

Application of DOE for the Study of a Multiple Jet Impingement System

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Abstract. Jet impingement is widely implemented in a variety of engineering applications and industrial processes where high average heat transfer coefficients and the uniformity of the heat transfer over the impinging surface are required to enhance the process and to avoid local hot (or cold) spots. Multiple jet impingement involves several parameters that interfere with the performance of the process, and there are no universal optimal solutions. To ensure the optimization of the process, it is important to understand the influence of these parameters in the heat transfer over the target surface. To perform this study an experimental research will be performed on a purpose-built test facility which has been commissioned, using a Particle Image Velocimetry system. However, to reduce time and costs associated to the experimental tests, it is important to perform a Design of Experiments, that allows to reduce the number of trials, focusing on the parameters that have a greater influence on the process performance. Taguchi's method allows the optimization of the process through the selection of the most suitable parameters values. This work presents the method that must be followed before the development of experiments related to the multiple jet impingement over a complex surface, from the design of the experimental setup to the design of the matrix of experiments.

Keywords: DOE · Jet impingement · Heat transfer

1 Introduction

Multiple jet impingement is a technology widely implemented in several applications since it provides high average heat transfer coefficients and enhance the uniformity of the heat transfer over the target surface [1]. To enhance this process, studies have been performed to increase the heat transfer over the impinging surface. The analysis of the influence of the process variables on jet impingement efficiency have been focused on: jets pattern [2], jet-to-jet spacing [3], nozzle-to-plate distance [4], nozzle shape [5–7], jet inclination [8], Reynolds number [2], [9–12], jet temperature [7] and target surface geometry [13, 14].

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As the multiple jet impingement process involves several variables, the study of all of them, each one with different levels, would result in a great number of combinations to be analyzed (for example 7 factors each one with three levels result in $3^7 = 2187$ different combinations). However, some of them are more relevant than others depending on the application. To reduce the number of experiments, it is fundamental to select the ones that have a higher influence on the heat transfer performance. In that sense, a Design of Experiment (DoE) methodology will be applied in this study. DoE has been used in several industries to improve the process performance, enhancing the process yield and to decrease the process variability [15]. One of the techniques widely applied in engineering design is the Taguchi's method. According to Karna and Sahai [16], the engineers adhered to this method since it applies parameter design, an engineering technique for product or process design which focuses on the determination of parameters (factors) producing the best levels of a quality characteristic (performance measure) with minimum variation. To determine the best design, Taguchi's method applies a DoE that expose the process to various levels of design parameters previously defined, without testing all the combinations, and thus reducing the total number of experiments [16]. In jet impingement studies, this DoE method was implemented by Lau et al. [17] as a tool to perform an optimization of the thermal stress of a solder joint and cooling rate of a ball grid array package. Other works [18–20] also applied Taguchi techniques to study specific problems of heat transfer in jet impinging a surface.

Considering the advantages of the application of Taguchi's method in DoE, it will be applied in this study. The aim of this paper is to develop the methodology for the study of multiple jet impingement over a non-flat plate. This work presents the design and construction of a purposed-build setup for the analysis of the influence of the target surface geometry and jet flow dynamic parameters on the heat transfer performance. Taguchi's method will be applied as a tool to identify the parameters that enhance the multiple jet impingement to optimize the process. It is not the aim of this paper to present experimental results regarding the heat transfer, in contrast, it is expected to be relevant for researchers that intend to start studies in this field.

