

**Design of Experiments and Computational Fluid Dynamics approach to  
Improve the product design process****Design of Experiments and Computational Fluid Dynamics approach to  
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**ABSTRACT**

Design of Experiments (DOE) techniques were applied to improve the thermal performance of a gas oven, aided with a Computational Fluid Dynamics (CFD) study in concept selection phase of Product Design Process PDP. Typical approaches to these types of activities involve developing all possible combinations of geometries changing one variable at a time, analyzing them with CFD, and predicting the main effects over the parameters surface heat flux and pressure drop, which in this application are the system responses. The develop plan for the team was to generate an script that allowed analyzing the sample space of the process variables and analyze much geometry configurations to study the geometric parameters. By utilizing DOE techniques the number of geometries was strategically reduced to 29. The metamodel of the system was obtained as a function of the input variables, with a statistical adjustment of 86.78% for the surface heat flux and 78% for the pressure drop. Subsequently we found the geometry that improves the performance of the product using the multiobjective optimization method “Normal Boundary Intersection - NBI”.

**Keyword:** Computational Fluid Dynamics (CFD), Design of experiment (DOE), Product Development Process (PDP), Multiobjective Optimization, Normal Boundary Intersection (NBI).

**RESUMO**

Técnicas de Design de Experimentos (DOE) foram aplicadas para melhorar o desempenho térmico de um forno a gás, auxiliado por um estudo de Dinâmica de Fluidos Computacional (CFD) na fase de seleção de conceito do Processo de Design de Produto PDP. Abordagens típicas para esses tipos de atividades envolvem o desenvolvimento de todas as combinações possíveis de geometrias alterando uma variável por vez, analisando-as com CFD e prevendo os principais efeitos sobre os parâmetros de fluxo de calor de superfície e queda de pressão, que neste aplicativo são as respostas do sistema. O plano de desenvolvimento para a equipe foi gerar um script que permitisse analisar o espaço amostral das variáveis do processo e analisar muitas configurações geométricas para estudar os parâmetros geométricos. Com o uso de técnicas DOE o número de geometrias foi estrategicamente reduzido para 29. O metamodelo do sistema foi obtido em função das variáveis de entrada, com um ajuste estatístico de 86,78% para o fluxo de calor superficial e 78% para a queda de pressão. Posteriormente encontramos a geometria que melhora o desempenho do produto utilizando o método de otimização multiobjetiva “Normal Boundary Intersection - NBI”.

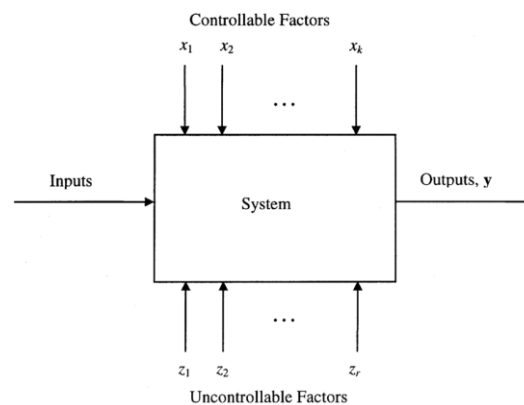
**Palavras-chave:** Dinâmica de Fluidos Computacional (CFD), Projeto de experimento (DOE), Processo de Desenvolvimento de Produto (PDP), Otimização Multiobjetiva, Intersecção de Limite Normal (NBI).

**1 INTRODUCTION**

Develop new products and improve the exist ones is a need for manufacturer businesses, in order to survive in a competitive enviroment. Dynamic needs of customers with increasing restrictions on time and resources, demands a rapid response to PDP on the market. To be minimized and solution to these limitations, application of computational systems, not only for drawing designs, but also for the development of concepts, virtual testing to obtain an optimized product in the conceptual phase are emerging (Yoshimura, 2010).

