi, enerji tasarrufu, sera gazı emisyonlarının azaltılması ve çevresel ayak izlerinin en aza indirilmesi gibi önemli etkilere sahiptir. Bu çalışmada endüstriyel fırın tasarımı ve en iyileştirilmesine yönelik sayısal analiz ve doğrulamaya yönelik sistematik bir yaklaşım geliştirilmiştir. Etkili tasarım değişkenlerini belirlemek için hesaplamalı akışkanlar dinamiği (HAD) ve Taguchi deney tasarım yöntemleri kullanılmıştır. 3 boyutlu HAD modellerinden çıkan sonuçlara bağlı olarak, sinyal-gürültü (S/N) oranları belirlenmiş, en yüksek verimlilik için, tasarım değişkenlerinin değerleri tespit edilmiş ve bu değerlere bağlı olarak deneysel bir fırın tasarımı geliştirilmiştir. HAD analizlerinden elde edilen sayısal değerler ile deneysel ölçümlerden elde edilen değerler arasında güçlü bir uyum görülmüştür. Tasarım, üretim ve analiz aşamalarını kapsayan önerilen yaklaşım, çeşitli endüstriyel fırın tasarımlarına uygulanabilir. Taguchi yöntemi kullanılarak, endüstriyel fırın için optimum yapılandırma aşağıdaki parametrelerle belirlendi: dört fan (A), 240 mm aralıklı (B) ve 250 mm yükseklikte konumlandırılmış (C). Bu yapılandırmanın, hava akışı dağılımı ve ısı transferi arasında en iyi dengeyi sağlayarak, hazne boyunca düzgün pişirme sağladığı bulundu.

INTRODUCTION

The aim of the design process is to address future customer demands. To achieve this, design offices should follow five key steps: identifying needs, defining requirements, conducting background research, developing solutions, and continuously improving solutions based on testing. In a world of rising energy costs and increased competition, there is a growing demand for multifunctional and modular designs that offer lower energy consumption. Furthermore, intense competition and rapidly changing market conditions require design offices and manufacturers to restructure their processes to deliver products to end-users faster and more reliably. This shift is also essential for industrial ovens operating at high capacities. Companies that align their design processes with this approach will gain a competitive advantage. In recent years, numerical simulations have been increasingly utilized to streamline the preliminary design, development, and testing processes of products. By reducing the number of required tests and prototypes, these simulations help to minimize costs. Numerous researchers have conducted studies on similar topics, highlighting the significance of this approach.

Norton and Sun reviewed the studies of using CFD as an effective design and analysis tool in the food industry (Norton & Da-WenSun, 2006). Boulet et al. modeled the transient heat transfer in a baking oven using Fluent (Boulet et al., 2010). Their model showed good agreement with the experiments and revealed the contribution of wall temperatures of the chamber. They did not take moisture into account. They used the reliable k-epsilon turbulence model. Kokolj et.al. studied different fan covers for a forced convection oven and presented a validation of numerical methodology. Uniformity between browning and temperature distribution is chosen as the assessment point. Their simulations were 3D time-dependent with both convective and radiative heat transfer mechanisms and also include an evaporation model for the baking process. They developed and validated a CFD model to predict the baking performance and grade of browning of a forced convection oven (Kokolj et al., 2017). Rek et.al. used CFD as a design tool for a new-generation cooking appliance. They created different discrete models and analyzed the influence of geometry boundary condition changes (Rek et al., 2012). They validated the result with measurements taken from an oven prototype. Fahey et.al. studied the flow through the door of a pyrolytic oven. They made a steady-state 2D numeric analysis using ANSYS CFX and compared the velocity and temperature results on specific points. They used hot-wire anemometry for velocity measurements and thermocouples attached with aluminum tapes and found all CFD results agree within %3 of the experimental results (Fahey et al., 2008). Smolka et.al. present CFD analysis and experimental analysis of the flow and heat transfer mechanism in a natural convection oven. They used extensive thermocouple arrays and PIV for verifying the temperature distribution and the velocity distribution (Smolka et al., 2013). Morales et.al. defined a linear programming problem and modeled the brick oven's combustion process to determine the burner's optimal location (Vizguerra-Morales et al., 2016). Tank et.al. developed a CFD model to study temperature profiles during the baking process for partially and fully loaded ovens (Tank et al., 2014). Yi et al developed a CFD model for simulating the thermal transfer efficiency of an existing hot air continuous convection oven. To increase the line speed, they investigated the effect of the velocity of airflow and temperature (Yia et al., 2017). Stojanovic and his colleagues examined the tribological behavior of an aluminum-based hybrid composite material using the Taguchi method and determined the factor that most affects the wear rate by examining it with the ANOVA method (Stojanović et al., 2015). Ünver and Küçük made an efficiency comparison for plate heat exchangers using the Taguchi method and CFD, and found that the most effective variables were duct height and air flow rate (Ünverdi & Küçük, 2019). Biçer and his colleagues proposed a new and innovative baffle design in shell-tube heat exchangers, using the CFD and Taguchi methods, to significantly reduce the shell-side pressure loss without losing thermal efficiency, and achieved a 49% reduction in the shell-side pressure drop compared to the traditional structure (Biçer et al., 2020). Tambolkar and his colleagues performed filter design optimization using CFD-Separated Phase Modeling and Taguchi approach to maximize filtration efficiency and increase the reusability of the liquid by changing the input parameters (Tambolkar et al., 2020). Obidowski et al. used the response surface method combined with genetic algorithm to develop an effective approach to the problem of geometry optimization of a non-axisymmetric flow channel (Obidowski et al., 2021). Amadene and his colleagues used a 3-level, 3-variable Taguchi approach and CFD simulations to optimize the variables affecting fuel cell efficiency (Amadane et al.). Chandra and his colleagues used CFD simulation and Taguchi experimental design method to optimize the natural ventilation of indoor spaces (Chandra et al., 2022). Aydin et al. designed and optimized a multi-compartment heat exchanger on the basis of lowest cost, using an optimization method he developed (Aydın et al., 2022). Yüce and his colleagues used Taguchi, ANOVA and GRA experimental methods and CFD simulations to optimize ventilation efficiency in buildings (Yuce et al., 2022). İç and Yıldırım used the Taguchi approach to determine the levels of factors that optimize the product quality of a washing machine (İç & Yıldırım, 2012). Özer et al. carried out CFD analysis of the squeezing phase of a washing machine and showed its compatibility with experimental results (Özer et al., 2016). Demir and Aküner determined the variables affecting the in-wheel asynchronous motor efficiency with the Taguchi approach and designed the experiment, and then determined the variable levels according to the experimental results using the ANSYS RMXprt program (Demir & Aküner, 2018). Türkan, on the other hand, carried out the experiments he designed using the Taguchi experimental design method for vehicle cooler optimization with CFD simulations and determined the levels of the variables that gave the best efficiency value (Türkan, 2024). Kahraman and Sugozu used Taguchi method to optimize the design parameters of brake pad (Kahraman & Sugözü, 2019). Shimpy et al. used Response Surface Methodology and CFD to design a domestic solar dryer. They defined design variables and created a design of experiment array. They used COMSOL software for experiment runs (Shimpy et al., 2024).