2 Experimental Apparatus

2.1 Experimental Setup

The experimental apparatus was specially designed and constructed for the study of the flow field of multiple jets impinging on a target surface. The 3D-model performed using the *SolidWorks*™ software is presented in Fig. 1. The aim of this apparatus is to reproduce with accuracy the reflow soldering process. This setup is flexible to allow to change the test conditions and process variables easily and to ensure the measurement of the flow field through Particle Image Velocimetry (PIV) technique. PIV method consist on the illumination of the measurement zone through a laser and the capture of the images through a camera positioned perpendicularly to the laser. These images allow the velocity field measurement of the airflow. In that sense, the walls of the test chamber (1) must have two transparent surfaces positioned perpendicularly,

represented in Fig. 1, by the numbers (2) and (3). The air is blown by a centrifugal fan (4) and flows through a nozzle plate (5), generating jets. Since the study will focus on the heating process, the air is heated by heaters positioned at the bottom of the oven (6). One of the critical aspects related to the jet impingement process is the uniformity of the heating, being extremely difficult to achieve. In order to stabilize the flow, ensuring a uniform heating over the target surface (7), a plenum (8) was created before the test chamber and a honeycomb structure (10) was applied in order to distribute the flow. To minimize the turbulence, a metallic mesh was introduced before the honeycomb structure (11). After impinging the surface, the air flows through another mesh (12) and re-enters inside the fan, since the setup is a closed loop. This oven has several characteristics which make it suitable for the development of different experimental tests. It is equipped by a frequency controller which is connected to the fan to increase or decrease the air velocity. The nozzle plate can be easily changed by another plate with different configuration and nozzle diameter, and the support base of the target surface can be positioned at different distance from the nozzle plate.

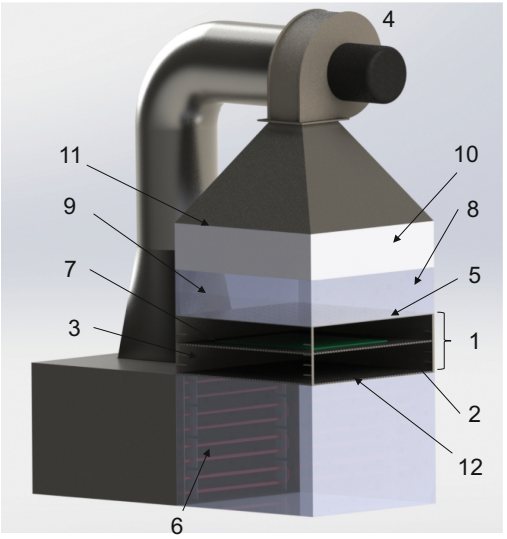


Fig. 1. Oven for experimental tests.

2.2 Procedure

The study of the flow field behaviour and its complex interaction with the target surface will be performed using a 2D-PIV system allowing the measurement of instantaneous velocity fields of a fluid flow through the image analysis of marker particles [21]. A double pulse laser illuminates a two dimensional plan across a seeded flow in two short pulses and a CCD camera records the images of the flow field [22]. In this study, the laser applied is a DualPower laser which emits two independently controlled beams with a pulse energy of 145 mJ at a wavelength of 532 nm, positioned at an angle of 90º

with the CCD camera, as shown by Fig. 2. The camera has a pixel size of 6.5 μm and a pixel resolution of 2560 × 2160 (5.5 Megapixel). The data acquisition and processing of the images is performed by the software Dynamic Studio.