Quality of product and reliability are crucial and differential factor to achieve world-class product. The manufacturers using techniques, tools and models to help improve quality for new and current products (Jiang, 2015)(Roy, 2001). Good results in the product development process are obtained with the use of combined techniques (Folkestad & Johnson, 2002). DOE is an important technique used in numerous industries to investigate the factors that affect the performance of the system (Myers, Montgomery, & Anderson-Cook, 2009). The system Figure 1 is a production process or a product and the objectives of the experiment can include to determine which variables are most influential on the response, to determine where to set the influential controllable factors so that the response(s) are almost always near their desired target values, to determine where to set the influential controllable factors so that the variability in the response(s) is small or to determine where to set the influential controllable factors that the effects of the uncontrollable variables on the response(s) are small. And achieve to variability reduction, control and stability, optimization (Montgomery, 1999). An efficient numerical technique for field flow analysis Heat exchange and phenomena associated with chemical reactions is the CFD, using mathematical models and simulation help solve problems in the aerodynamics, hydrodynamics, turbomachinery, cooling of electrical components And electronics, among other industrial application (Versteeg & Malalasekera, 1995).

Figure 1. General model of a system (Montgomery, 1999)



The PDP is a set of activities that begins with the perception of a market opportunity and ends in the production, sale and delivery of a product. Generally this process consists of six phases, the planning phase known as zero phase, the concept development phase, the system-level design phase, the detail design phase, the testing and refinement phase, the last one start production phase. Perhaps, the concept development phase is the most complex phase of the entire PDP, due to the coordination between the various related activities(Ulrich & Eppinger, 2008). This phase begins by

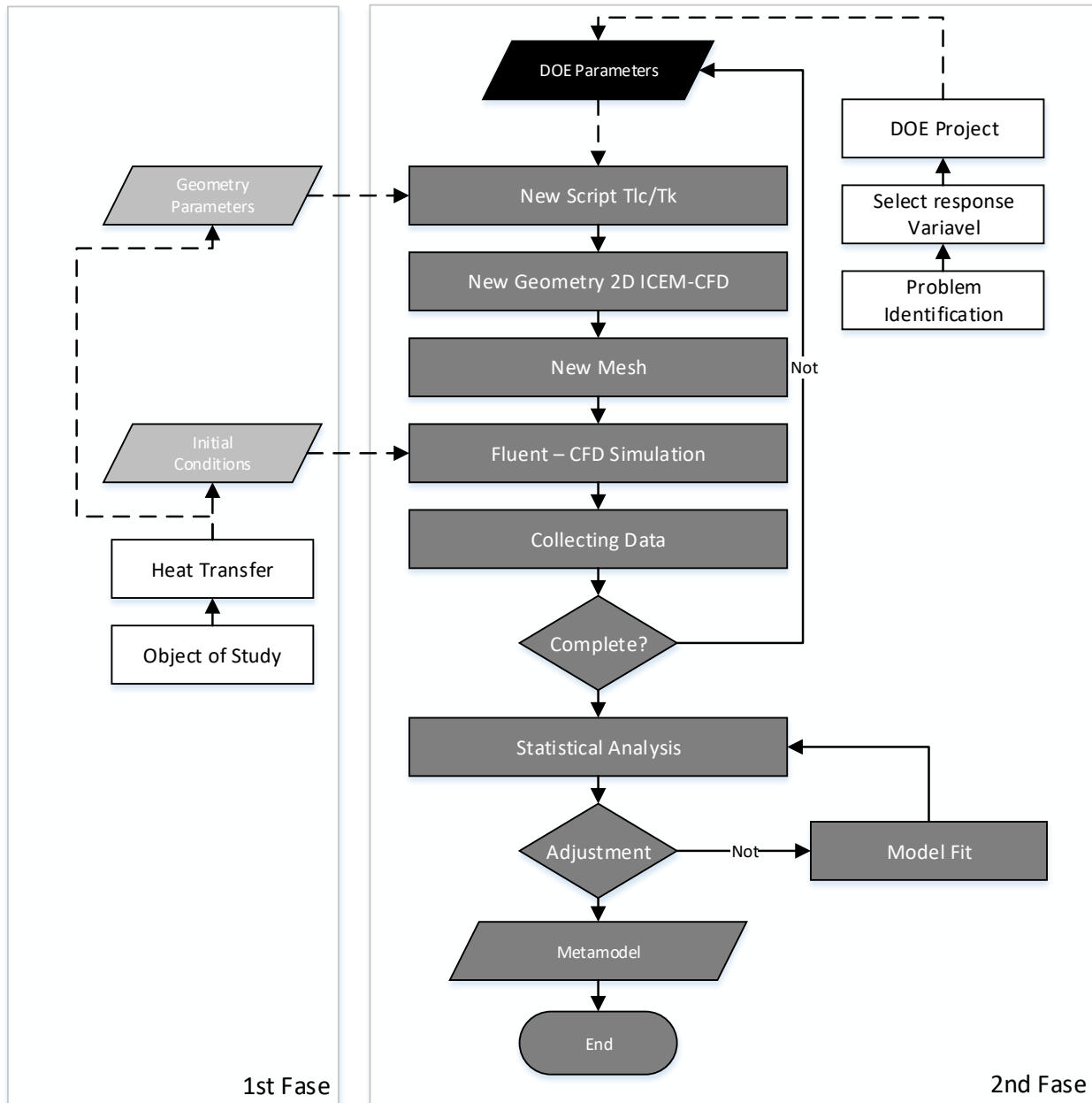
receiving the mission statement and ends by delivering a product development plan. The intermediate activities are: identifying customer needs, setting target specifications, generating concepts, selecting concept, testing concept, setting final specifications, planning development.