This study focuses on optimizing the internal velocity and heat distribution in an industrial belt oven with forced convection, utilizing the Taguchi design method developed by Dr. Genichi Taguchi. The objective is to meet the demands for low operating costs and low product prices by enhancing the homogeneity of internal air and heat distribution in the oven. By achieving improved product quality and reducing operating and manufacturing costs, the study aims to optimize the oven's performance. The modeling of in-oven airflow is conducted using a three-dimensional cooking volume, employing computational fluid dynamics (CFD) with the Ansys CFX commercial software. The conservation equations for mass, momentum, and energy are solved using the finite volume method for incompressible flow. The design variables considered are the number of fans, the distance between fans, and distance from fans to the belt surface. Evaluation criteria include belt surface temperature, heat gradient deviation, and belt surface velocity deviation, each with three different levels. To validate the accuracy of the CFD analysis, an experimental oven design is created based on optimal signal-to-noise (S/N) ratios. The study parameterizes different geometries and determines their impact on air distribution. The findings of the numerical model are corroborated through experimental measurements, demonstrating a strong agreement. This comprehensive study fills a gap in the literature by providing a detailed experimental investigation of forced convection in a continuous-feed belt oven. The combination of CFD simulations and the Taguchi design method offers a systematic approach to optimizing industrial oven performance. The proposed approach, encompassing design, manufacturing, and analysis stages, can be applied to a wide range of industrial oven designs.

METHOD

In this research, a comprehensive design methodology comprising several steps has been developed to address the project's objectives. The initial stage involves formulating a preliminary design based on specific customer requirements, followed by the identification of potential variables and their respective levels. To efficiently manage the experimentation and analyses, orthogonal variable level strings are constructed using an experimental design approach, effectively reducing the number of required tests. These identified variable level strings are then utilized to create the necessary geometry through CAD software, which is subsequently imported into mesh software for mesh generation.

The next crucial step entails performing numerical modeling within a specialized CFD software. This involves establishing a robust mathematical model, defining material properties, and setting boundary conditions to accurately simulate the system under investigation. The CFD results are meticulously evaluated using the experimental design approach, leading to the determination of optimal parameter values.

Furthermore, a physical prototype is manufactured based on the identified optimal variable values, and its performance is compared to the results obtained from the CFD analysis conducted with the same optimal variable values. Should the observed differences between the physical prototype and the CFD analysis be justifiable and fall within acceptable levels, the design and its corresponding variable levels are accepted, paving the way for the commencement of the detailed design process. Conversely, if the differences prove unacceptable or unexplainable, the project undergoes a thorough reevaluation, necessitating a return to the preliminary design phase to rectify any discrepancies.

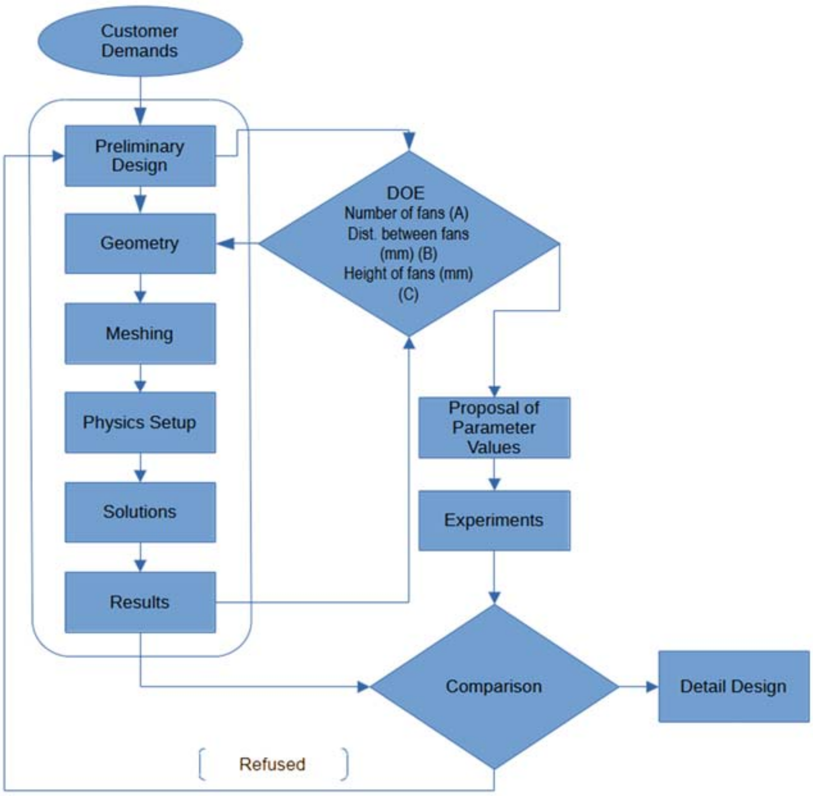

Fig.1 Methodology

The Intended Oven Geometry and Operation of the Device

When the forced convection industrial ovens are examined, it is seen that the fans with radial geometry are mostly aligned along the direction of travel. Fans can be blown directly over the belt or air can be sucked and redirected through a channel. In such a discrete channel structure, the position of the suction holes and the location of the blow holes in which the air is directed to different regions of the belt is of high importance for the air distribution in the oven and therefore for the optimization of the heat distribution. The heaters can be placed in parallel with the flow direction. The amount of heat needed will be reduced as a result of the optimization of the indoor air distribution.

In the general design stages of the belt oven, the systematic steps of conformity were followed. The design has been realized by taking into consideration the ease of installation and manufacturing, based on the use of modular, common parts. In the detail design phase, the assembly and manufacturing difficulties encountered during the prototype production were eliminated and visual improvements were made. The dimensions of the main cooking chamber are 1128mm in length, 295mm in width, and 337 mm in height with a porous belt surface located at the height of 100 mm. Fans sucked the air inside the chamber to a discrete channel structure and the air is blown back to the main cooking chamber with blowing holes located at a height of 63mm.

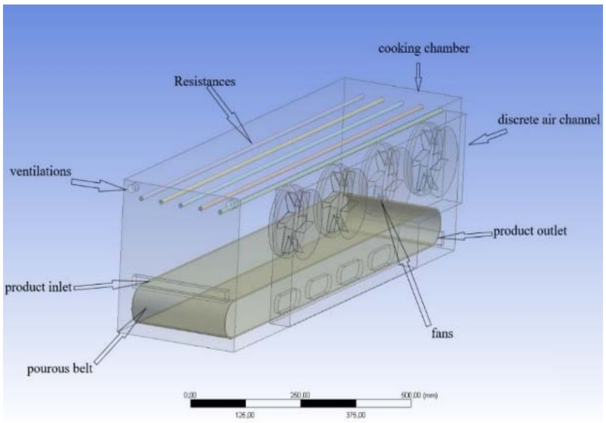

Fig.1 General layout

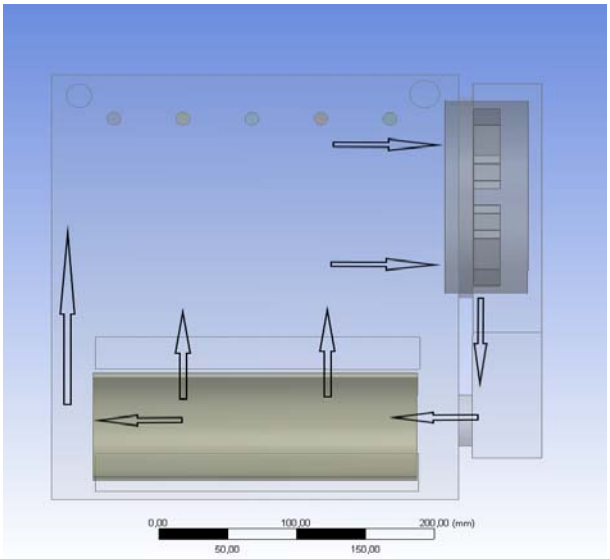

Fig.2 Air circulation

The distance between the suction fans (L_f) is parameterized, which changes between 170 mm to 240 mm with 35mm increments. Also, the vertical location of fans is parameterized, which is changed between 200mm to 250mm with 25 mm increments. The number of fans changed between 2 to 4. Fans are positioned symmetrically on both sides of the oven centerline. Product inlet and product outlet details are excluded from the design because of the complexity. Air circulating hole dimensions and locations were kept constant due to construction issues. A stainless-steel chain belt with a porosity of 0.5 volume fraction is used. Resistances are located under the top side of the oven. Each resistance has a power of 900W. Although the total power of the heaters used in the oven is 4.5kw, only a certain amount of this power will be used to maintain the temperature inside the oven after the set temperature is reached. In Fig.1, the schematic drawing of the proposed oven is given. In Fig.2, a schematic of the proposed air circulation is given.