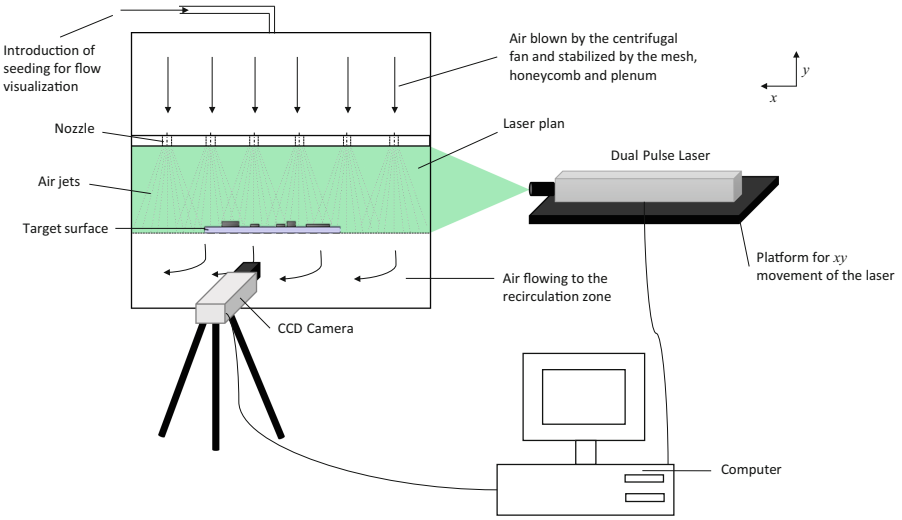


Fig. 2. Scheme of the experimental setup.

The seeding is crucial for the accurate measurement of the velocity field of the flow, being fundamental that the particles follows the instantaneous motion of the air [23]. In this study, high density homogeneous smoke was used for flow tracking, being generated by an Aerotech Smoke Generator. In addition, to measure the heat flow, a flux sensor will be mounted on the target surface. Thermocouples will also be placed on the impinging plate in the vicinity of the sensor to measure the surface temperature locally. It will also be necessary to place thermocouples near the nozzle exit to monitor the temperature. The heat flux sensor that will be applied for the heat flux measurement is a thin-film heat flux sensor which contains an integral thermocouple for discrete temperature measurement needed to describe the heat flux over the surface. The difference in temperature across thermal barrier is proportional to the heat flow through the sensor.

Before starting the experiments, it is important to identify the variables and to choose the ones that have a higher impact on the heat transfer over the target surface to develop a plan of the experimental tests that must be performed. After the selection of the process variables, a DoE must be implemented to focus the experiments on the most relevant variables, discarding the ones that have a low effect. To perform a simple and low-cost DoE, the Taguchi's method is implemented in this study.

3 Design of Experiments

The analysis of the influence of each variable in the heat transfer, as well as the interaction between them, is a great challenge. Proceeding to a careful analysis, the following 14 variables were identified in the literature review: jet pattern; jet-to-jet spacing; nozzle shape; nozzle-to-plate distance; jet inclination; target surface geometry; target surface inclination; target surface motion; nozzle plate motion; crossflow; jet temperature; Reynolds number; Prandtl number; Mach number. If for each variable, 2 values (or levels) are tested, the number of possible different combinations rises up to $2^{14} = 16384$ experiments (if a full factorial method is applied). Considering that, conclusions should not be drawn based on a single evidence, each experiment should be repeated increasing the total number of experiments. This is impracticable in laboratory, or in industry, which could be considered an unjustified waste of time and resources.

The Taguchi's method consists of three main stages: system design, parameter design and tolerance design [24]. Considering the aim of this work, it seems that the parameter design approach is the most suitable to perform the DoE, since it is intended to select the best combination of control factors in order to optimize the process and increase its robustness towards the noise factors [25]. While control factors are employed to select the best conditions for stability in design of manufacturing process, the noise factors are related to the factors that cause variations in the process [20]. The use of this approach requires the application of a fractional factorial [26], which are displayed in standard tables known as orthogonal arrays (OA).

To perform a DoE based on Taguchi's approach, the following steps need to be conducted [25]: (1) Determination of the quality characteristic to be optimized; (2) Identification of the noise factors and test conditions; (3) Identification of the control factors and their levels; (4) Design of the matrix experiment and definition of the data analysis procedure; (5) Conduct the matrix experiment; (6) Data analysis and determination of the optimum levels for control factors; (7) Prediction of the performance at these levels. This work focuses on the steps (1) to (4).