The costs involved in each PDP part increases drastically once the production and manufacturing process begins to develop. Maintaining a cost balance in the PDP requires that the conceptual and design phases of the product accumulate the lowest costs for the company. Suggestions for this solution include using less expensive tools in the production phase, minimizing design changes in the product, finding cheaper labor and outsourcing materials in the production phase (Berliner & Brimson, 1988) (López-Arcos, 2013).

The aim of this research is to introduce a method to develop products with certain characteristics that offer quality and reliability from the conceptual development phase of the PDP using a combination of techniques such as Design of Experiments DOE and Computational Fluid Dynamics CFD for this case applied to improve the thermal performance of a gas oven. Resulting in a faster PDP, also a better quality and reliability product. The method for combining the DOE and CFD techniques in the PDP is discussed in the next session.

## **2 DEVELOPMENT METHOD**

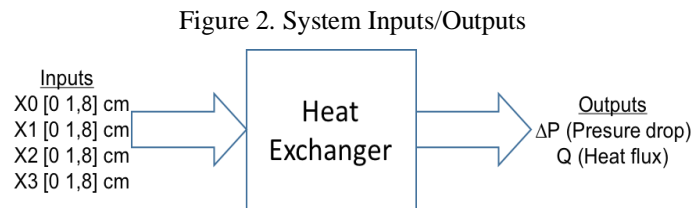
In this section, the method was developed to formulate the synergy combination of DOE and CFD for the PDP, Figure 2 presents a graphical summary. López-Arcos (2013) worked with a FAPEMIG (EDT-101654/05) project, a gas oven as product, performed the QFD, and established the object of study, a heat exchanger to improve the performance.



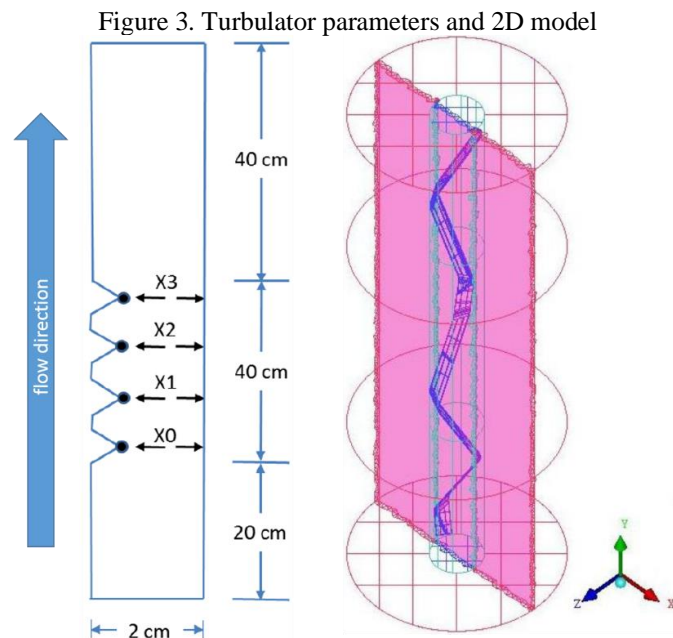
In the first phase the heat transfer problem was analyzed and described, this subsystem must transfer the thermal energy from one fluid to another efficiently. This subsystem consists of a tube, where the hot fluid will travel at a temperature of 483 K and an average speed of 1.3 m/s., and a turbulator that is inserted to disrupt laminar flow, which improves heat transfer (Fan, Deng, Guo, & Liu, 2011)(Wang & Sunden, 2002).