All sides of the heating chamber were covered with 20 mm glass wool isolation material except the product inlet, the product outlet, and the ventilation openings. The heating chamber was isolated from the main chassis to prevent critical areas such as maintenance doors and electronics from overheating.

Design of Experiments

The most important factor on product quality is minimizing the changes in the conditions on the belt surface where the products start to bake. Therefore, the temperature and velocity standard deviation over the belt surface was determined as the oven's performance criterion. First of all, all the factors affecting the oven performance were revealed by using the fishbone diagram. Based on the fishbone diagram, the factors to be taken as constant and variable during the experiments were decided (Fig. 3). The type and humidity of the grains to be processed are not controllable parameters due to the multifunctionality of the oven. Depending on the user's needs, the operating temperature and fan speed can be changed by the user, so these two parameters are considered fixed. Ambient temperature and ambient humidity are also not controllable variables. For economic reasons, the material variables are assumed to be constant. equipment parameters have been chosen as variables. The Taguchi experimental design method used to define orthogonal arrays containing variables and the different levels of variables to investigate how different variables affect process performance. Instead of testing all variable combinations as in the classical factorial design, combination pairs are tested in the Taguchi method, reducing the number of tests necessary to collect the necessary data to determine the variables that affect the process the most, thus saving time and resources.

Three different factors and three different levels for each factor are given in Table 1. After the experimental parameters and levels were determined, the three-variable, three-level Taguchi orthogonal array, L9(3^3), is created and given in Table 2. While 27 experiments will be conducted with factorial design, only 9 experiments were conducted using Taguchi experimental design.

Table 1 Parameters and levels

Parameters	L1	L2	L3
Number of fans (A)	2	3	4
Dist. between fans (mm) (B)	170	205	240
Height of fans (mm)(C)	200	225	250

Table 2 Taguchi L9 Orthogonal Array

	Taguchi L9 (3^2), P3, L3		
Run	A	B	C
1	2	170	200
2	2	205	225
3	2	240	250
4	3	170	225
5	3	205	250
6	3	240	200
7	4	170	250
8	4	205	200
9	4	240	225

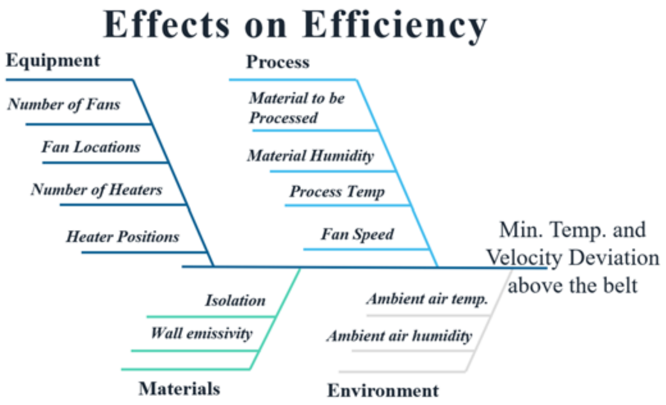

Fig. 3 Fishbone diagram

Numerical Solutions

To analyze a continuous and differential fluid flow, Navier-Stokes equations, which are derived from the laws of conservation of mass (continuity), conservation of energy (first law of thermodynamics), and conservation of momentum (Newton's second law of motion), are used. Conservation of mass is the general law that states that the amount of mass change in a given fixed control volume is equal to the difference between the amount of mass entering and leaving. The law can be formulated for compressible flows in differential form as:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho V) = 0 \tag{1}$$

And for incompressible flows $\left(\frac{\partial \rho}{\partial t} = 0\right)$, law of continuity will be:

$$\nabla.(V) = 0 \tag{2}$$

Conservation of energy or the first law of thermodynamics simply states that energy can neither be created nor destroyed, it can only be converted from one form to another. In other words, for a fixed control volume, the rate of energy change is equal to the heat addition and work done, total energy remains constant. For the steady state, incompressible flow conservation of energy law will be:

$$\rho c_v \frac{dT}{dt} = k\nabla^2 T + \theta \tag{3}$$

The Law of conservation of momentum or Newton's second law of motion states that the rate of momentum change in a control volume is equal to the sum of the external forces. For the steady state, incompressible flow conservation of momentum law will be:

$$\rho \frac{dV}{dt} = \rho g - \nabla p + \mu \nabla^2 V \tag{4}$$

For the above equations, V is the velocity field, p is the pressure, T is the temperature, k is the thermal conductivity, ρ is the density, g is the gravity, t is the time, μ is the viscosity, ϴ is the viscous dissipation function.

The Navier-Stokes equations have no analytical solutions except for very simple flows under ideal conditions. To find solutions in real flows, numerical methods using algebraic approaches must be used. For numerical modeling and solving the conservation equations, ANSYS CFX, a computational fluid dynamics program that uses the finite volume method, was used. ANSYS CFX uses an element-based finite volume method, which first involves discretizing the spatial domain using a mesh. The mesh is used to construct finite volumes, which are used to conserve relevant quantities such as mass, momentum, and energy (Inc A. , 2011). The finite volume method is widely used in fluid dynamics and heat transfer problems (Norton & Da-WenSun, 2006).

All fans are modeled as rotating bodies that had transient rotor-stator interface model boundary conditions in a stationary fluid domain, based on the standard Φ150mm diameter oven fan (Fig.4).

Fig.4 Φ150mm oven fan

Angular velocities of all rotating fan bodies are equal to 2800rpm and constant. Possible rpm changes due to temperature are neglected. All walls have a thermal conductivity value of 0.04W/m.K.

The standard k-epsilon turbulence model is not recommended for flows impinging on surfaces because the turbulence energy may be over-predicted at the stagnation points (Durbin, 1996). SST (shear stress turbulence) method is validated by researchers (Kokolj et al., 2017) (Kokolj et al., 2017) and also used for this analysis. For the heat transfer mechanism Total Energy and for thermal radiation Monte Carlo approaches were used. For more accurate solutions, physical modeling errors and mesh quality must be considered. Ansys CFX uses scalable wall functions to solve the boundary layer profile near-wall regions in turbulent flow with an acceptable computational load. But there is a danger of overestimating the boundary layer so a non-dimensional parameter y+ (YPLUS) is used for quality check. y+ is a non-dimensional variable representing the distance from the wall to the first node away from the wall. As the y+ increase, the wall-type conditions will be imposed further from the wall by scalable wall functions. By definition, y+ is dependent on the size of the mesh near wall regions (Inc., 2011). The upper limit of y+ is a function of the Reynolds number and for large Reynolds numbers as Re=10^9, y+ can be around 1000 or more but for typical applications which have lower Reynolds numbers, entire boundary layers might only extend around y+=300 for not overestimations, and not to underestimate the boundary layer, lower bound for y+ will be y+=30. (Inc A. , 2011). As Ansys CFX uses scalable wall functions, no need to worry about the lower limit for y+. The growth rate of the elements was kept low to avoid poor quality cells but as a result of the low growth rate and complex oven geometry. Mesh size range changes due to geometric parameterization. In
Table **3** summary of the settings used in the simulation is given.