3.1 Quality Characteristic, Noise Factor and Test Conditions

The aim of this study consists on the analysis of the influence of several process parameters on the heat transfer over a complex target surface. In that sense, according to Taguchi's method, heat transfer is the quality characteristic to be optimized. To calculate the deviation between the experimental values and the desired ones, Taguchi used a loss function which is transformed into a signal-to-noise ratio (SN) [20]. Considering the jet impingement process the "larger the better" [27] was selected since it is expected to obtain the maximum heat transfer over the target surface, being evaluated by Eq. (1).

$$\mathrm{SN} = -10 \log\left(\frac{1}{n}\sum\nolimits_{i=1}^{n}\frac{1}{Y_i^2}\right) \tag{1}$$

Where SN indicates the signal to noise ratio (for each test or combination given by a matrix row), n is the number of repetitions of each combination, Y_i is the quality characteristic measured in each test [28].

The experiments will be conducted at an air temperature of 150 °C and a velocity of 10 m/s at the exit of the nozzles. The target surface will be introduced inside the oven at an ambient temperature which can vary in function of the day of the year. This is a noise factor, since it is an uncontrollable parameter that can interfere with the performance of the system. Thus, half of the repetitions of each test should be made with the target surface at low temperature and the other half with higher temperature.

3.2 Control Factors and Levels

The factors selected need to be the ones that influence the process, and for each one the number of levels (values that a factor assumes when applied in an experiment) need to be defined. Considering the number of variables registered in multiple jet impingement, traduced as factors in DoE method, it is important to limit the number of levels, in order to analyze the effect of the parameters with the minimum number of experiments.

Considering the information presented in the state of the art, and to reduce the number of experiments, it is possible to exclude the variables that, in one hand, have minimal effects in heat transfer and, on the other hand, the ones that present just one significant value/configuration. This is the case of the nozzle shape factor, since the circular shape was considered the one that enhance the heat transfer over the target surface. Due to the limitations of the experimental setup, the Prandtl and Mach numbers, target surface inclination and motion, nozzle plate motion, crossflow and jet temperature will also be discarded, reducing the study to 6 parameters. The variables relevant to the process are defined by Taguchi's as control factors, and the values that need to be tested (levels), are summarized in Table 1. These values were selected based on literature review and expert's opinions. If Taguchi's method was not applied, the total amount of experiments would rise to up to $2^4 \times 4^2 = 256$ experiments. In addition, Table 1 also includes the degrees of freedom (DoF) of each factor, which is equal to the number of levels minus one, being relevant to select the appropriate OA.

Table 1. Selected factors and their levels.

Control factor	Level				DoF
	1	2	3	4	
Jet-to-jet spacing, $S_x = S_y$ (A)	$2D$	$3D$	$5D$	$6D$	3
Nozzle-to-plate distance (B)	$2D$	$3D$	$5D$	$7D$	3
Jet pattern (C)	Inline	Staggered			1
Jet inclination (D)	20º	0º	-	-	1
Plate geometry (E)	Flat	Non-Flat	-	-	1
Reynolds number (F)	2000	1000	-	-	1

3.3 Selection of the Orthogonal Array

According to Table 1, ten degrees of freedom are identified. Proceeding to the analysis of the OA presented by the Taguchi's model, the L_{16} seems to be the most appropriate OA, since it allows a mix between 2 and 4 levels. In that sense, the array was generated by Minitab™ [19]. As it can be observed through Table 2, a total of 16 experiments need to be performed. As mentioned by [28], trials should be repeated. Considering that the analysis of the influence of the noise factor must also be analyzed, three repetitions will be performed in each test, one with the target plate at cold (≈10°C), medium (≈20 °C) and hot temperature (≈30 °C). The design of the experiments is presented by the OA (Table 2). To obtain the optimal process parameters configuration, the results obtained must be analyzed using the signal-to-noise ratio (*SN*) presented above, which represents the ratio between the mean (signal) and the standard deviation (noise) [25]. The *SN* of each parameter are compared and the parameter value that influence the most the quality characteristic is determined. From this analysis, an optimization of the quality characteristic must be performed.

Table 2. Design orthogonal array generated using Minitab.