The development of the turbulator is empirical, if the holding time of the hot fluid inside it is high, the heat transfer between fluids will be better. However, if the number of turbulators is high, the pressure drop will be higher. Making it not a safe product, because of the risk of explosion (White, 1999).

In order for the phenomenon to be solved numerically, it is necessary to establish a mathematical model (conservation equations) that represents the physical behavior of the problem. To reduce the empiricism in the design of the turbulator in order to maximize the heat transfer rate but without increasing the pressure drop, the DOE approach is used. Figure 2 presents the system inputs/outputs; where the physical parameters of the heat exchanger will be used such as flow velocity and temperature, besides the length and the diameter of the tube.



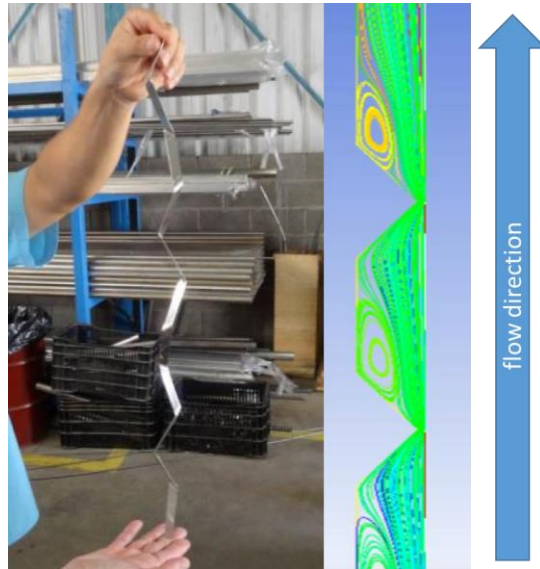
In phase 2, by varying the geometric characteristics of the turbulator and using CFD simulation software, Figure 3b. (López-Arcos, 2013). It is executed for each variation of parameters, Figure 3a. By measuring its performance in the pressure drop and the heat transfer rate as system response.



During the experiment phase development, monitor carefully the experimentation processes it is important to making sure that everything goes as planned, an error at this stage may compromise the experiment. To test it pilot experiments can be planned. (del Castillo, 2007)

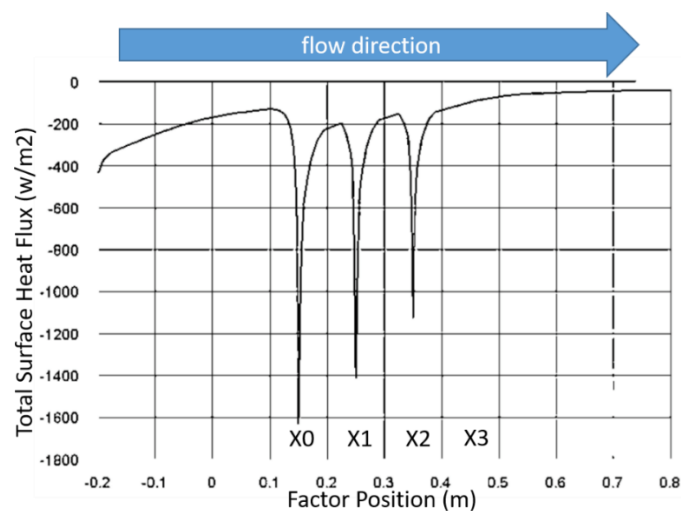
The first experiment is to simulate the current state of the turbulator and compare it with the performance of the turbulator used in the heat exchanger. Figure 4 presents the airflow lines under the presence of the turbulator with the factors of X0, X1, X2, X3 with values of 1,8 cm each.

Figure 4. Real turbulator vs Simulation CFD



The first experiment is to simulate the current state of the turbulator and compare it with the performance of the turbulator used in the heat exchanger. Figure 4 presents the airflow lines under the presence of the turbulator with the factors of X0, X1, X2, X3 with values of 1,8 cm each.