Table 3 Summary of settings used in simulations Governing equations

Total Energy for conduction and convection
Monte Carlo for thermal radiation
SST (shear stress turbulence) method for turbulence modeling
Material properties
All air properties temperature-dependent
Thermal conductivity of the wall insulation, 0.04 W/(mK)
Constant solid material properties
Boundary conditions
Product inlet, product outlet, and ventilation holes defined as openings
External walls, mixed convective and radiative heat flux

The mesh is a hybrid of tetrahedra and hexahedra elements. The maximum element skewness, aspect ratio, and orthogonal quality index values of the elements and their recommended values (Inc A. , 2009) are given in Table 4. Air is defined as an incompressible ideal gas. The thermal conductivity, viscosity, density, and specific heat of air were considered temperature-dependent. All solid material properties were considered fixed. Product inlet, product outlet, and ventilation holes are defined as openings to the atmospheric pressure and ambient room temperature (25 °C). The belt speed is not included in the simulations as it varies according to the product to be processed.

All analyses were performed as transient with a full buoyancy model due to the extreme complexity of the flow and heat transfer mechanisms. The first-time step is 1 s with an adaptive timestep setting and the max number of the time steps is 80. The target max loop number is 5 and the target min loop number is 2. The Total Energy heat transfer model and Monte Carlo thermal radiation model with isotropic scattering model were used. The inflation layer settings for meshing were defined with a transition ratio of 0.77, maximum layers of 5, and a growth rate of 1.2. The smooth transition option was used to ensure a gradual increase in layer thickness, optimizing the boundary layer resolution without a sharp size change in the mesh elements (Fig.5). Grid sensitivity analysis is done for Run1 with 2.5, 3, 3.5 and 4 million elements. And found that for above 3 million elements, belt surface temperatures deviations for intended point is below % 2. For timestep 80, temperature levels stabilized. From these results model concluded as grid independent.

Table 4 Mesh quality parameters

	Model	Recommended
Elm. size range	~3,500.000	
Max.Elm. skewness	0.9481	<0.95
Max. Aspect ratio	34.186	<35/1
Orthogonal quality	0.25	>0.14

A grid sensitivity analysis was conducted to ensure the accuracy and reliability of the CFD results for the industrial oven, specifically focusing on the belt surface temperature at three distinct points (x:0.24, y:0.15; x:0.502, y:0.15; x:0.753, y:0.15) (Table 5). The analysis was performed using four different grid sizes: 2.5, 3, 3.5, and 4 million cells. The belt surface temperatures at the selected points demonstrate that, as the grid resolution increases, the temperature values converge. For instance, at Point 1 (x:0.24, y:0.15), the temperature increases from 204.8°C with a 2.5M grid to 278.7°C with a 3.5M grid, before slightly stabilizing at 272.3°C with a 4M grid. Similar trends are observed at Points 2 and 3, where the temperature values fluctuate initially but show stabilization as the grid resolution increases. These results indicate that the solution becomes grid-independent between 3.5M and 4M cells, confirming that further refinement would not significantly alter the simulation outcomes. Therefore, a grid size of 3.5M cells was selected as a compromise between accuracy and computational efficiency.

Table 5 Grid Sensitivity

	Belt surface temp at point		
	x:0.24 y:0.15	x:0.502 y:0.15	x:0.753 y:0.15
Grid	p1	p2	p3
2.5	204.8	148.1	192.5
3	259.2	153.3	158.0
3.5	278.7	157.5	169.9
4	272.3	164.9	162.3

For each model, it took approximately 8 hours to calculate the mesh structure and numerical simulations. All calculations were made on a workstation with a quad-core 3.80GHz Xeon processor and 32GB of ram.

In the Taguchi method, the signal-to-noise ratio (S/N Ratio) is used to measure the variability between experimental data. Three types of S/N Ratios are defined in the Taguchi method: smaller is the best, nominal is the best, and larger is the best. In this study, the smaller is the best (Eq.(5)) approach was used since it is aimed to have the lowest deviations in the temperature and velocity distribution on the belt surface where the product is treated. CFD models were compared due to belt surface velocity and temperature deviations. Belt surface temperature and velocity deviations transformed into S/N ratios are given in Table 6 . The aim of this study is to minimize the deviations so the S/N ratio is defined as in equation (5).

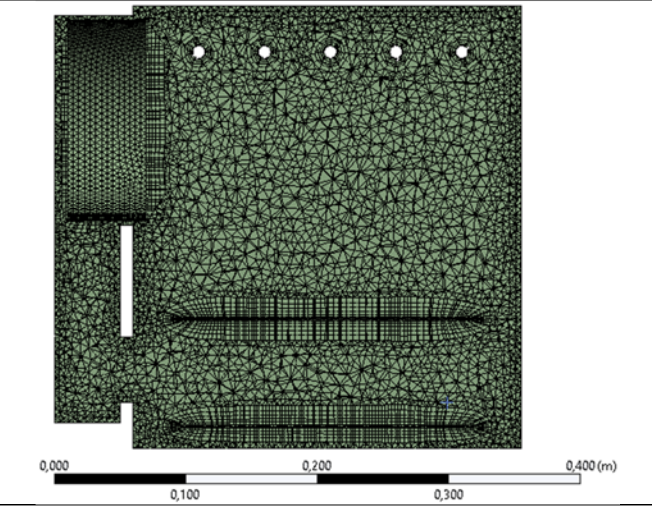

Fig.5 Mesh structure with inflation layers

$$SN_s = -10\log(\frac{1}{n}\sum_{i=1}^{n} y_i^2) \quad (5)$$

Table 6 S/N ratios for Taguchi DOE runs

Run	A	B	C	SNRA-Temp	SNRA-Vel
1	1	1	1	-32.856	-0.172
2	1	2	2	-34.762	0.468
3	1	3	3	-29.971	3.715
4	2	1	2	-33.174	-0.442
5	2	2	3	-32.690	0.250
6	2	3	1	-29.311	-0.649
7	3	1	3	-30.365	4.243
8	3	2	1	-32.826	-2.047
9	3	3	2	-31.716	0.543

Table 7 Response Table of means of SN Ratios for temperature deviations

Level	Mean A-Temp	Mean B-Temp	Mean C-Temp
1	-32.529	-96.395	-94.993
2	-31.725	-100.278	-99.651
3	-31.636	-90.998	-93.026
Delta	0.089	5.397	6.626
Rank	3	2	1

Table 8 Response Table of means of SN Ratios for velocity deviations

Level	Mean A-Vel	Mean B-Vel	Mean C-Vel
1	1.337	3.629	-2.868
2	-0.280	-1.329	0.569
3	0.913	3.608	8.207
Delta	0.424	-0.020	7.638
Rank	2	3	1

In Fig.6 and Fig.7 mean velocity change and mean temperature change are given in the X direction. To find the belt surface average temperature, 100 different point values were taken along the X-axis at the Y=0.05m, Y=0.15m, and Y=0.25m positions. All values were taken 0.01 m above the belt.

The purpose of this study is to provide the most appropriate heat and air speed distribution on the belt surface in order to ensure the continuity of the desired quality in the products to be cooked, in other words, to prevent product burning due to excessive heat formation in any area on the belt or insufficient cooking due to insufficient heat formation. For this, it is desired that the deviations in the belt temperature distributions given in Table 7 and the belt air speed distributions given in Table 8 are low. For the factors examined, the average of the signal-to-noise ratios was calculated and the factors that most affected the deviations in the temperature (Table **7**) and velocity distribution (Table 8) were determined. Regardless of which of the smaller is the best, nominal is the best, and larger is the best approaches are used to evaluate the experimental results, in calculating the S/N ratio, as the value of the calculated S/N ratio gets higher, its effect on the test result increases. For belt surface temperature deviation minimization, with the respect to the criteria smaller is the best, and the best combination of factors is A3B3C3. For belt surface velocity deviation minimization, with the respect to the criteria smaller is the best, and the best combination of factors is A1B1C3.