Trials nº	A	B	C	D	E	F
1	2D	2D	Inline	0º	Flat	1500
2	2D	3D	Inline	0º	Flat	5000
3	2D	5D	Stag.	20º	Non-Flat	1500
4	2D	7D	Stag.	20º	Non-Flat	5000
5	3D	2D	Inline	20º	Non-Flat	1500
6	3D	3D	Inline	20º	Non-Flat	5000
7	3D	5D	Stag.	0º	Flat	1500
8	3D	7D	Stag.	0º	Flat	5000
9	5D	2D	Stag.	0º	Non-Flat	5000
10	5D	3D	Stag.	0º	Non-Flat	1500
11	5D	5D	Inline	20º	Flat	5000
12	5D	7D	Inline	20º	Flat	1500
13	6D	2D	Stag.	20º	Flat	5000
14	6D	3D	Stag.	20º	Flat	1500
15	6D	5D	Inline	0º	Non-Flat	5000
16	6D	7D	Inline	0º	Non-Flat	1500

4 Conclusions

This work presents an experimental setup that will be used for the development of experiments that aim to study the heat transfer of multiple jets impinging over a target surface. Through this study, it is expected to fully understand the influence of the process variables on the heat transfer performance of a multiple jet impingement process. This work presents the variables that interfere with the process and the values,

cited in the literature, that enhance the heat transfer. Through this state of the art, it was easier to understand which are the process variables that have more influence on the quality characteristic and which are the range of values that improve the performance of the system. This information was used to develop a design of experiment using the Taguchi's method. The construction of an OA was fundamental to define the experiments that must be conducted throughout the study. This work summarizes the steps that will be conducted before the development of experiments, focusing on the most relevant parameters, minimizing the time and costs. In that sense, it can be an added value for all the researchers that pretends to start their studies in the multiple jet impingement field.

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References

1. Can, M., Etemoglu, A.B., Avci, A.: Experimental study of convective heat transfer under arrays of impinging air jets from slots and circular holes. Heat Mass Transf. und Stoffuebertragung **38**(3), 251–259 (2002)
2. Florschuetz, L.W., Metzger, D.E., Truman, C.R.: Streamwise flow and heat transfer distributions for jet array impingement with crossflow. ASME Gas Turbine Div. **3**(Jan), 1–10 (1981)
3. Yong, S., Zhang, J.Z., Xie, G.N.: Convective heat transfer for multiple rows of impinging air jets with small jet-to-jet spacing in a semi-confined channel. Int. J. Heat Mass Transf. **86**, 832–842 (2015)
4. Lee, J., Lee, S.J.: The effect of nozzle configuration on stagnation region heat transfer enhancement of axisymmetric jet impingement. Int. J. Heat Mass Transf. **43**(18), 3497–3509 (2000)
5. Dano, B.P.E., Liburdy, J.A., Kanokjaruvijit, K.: Flow characteristics and heat transfer performances of a semi-confined impinging array of jets: effect of nozzle geometry. Int. J. Heat Mass Transf. **48**, 691–701 (2005)
6. Reodikar, S.A., Meena, H.C., Vinze, R., Prabhu, S.V.: Influence of the orifice shape on the local heat transfer distribution and axis switching by compressible jets impinging on flat surface. Int. J. Therm. Sci. **104**, 208–224 (2016)
7. Vinze, R., Chandel, S., Limaye, M.D., Prabhu, S.V.: Influence of jet temperature and nozzle shape on the heat transfer distribution between a smooth plate and impinging air jets. Int. J. Therm. Sci. **99**, 136–151 (2016)
8. Attalla, M., Maghrabie, H.M., Specht, E.: Effect of inclination angle of a pair of air jets on heat transfer into the flat surface. Exp. Therm. Fluid Sci. **85**, 85–94 (2017)
9. Caliskan, S., Baskaya, S., Calisir, T.: Experimental and numerical investigation of geometry effects on multiple impinging air jets. Int. J. Heat Mass Transf. **75**, 685–703 (2014)
10. Metzger, D.E., Florschuetz, L.W., Takeuchi, D.I., Behee, R.D., Berry, R.A.: Heat transfer characteristics for inline and staggered arrays of circular jets with crossflow of spent air. J. Heat Transf. **101**, 526–531 (1979)