Figure 5. Turbulator performance to Heat Flux





From the pilot experiment, it can be concluded that the design variables  $X_0$ ,  $X_1$ ,  $X_2$ ,  $X_3$  drive the vortex generation that affect the performance in the heat exchange and the pressure drop, Figure 5.

At the Response Surface Methodology, the Central Composite Design (CCD) project has been the most used experimental arrangement for the exploration and analysis in sample spaces of experiments. This project has the advantage of providing a constant and minimum variance in the prediction for all points located at the same distance from the center (Gomes *et. al.* 2013). For this case, the DOE will have 29 experiments, composed of 16 factorial points, 8 axial points and 5 central points,  $\alpha = 2$ . Having the initial conditions for the CFD and the established DOE project, next stages of the method is developed.

A script in the Tlc/Tk language receives the data from the experiment to be run from the DOE project, this script contains the necessary commands to create the 2D geometry and the mesh at FLUENT CFD simulation software. Made the simulation process, the values of the pressure drop and heat flux corresponding to the experiment are collected. This process is repeated until all the experiments are completed. According to the procedures described previously, the results are obtained and evaluated with a residue analysis in search of random patterns or suspect data. Where the experimenter can choose whether to continue with the next phase or redo the experiment (Montgomery, 2006).

The method for Ordinary Least Squares OLS for Mathematical modeling for answers is used.

$$\begin{aligned}
 Y1(\dot{q}) &= 82,5541 + 10,5045X_0 + 10,3622X_1 + 9,5331X_2 + 7,5314X_3 \\
 \text{Heat Flux} &+ 5,5837X_0^2 + 5,8172X_1^2 + 5,5857X_2^2 + 4,7026X_3^2 - 0,7146X_0X_1 \\
 &- 0,4238X_0X_2 - 0,3652X_0X_3 - 0,6284X_1X_2 - 0,2600X_1X_3 \\
 &- 0,4912X_2X_3
 \end{aligned} \tag{1}$$

$$\begin{aligned}
 Y2(\text{Ln}(\text{Abs}(\Delta P))) \\
 \text{Pressure} &= 1,521 + 0,411X_0 + 0,409X_1 + 0,406X_2 + 0,403X_3 + 0,268X_0^2 \\
 \text{drop} &+ 0,268X_1^2 + 0,267X_2^2 + 0,267X_3^2 - 0,065X_0X_1 - 0,065X_0X_2 \\
 &- 0,065X_0X_3 - 0,060X_1X_2 - 0,061X_1X_3 - 0,0567X_2X_3
 \end{aligned} \tag{2}$$

The statistical adjustment of the regression for equations (1) and (2) is 86.8% and 78% respectively.

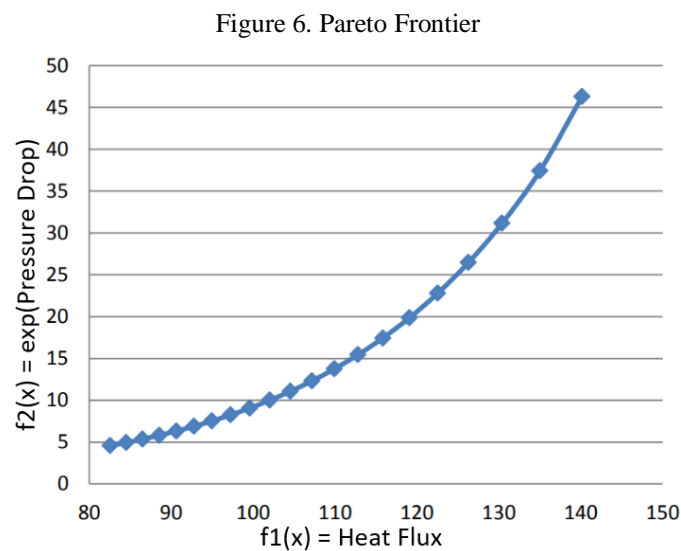
The last method phase is the concept optimization, the ratio of the dimension of the turbulator is directly proportional to the increase of the heat flux and inversely to the pressure drop. The increase of the heat flux is ideal to have an efficient product, less pressure drop to make it safer. Satisfy this condition, requires a multiobjective solution. Normal Boundary Intersection Method



(Das & Dennis, 1998); has been presented as an excellent solution to these conflicts (Costa *et. al.*, 2016; Lopes *et. al.*, 2016; López-Arcos, 2013; Naves *et. al.*, 2017).