Variance analyzes of the parameters were performed using the S/N ratios obtained from the experimental results (Table 9, Table 10). In Table 9 and Table 10 Param. is for parameter, DOF is for degree of freedom, SS is for sum of squares, MS is for mean of squares and Cont. is for contribution.

The purpose of analysis of variance is to determine to what extent the examined variables affect the targeted values and how different levels cause variability, and at the same time to test the statistical reliability of the results obtained. The F values calculated in the analysis of variance were compared with the values taken from the F value table for $F_{0.05,2,6}$ and it was seen that 95% confidence level was provided. A3B3C3 variance is chosen for product verification.

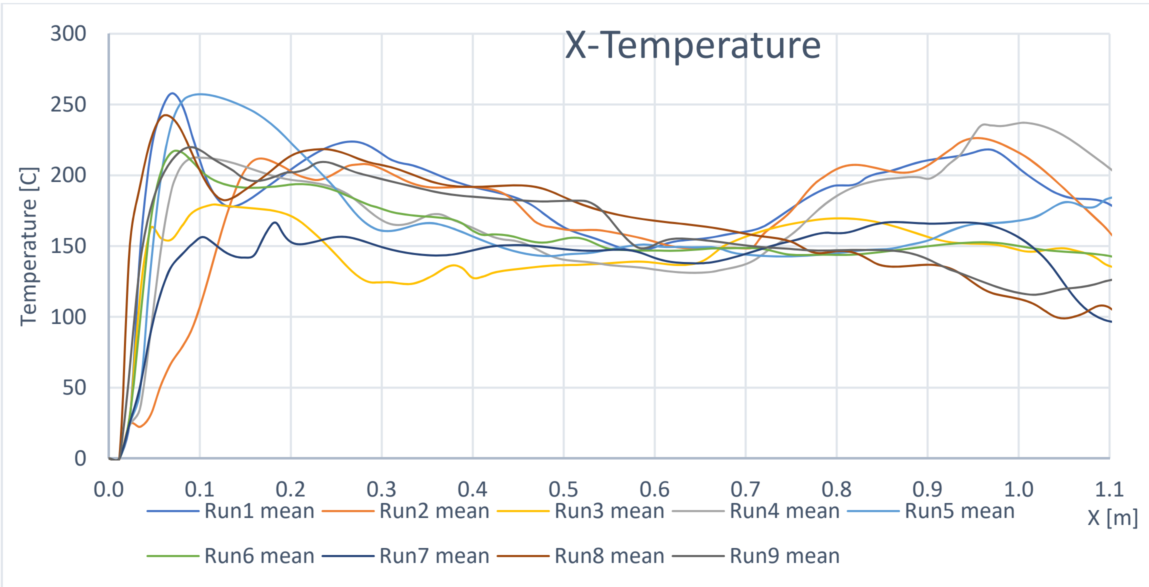

Fig.6 Velocity change in the X direction

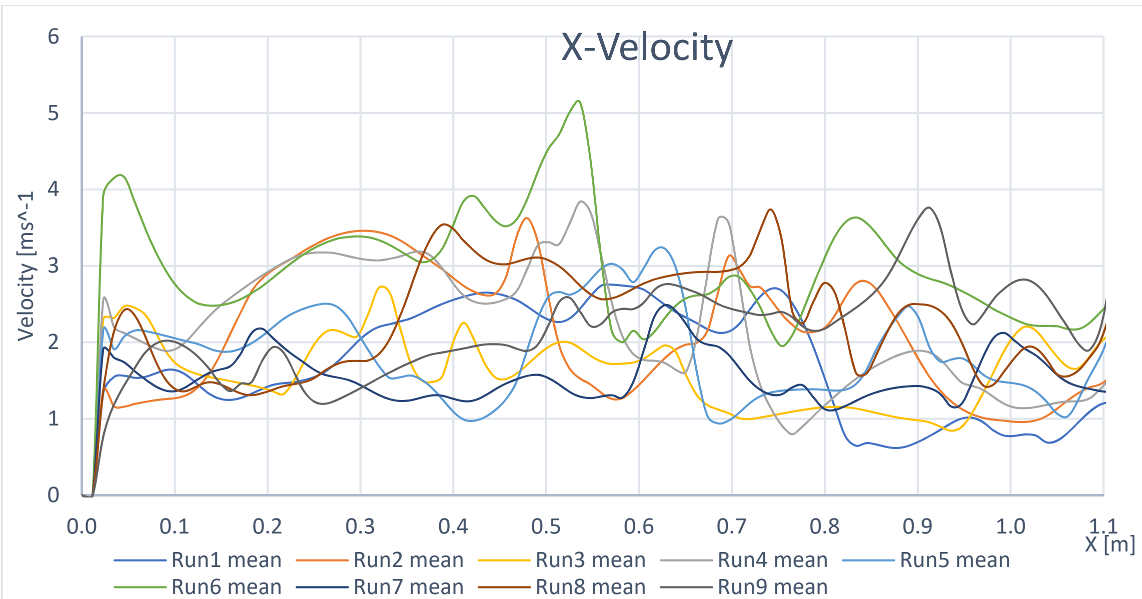

Fig.7 Temperature change in the X direction

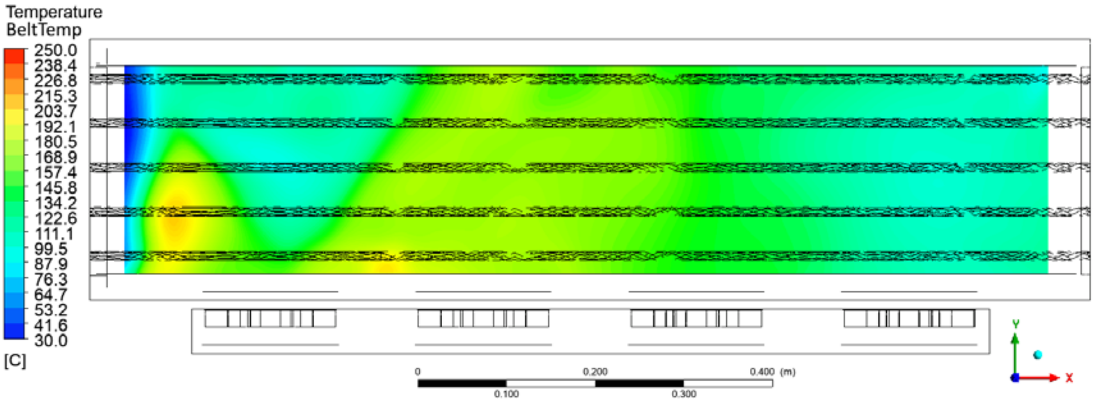

Figure 8 Belt Surface Temperature Distribution for A3B3C3 variant

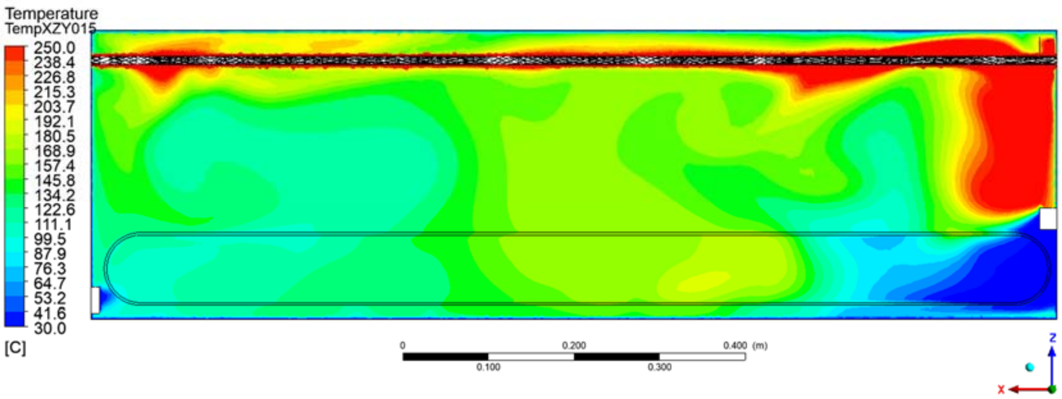

Figure 9 Mid-Section Surface Temperature Distribution for A3B3C3 variant

Table 9 Analysis of variance table for heat distribution

Param.	DOF	SS	MS	Cont. %	F
	2	16348	8174	66%	1528
B	2	4217	2108	17%	394
C	2	4156	2078	17%	388
Err.	2	11	5	0%	
Ttl.	8	24732		100%	