11. Xing, Y., Spring, S., Weigand, B.: Experimental and numerical investigation of heat transfer characteristics of inline and staggered arrays of impinging jets. J. Heat Transf. **132**(9), 092201 (2010)
12. Li, W., Li, X., Ren, J., Jiang, H., Yang, L.: Effect of reynolds number, hole patterns, target plate thickness on cooling performance of an impinging jet array: part II—Conjugate heat transfer results and optimization. Vol. 5B Heat Transf. **139**(April), V05BT16A009 (2016)
13. Andrews, G.E., Abdul Hussain, R., Mkpadi, M.C.: Enhanced impingement heat transfer : Comparison of co-flow and cross-flow with rib turbulators. In: Proceedings of International Gas Turbine Congress, Tokyo, Japan, IGTC 2003, Tokyo TS-075 (2003)
14. Caliskan, S., Baskaya, S.: Experimental investigation of impinging jet array heat transfer from a surface with V-shaped and convergent-divergent ribs. Int. J. Therm. Sci. **59**, 234–246 (2012)
15. Zahraee, S.M.: Teaching the Design of Experiment and Response Surface Methodology Using Paper Helicopter Experiment, no. April (2013)
16. Karna, S.K., Sahai, R.: An overview on Taguchi method. J. Eng. Math. Sci. **1**, 11–18 (2012)
17. Lau, C.S., Abdullah, M.Z., Ani, F.C.: Optimization modeling of the cooling stage of reflow soldering process for ball grid array package using the gray-based Taguchi method. Microelectron. Reliab. **52**(6), 1143–1152 (2012)
18. Chandramohan, P., Murugesan, S.N., Arivazhagan, S.: Heat transfer analysis of flat plate subjected to multi-jet air impingement using principal component analysis and computational technique. J. Appl. Fluid Mech. **10**(1), 293–306 (2017)
19. Caliskan, S., Nasiri Khalaji, M., Baskaya, S., Kotcioglu, I.: Design analysis of impinging jet array heat transfer from a surface with V-shaped and convergent-divergent ribs by the Taguchi method. Heat Transf. Eng. **37**(15), 1252–1266 (2016)
20. Celik, N., Turgut, E.: Design analysis of an experimental jet impingement study by using Taguchi method. Heat Mass Transf. **48**(8), 1407–1413 (2012)
21. Keane, R.D., Adrian, R.J.: Theory of cross-correlation analysis of PIV images. Appl. Sci. Res. **49**(3), 191–215 (1992)
22. O'Donovan, T.: Fluid Flow and Heat Transfer of an Impinging Air Jet, University of Dublin (2005)
23. Melling, A.: Tracer particles and seeding for particle image velocimetry. Meas. Sci. Technol. **8**, 1406–1416 (1997)
24. Chamoli, S.: A Taguchi approach for optimization of flow and geometrical parameters in a rectangular channel roughened with V down perforated baffles. Case Stud. Therm. Eng. **5**, 59–69 (2015)
25. Dean, E.B., Unal, R.: Taguchi approach to design optimization for quality and cost: an overview. In: 1991 Annual Conference of the International Society of Parametric Analysts, pp. 1–10 (1991)
26. Athreya, S., Venkatesh, Y.D.: Application of Taguchi method for optimization of process parameters in improving the surface roughness of lathe facing operation. Int. Ref. J. Eng. Sci. **1**(3), 13–19 (2012)
27. Semioshkina, N., Voigt, G.: An overview on Taguchi method. J. Radiat. Res. **47**(Suppl. A, 2), A95–A100 (2006)
28. Roy, R.K.: A Primer on the Taguchi Method. Society of Manufacturing Engineers, USA (2010)