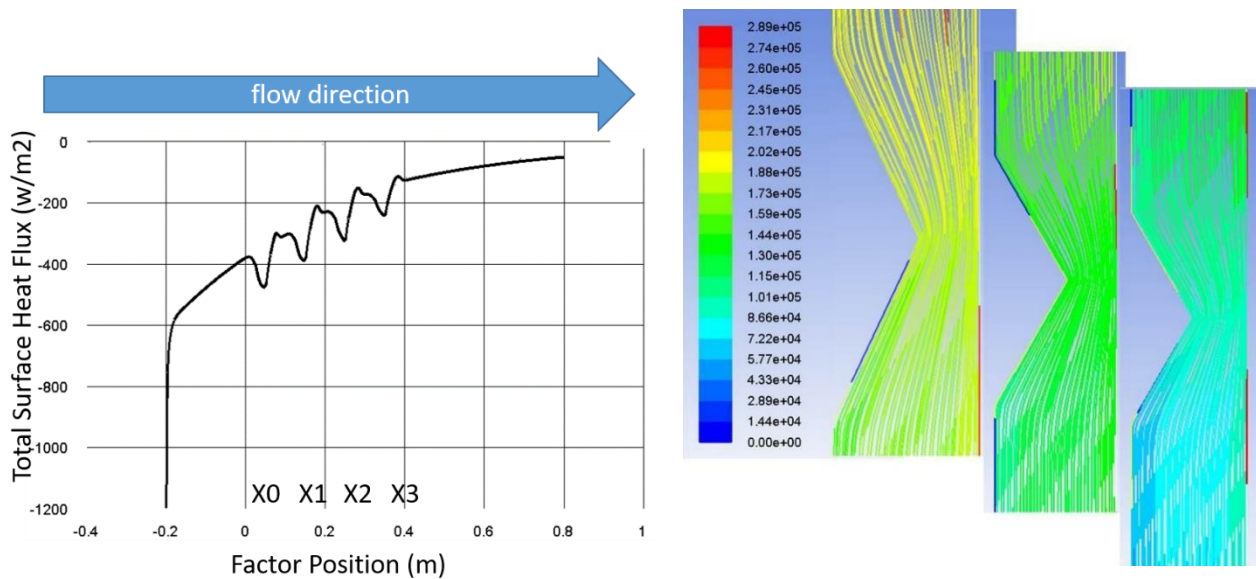
$$\begin{aligned} \min f_1^*(u) & & f_1^*(x) &= \left[ \frac{f_1(x) - T}{f_1^{\max}(x) - f_1^{\min}(x)} \right] \\ \text{s.t: } f_1^*(u) - f_2^*(u) + 2w - 1 &= 0 & \text{where,} & \\ X^T X &\leq \hat{\rho}^2 & f_2^*(x) &= \left[ \frac{f_2(x) - \Delta P}{f_2^{\max}(x) - f_2^{\min}(x)} \right] \end{aligned}$$

The tabulation of the weights  $w$ , allows the construction of the Pareto efficient frontier, after the higher prioritization to heat flux response, the optimal values for the factors  $X_0$ ,  $X_1$ ,  $X_2$  and  $X_3$  are obtained.  $X_0=1.04$ ;  $X_1=1.29$ ;  $X_2=1.43$ ;  $X_3=1.41$ .



A CFD simulation to validate the optimization with the new values is done Figure 7. It is verified that there are no vorticity regions that would cause greater loss of load, thus, it can be affirmed that the criterion of the lower pressure drop was met.

Figure 7(a,b). Optimal Turbulator performance to Heat Flux and Pressure drop.



### 3 CONCLUSIONS

The integration of numerical processes was used; Computational Fluid Dynamics (CFD), Experimental Design (DOE), and the construction of metamodels for the preliminary design of a turbulator for an gas oven. The model existence serves as a tool for new optimizations in the development of new turbulator, resulting in the PDP reduction for time and costs, when compared to the current empirical system. It should be emphasized that the metamodel contemplates two correlated and conflicting responses that could hardly be optimized empirically.

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