Table 10 Analysis of variance table for vel. distribution

Param.	DOF	SS	MS	Cont. %	F
A	2	11.1	5.6	4%	10.2
B	2	50.7	25.3	20%	46.5
C	2	194.5	97.3	76%	178.6
Err.	2	1.1	0.5	0%	
Ttl.	8	257,4		100%	

RESULTS AND DISCUSSIONS

Mathematical approaches, limited computational capacity, and insufficient understanding of the physical model cause uncertainties in computational fluid dynamics (CFD) simulations. As a result, the reliability of CFD in design processes depends on the experiments performed during the design verification process (Marvin, 1988). Due to this necessity, a prototype was manufactured and tested according to the dimensions specified in the A3B3C3 factors (Table 11) and CFD results compared with the temperature and velocity measurements, taken 1 cm above the porous band, which is thought to be the most important region in terms of product quality. Fahey et al (Fahey et al., 2008) indicated that the difference between the flow rates of heated and nonheated air passing around the cooling circuit can be neglected. Flow velocities are measured in ambient air in the unheated oven using hot-wire anemometry in specified locations. Typical accuracy for hot wire anemometers usually provides an accuracy within ±1% to ±5% of the measured velocity under optimal conditions and the manufacturer spec value for device is ±4% which is high but acceptable for highly turbulent flow.

Table 11 Prototype values

Parameters	Value
Number of fans (A)	4
Dist. between fans (mm) (B)	240
Height of fans (mm)(C)	250

To find the temperature distribution on the belt surface, standard J-type thermocouples consisting of iron and constantan which are operating in the range of 0-760 centigrade were attached 1 cm above the band surface. Thermocouples were placed along the lines Y=0.05 and Y=0.25, from the position X=0.15m to X=1.05m with 0.15m increments. For thermostat input, a thermocouple is located at x=0.4m at the midsection. When the thermostat was set to 160 °C, the oven reached a steady state at 20 minutes with 5 °C fluctuations. Iron–constantan thermocouples (Type J) offer a sensitivity of 55 μV/°C and are commonly used for general temperature measurements within the range of −40 °C to +750 °C, with an average measurement error of ±0.75% and is neglectable for a highly turbulent flow. Their functionality remains largely unaffected in both oxidizing and reducing environments (Morris & Langari, 2016).

A comparison of simulation results with experimental results is given in Fig. 10 and Fig. 11. In order to avoid human-induced errors, all experimental measurements were repeated 3 times and averaged To determine the accuracy of the simulation, the measurement values, and relative deviations are given in Table 12 and Table 13. The deviations were calculated according to the formulas below:

$$\Delta V = \frac{V_{calc} - V_{meas}}{Vmeas} x100\% \quad (6)$$

$$\Delta T = \frac{T_{calc} - T_{meas}}{Tmeas} x100\% \quad (7)$$

The model can simulate velocity and temperature profiles with acceptable accuracy for a turbulence convection heat transfer study. Deviations may be due to measurement techniques and limited access to the oven due to it being a closed volume. Specifically, the measured velocities were predicted with a relatively low deviation at most points. For measurement on the Y0.05 line, the line close to fans, most points are underpredicted with a maximum deviation of 25.28% at X=0.90m, which is near the product outlet. For measurements on the Y0.25 line, points are over or underpredicted with a maximum deviation of 19.12% at X=0.15 which is a more acceptable value for such a complex analysis. The error rate also shows a certain height because the velocity measurements are made when the oven is cold but the trend of experimental measurements is similar to the trend of CFD results.

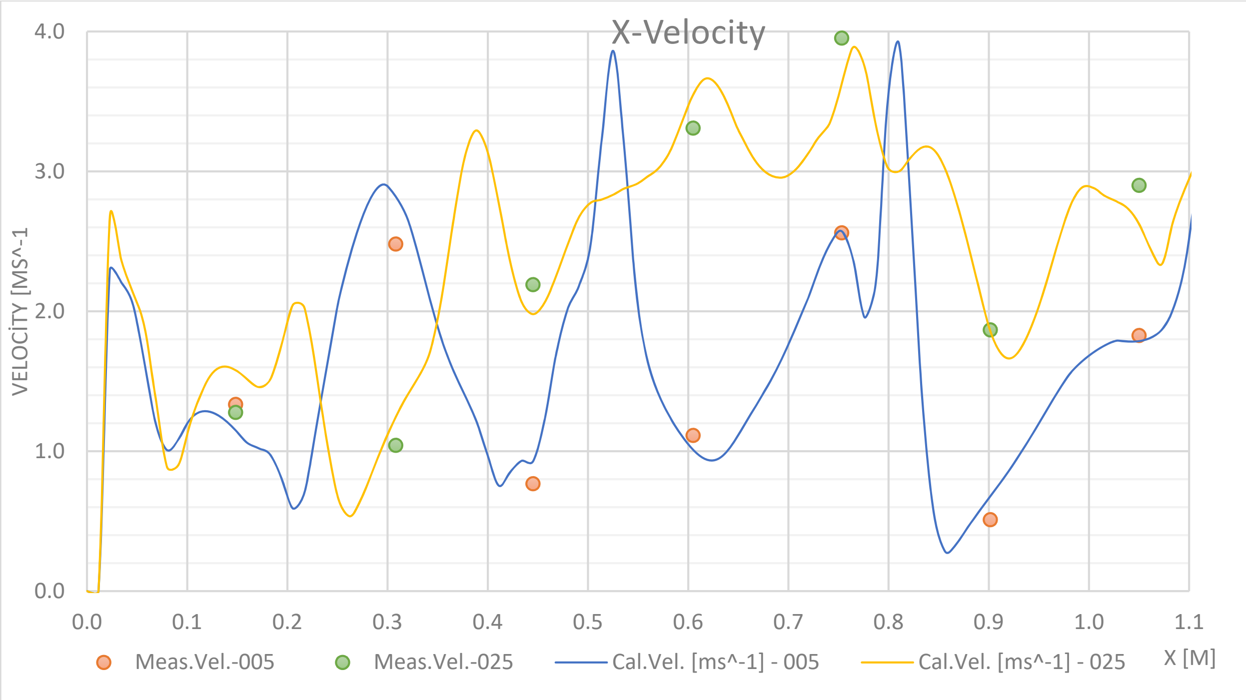

Fig. 10 Velocity distribution in the longitudinal direction

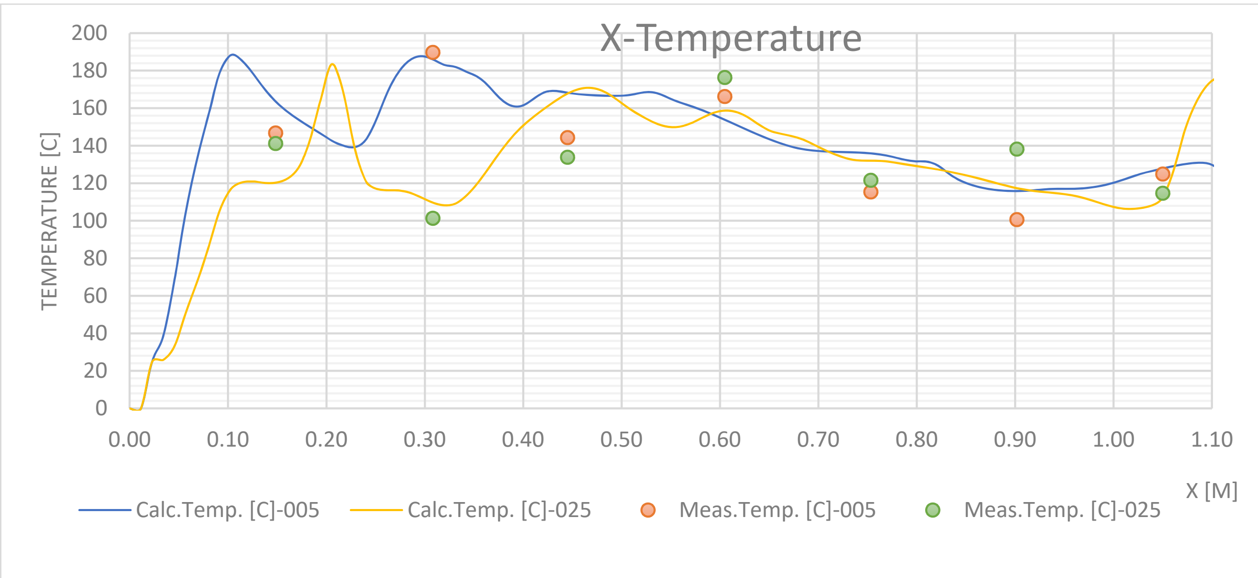

Fig. 11 Temperature distribution in the longitudinal direction

Table 12 Velocity Measurements

Vel.	Y 0.05			Y 0.25		
X [m]	Calc.(m/s)	Meas.(m/s)	Dev.%	Calc.(m/s)	Meas.(m/s)	Dev.%
0.15	1.15	1.33	16.13%	1.58	1.28	-19.12%
0.31	2.82	2.48	-11.95%	1.24	1.04	-16.39%
0.45	0.93	0.77	-17.41%	1.98	2.19	10.58%
0.60	1.01	1.11	10.12%	3.55	3.31	-6.76%
0.75	2.57	2.56	-0.47%	3.63	3.95	8.95%
0.90	0.68	0.51	-25.28%	1.85	1.87	0.67%
1.05	1.79	1.83	2.17%	2.62	2.90	10.47%

Table 13 Temperature Measurements

Temp.	Y 0.05			Y 0.25		
X [m]	Calc (°C)	Meas. (°C)	Dev.%	Calc (°C)	Meas. (°C)	Dev.%
0.15	163.54	146.77	-10.25%	120.30	141.09	17.28%
0.31	185.96	189.70	2.01%	109.71	101.31	-7.66%
0.45	168.25	144.23	-14.28%	167.86	133.76	-20.31%
0.60	153.76	166.18	8.08%	158.75	176.32	11.06%
0.75	135.94	115.26	-15.21%	132.06	121.54	-7.97%
0.90	115.86	100.58	-13.18%	117.40	138.15	17.67%
1.05	127.88	124.83	-2.38%	112.59	114.64	1.82%

Values read in temperature measurements show lower deviation rates compared to velocity measurements. While the maximum deviation in the measurements made on the Y0.05 line is -15.21% at X=0.75m, the maximum deviation in the measurements made on the Y0.25 line is 20.31%. at X=0.45m. The general distribution of the measurements made on both lines is compatible with the trend created based on the calculated values.

Although the deviation values are generally high, the experimentally measured values show a distribution by the trend drawn depending on the calculated values. Relatively high deviations can be accepted in such complex geometry problems where heat and fluid transfer in different environments are examined. Difficulties in reaching the closed oven volume and related measurement errors should not be ignored.

CONCLUSION

The performance of industrial ovens plays a critical role in achieving efficient and uniform drying and cooking processes. In this study, we focus on optimizing the internal velocity and heat distribution of an industrial belt oven utilizing Taguchi design principles. By employing computational fluid dynamics (CFD) simulations and experimental measurements, we aim to identify the key design variables and their impact on the oven's performance. This research provides valuable insights for designing and analyzing industrial ovens in various applications.

The continuous belt oven under investigation consists of a permeable stainless-steel belt and axial fans with stick-type heaters. The fans draw hot air from the main chamber and deliver it beneath the permeable belt through a back chamber. To improve the airflow distribution, the positioning of the fans and the geometry of the back chamber were carefully assessed. The internal flow patterns were analyzed to ensure optimal heat transfer and uniform drying/cooking throughout the oven.

The Taguchi design of experiments was employed to determine the most influential design variables affecting the oven's performance. The number of fans, the distance between fans, and the distance from fans to the belt surface were selected as the key design factors. The objective was to minimize belt surface temperature deviation and belt surface velocity deviation.

A 3D computational fluid dynamics model was developed to simulate the airflow and heat transfer within the oven. By systematically varying the design variables defined in the Taguchi experiment, the model allowed us to assess their impact on the internal velocity and heat distribution. This approach enabled efficient exploration of the design space and facilitated the identification of optimal settings. The proposed approach, encompassing the design, manufacturing, and analysis stages, can be applied to diverse industrial oven designs. Using the Taguchi method, the optimal configuration for the industrial oven was determined with the following parameters: four fans (A), spaced 240 mm apart (B), and positioned at a height of 250 mm (C). This configuration was found to provide the best balance of airflow distribution and heat transfer, ensuring uniform cooking throughout the chamber.

To validate the accuracy of the numerical findings, an experimental oven design was developed based on the optimal S/N ratios obtained from the Taguchi analysis. Experimental measurements were conducted to compare the actual oven performance with the CFD predictions. The results demonstrated a strong correlation between the two, confirming the reliability of the numerical model.

This study successfully optimized the internal velocity and heat distribution in an industrial belt oven using Taguchi design principles and computational fluid dynamics simulations. By determining the key design variables and their effects on performance, the study provides valuable insights for the design and analysis of industrial ovens in various applications. The experimental validation further reinforces the reliability of the proposed approach. Future work may involve applying this methodology to optimize other types of industrial ovens, thereby enhancing their efficiency and uniformity in heat distribution

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Conflicts of interest

The authors declare no conflicts of interest.

REFERENCES

Amadane, Y., Mounir, H., Marjani, A., Ettouhami, M., & Atifi, A. (n.d.). Using CFD Simulation and Taguchi Approach to Optimize the Parameters Influencing the Performance of PEM Fuel Cell with the Serpentine Flow Field. *Ezziyyani, M. (eds) Advanced Intelligent Systems for Sustainable Development (AI2SD'2019). AI2SD 2019. Lecture Notes in Electrical Engineering*(624). https://doi.org/10.1007/978-3-030-36475-5_29

Aydın, A., Yaşar, H., Engin, T., & Büyükkaya, E. (2022). Optimization and CFD analysis of a shell-and-tube heat exchanger with a multi segmental baffle. *Thermal Science, 1*(26), pp. 1-12. https://doi.org/10.2298/TSCI200111293A

Biçer, N., Engin, T., Yasar, H., Büyükkaya, E., Aydın, A., & Topuz, A. (2020). Design optimization of a shell-and-tube heat exchanger with novel three-zonal baffle by using CFD and taguchi method. *International Journal of Thermal Sciences, 155.* https://doi.org/10.1016/j.ijthermalsci.2020.106417.

Boulet, M., Marcos, B., Dostie, M., & Moresoli, C. (2010). CFD modeling of heat transfer and flow field in a bakery pilot oven. *Journal of Food Engineering, 97*(3), pp. 393-402. https://doi.org/10.1016/j.jfoodeng.2009.10.034

Chandra, A. S., Reddy, P. N., & R, H. (2022). ArticleNatural ventilation in a lege space with heat source: CFD visualization and taguchi optimization. *Journal of Thermal Engineering*(8), pp. 642-655. https://doi.org/10.18186/thermal.1190545

Demir, U., & Aküner, M. C. (2018). Elektrikli bir araç için tekerlek içi asenkron motorun tasarım ve optimizasyonu. *Journal of the Faculty of Engineering and Architecture of Gazi University, 33*(4), pp. 1517-1530. https://doi.org/10.17341/gazimmfd.416448

Durbin, P. (1996). On the k-3 stagnation point anomaly. *International Journal of Heat and Fluid Flow, 17*(1), pp. 89-90. https://doi.org/10.1016/0142-727X(95)00073-Y

Fahey, M., Wakes, S. J., & Shaw, C. T. (2008). Use of computational fluid dynamics in domestic oven design. *Int. Jnl. of Multiphysics, 2*(1). https://doi.org/10.1260/175095408784300216

İç, Y. T., & Yıldırım, S. (2012). Çok kriterli karar verme yöntemleriyle birlikte taguchi yöntemini kullanarak bir ürünün tasariminin geliştirilmesi. *Journal of the Faculty of Engineering and Architecture of Gazi University, 27*(2), pp. 447-458.

Inc, A. (2009). *ANSYS Fluent User Guide Release 12.* Ansys Inc.

Inc, A. (2011). *ANSYS CFX-Solver Theory Guide, Release 14.* Canonsburg, PA: ANSYS Inc.

Inc., A. (2011). *ANSYS CFX-Solver Modeling Guide*, Rel. 14. 452-453.

Jegede, F., & Polley, G. (1992). Optimum Heat-Exchanger Design. *Chemical Engineerıng Research & Design*(70), pp. 133-141.

Kahraman, F., & Sugözü, B. (2019). An integrated approach based on the taguchi method and response surface methodology to optimize parameter design of asbestos-free brake pad material. *Turkish Journal of Engineering, 3*(3), pp. 127-132. https://doi.org/10.31127/tuje.479458

Kokolj, U., Škerget, L., & Ravnik, J. (2017). A numerical model of the shortbread baking process in a forced convection oven. *Applied Thermal Engineering, 111*, pp. 1304-1311. https://doi.org/10.1016/j.applthermaleng.2016.10.031.

Kokolj, U., Škerget, L., & Ravnik, J. (2017). The Validation of Numerical Methodology for Oven Design Optimization Using Numerical Simulations and Baking Experiments. *Strojniški vestnik - Journal of Mechanical Engineering, 63*(4), pp. 215-224. https://doi.org/10.5545/sv-jme.2016.4089

Marvin, J. G. (1988). *Accuracy Requirements and Benchmark Experiments for CFD Validation.* National Aeronautics and Space Administration.

Morris, A. S., & Langari, R. (2016). *Measurement and Instrumentation (Second Edition).* Elsevier Inc. https://doi.org/10.1016/C2013-0-15387-1

Norton, T., & Da-WenSun. (2006). Computational fluid dynamics (CFD) – an effective and efficient design and analysis tool for the food industry: A review. *Trends in Food Science & Technology, 17*(11), 600-620. https://doi.org/10.1016/j.tifs.2006.05.004

Obidowski, D., Stajuda, M., & Sobczak, K. (2021). Efficient Multi-Objective CFD-Based Optimization Method for a Scroll Distributor. *Energies, 14*(2-377). https://doi.org/10.3390/en14020377

Özer, M., Altınkaynak, A., Temiz, V., Mutlu, T., Dışpınar, T., Özgen, A. K., & Yücel, M. (2016). Önden yüklemeli bir çamaşır makinesinin sonlu elemanlar yöntemiyle dinamik olarak modellenmesi. *Journal of the Faculty of Engineering and Architecture of Gazi University, 31*(3), pp. 773-780. https://doi.org/10.17341/gummfd.78923

Rek, Z., Rudolf, M., & Zun, I. (2012). Application of CFD Simulation in the Development of a New Generation Heating Oven. *Strojniški vestnik - Journal of Mechanical Engineering*(58), pp. 134-144. https://doi.org/10.5545/sv-jme.2011.163

Shimpy, S., Kumar, M., & Kumar, A. (2024). Design and optimization of a domestic solar dryer: an analytical approach. *Engineering Computations, 41*(4), pp. 947-965. https://doi.org/10.1108/EC-12-2023-0916

Smolka, J., Bulinski, Z., & Nowak, A. J. (2013). The experimental validation of a CFD model for a heating oven with natural air circulation. *Applied Thermal Engineering*, pp. 387-398. http://dx.doi.org/10.1016/j.applthermaleng.2013.02.014

Stojanović, B., Babić, M., Veličković, S., & Blagojević, J. (2015). Optimization Of Wear Behaviour In Aluminium Hybrid Composites Using Taguchi Method. *14th International Conference on Tribology, SERBIATRIB '15.* Belgrade, Serbia.

Tambolkar, P., Ponkshe, A., Mulay, V., & Bewoor, A. (2020). Use of Taguchi DOE for CFD Simulation to maximize the Reusability of Working Fluids of Centrifugal Filter. *Procedia Manufacturing, 46*, pp. 608-614. https://doi.org/10.1016/j.promfg.2020.03.087

Tank, A., Chhanwal, N., Indrani, D., & Anandharamakrishnan, C. (2014). Computational fluid dynamics modeling of bun baking process under different oven load conditions. *J Food Sci Technol, 51*(9), pp. 2030-2037. https://doi.org/10.1007/s13197-012-0736-6

Türkan, B. (2024). Elektrikli araçlarda optimum soğutucu tasarımı için TRIZ algoritmasının uygulanması ve Taguchi analizi. *Journal of the Faculty of Engineering and Architecture of Gazi University, 39*(1), pp. 521-534. https://doi.org/10.17341/gazimmfd.1072512

Ünverdi, M., & Küçük, H. (2019). Taguchi yöntemi ve hesaplamalı akışkanlar dinamiği kullanılarak tasarlanan levhalı ısı değiştiricilerin performanslarının karşılaştırılması. *Pamukkale Univ Muh Bilim Derg, 25*(4), pp. 373-386. https://doi.org/10.5505/pajes.2018.35493

Vizguerra-Morales, P., Va´zquez-Castillo, J. A., Romero-Toledo, R., Aguilera-Alvarado, A. F., & Ponce-Ortega, J. M. (2016). Optimization and CFD modeling of an improved rustic oven for producing bricks. *Clean Techn Environ Policy*(18), pp. 1599-1609. https://doi.org/10.1007/s10098-016-1139-6

Yia, Y., Salonitisa, K., Tsoutsanisb, P., Litos, L., & Patsavelas, J. (2017). Improving the curing cycle time through the numerical modeling of air flow in industrial continuous convection ovens. *The 50th CIRP Conference on Manufacturing Systems. 63*, pp. 499-504. Procedia CIRP. https://doi.org/10.1016/j.procir.2017.03.167

Yuce, B. E., Nielsen, P. V., & Wargocki, P. (2022). The use of Taguchi, ANOVA, and GRA methods to optimize CFD analyses of ventilation performance in buildings. *Building and Environment*(225). https://doi.org/10.1016/j.buildenv.2022.109587