DESIGN ANALYSIS OF FLUID-FLOW THROUGH PERFORATED PLATES

by

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The performance of the perforated plates in fluid-flow applications is evaluated by measuring the pressure drop of the working fluid. The purpose of this investigation is to determine how different parameters affect the capability of the perforated plates and modify the design by using a design of experiment analysis, namely Taguchi method for optimization. The flow characteristics, which were obtained by the CFD software package ANSYS-CFX, were used for this analysis. The design parameters which affect the pressure loss are Reynolds number (A), porosity (B), non-dimensional thickness of the plate (C), and hole pattern (D). The level of importance of the design parameters are determined by use of analysis of variance method. According to the analysis, the optimum values are obtained for the case A8B2C2D1 (Re = 15000, porosity = 50.3, t / D = 1, and staggered hole). The most effective design parameter on the results is found as porosity (92%), while the least effective is the hole pattern (0.2%). A special dividend of this work was to demonstrate the capabilities of the Taguchi method as a powerful means of increasing the effectiveness of numerical simulation.

Key words: *perforated plates, CFD, Taguchi, design of experiment*

Introduction

Taguchi method is a statistical methodology which was developed and introduced by the quality control statistician *Genichi Taguchi* to improve the quality of manufactured items. It has been employed in numerous engineering applications. A sampling of recently published papers [1-7] bears witness to the breadth of engineering applications to which the Taguchi method is being applied. This method can be used for designing experiments in order to:
– investigate how various parameters affect the mean target and
– determine the variance of a process-performance characteristic that defines how well the process is functioning.

In the implementation of the Taguchi method, an experimental-design methodology also applicable to numerical simulation is employed where orthogonal arrays are used to organize the parameters in a manner that diminishes the number of experiments or computer runs that are required to differentiate among the importance of the participating parameters [1]. Instead of having to test all possible independent variables as in the design of experiments (DOE),

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the Taguchi method tests pairs of those variables [2, 3]. This enables the collected data to be processed in such a way as to determine which parameters have the greatest effect on product quality with a minimum amount of experimentation or numerical simulation, thus saving time and resources [4]. The Taguchi method is best used when there are an intermediate number of participating variables (3-50), few interactions between variables, and only a few of the variables contribute significantly [5]. Thus, it can be said that the Taguchi approach provides two advantages:

– the reduction in the variability (improved quality) of a product or process represents a lower loss to society and
– the optimal development strategy can directly reduce variation [6]. An additional advantage, set forth here for the first time, is that the method can be used to decrease the number of numerical simulation runs to achieve a targeted result.

Although the Taguchi method is primarily used to augment application of DOE methodology to physical experiments, the method can also be applied to numerical simulations. In this paper, the specific steps involved in the application of the Taguchi method to the numerical simulation of flow through perforated plates will be described. There is considerable interest in using perforated plates as a means for controlling the quality of a flowing fluid. In particular, highly disturbed flows are often ill-conditioned to perform a target task; rather, uniformity is desired. The issue to be considered is the optimum characteristics of a perforated plate with regard to such parameters as the Reynolds number, plate thickness, hole deployment pattern, and the porosity of the plate [7, 8]. The degree of uniformity of the flow created by the presence of a perforated plate has been determined in a study of Bayazit *et al.* [9], by using numerical software ANSYS-CFX.

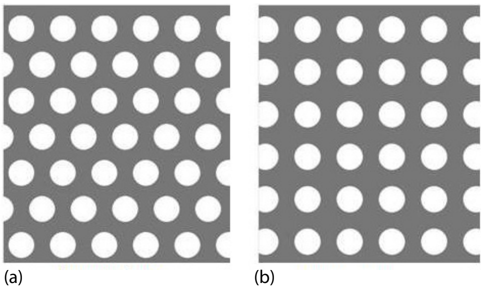

Figure 1. Perforated plates used in the work; (a) staggered array, (b) square array

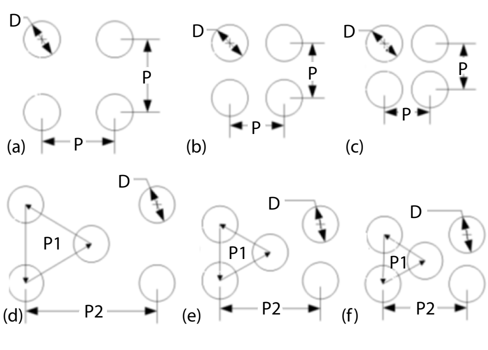

Figure 2. Dimension layouts and identification of the cases to be considered; square array; a) P/D = 2, (b) P/D = 1.5, (c) P/D = 1.25; staggered array: (d) P_1/D = 2.14, P_2/D = 3.70, (e) P_1/D = 1.61, P_2/D = 2.82, (f) P_1/D = 1.34, P_2/D = 2.36; these dimensional ratios apply to both them t/D = 0.5 and 1.0 perforate plates [9]

Fundamental numerical study and Its results

In this investigation, numerical simulation is employed to quantify the pattern of fluid flow through a perforated plate. The simulations are performed for parametric values of the Reynolds number, plate thickness, spatial deployment of the perforation apertures, and the porosity of the plate. Subsequent to the numerical simulations, the Taguchi method may be used to identify the optimal combination of these independent variables that yields the lowest pressure drop for a given value of the rate of fluid flow. The flowing fluid is air, and perforated plates with two different types of hole deployment patterns, square and staggered, are examined (the arrangement of the holes is seen in figs. 1 and 2. The dimensionless thickness of the plate for both square and staggered arrays varied as t/D = 0.5 and 1.

The numerical simulation requires the solution of a 3-D, steady fluid-flow. The turbulent flow simulations use the RANS equations supplemented by the SST turbulence model of Menter [10].

The RANS equations are presented:

$$\rho \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} = \frac{\partial}{\partial x_j}\left[-\overline{p}\delta_{ij} + \mu\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i} \right) - \rho \overline{u'_i u'_j} \right] + \rho \overline{f}_i, \quad \text{i, j} = 1, 2, 3 \tag{1}$$

The numerical calculations were performed by making use of ANSYS CFX 14 finite-volume-based software to solve RANS equations for the solution domain which was already exhibited in [9].

The pressure drop results are shown with $C_p = \Delta p/\rho U^2$. Figure 3 represents the numerical results of the pressure drop with respect to various Reynolds numbers with four sub-figures. It is seen from the sub-figures that, the flow can be regarded as fully turbulent for Re > 4000. It is also evident that, the arrangement of the plates has not a dominant effect on the pressure drop. A comparison between sub-figures also reveals that the pressure drop is highly related to the plate thickness, since the higher pressure drops belonging to the thinner plate in all cases [9]. Finally it can be seen from the figures that, the pressure drop increases with the porosity of the holes on the plate, as expected. Also, it should be noted that, the insensitivity of the results displayed in sub-figures to Reynolds number is due to the fact that the pressure drop increases with the square of the velocity.

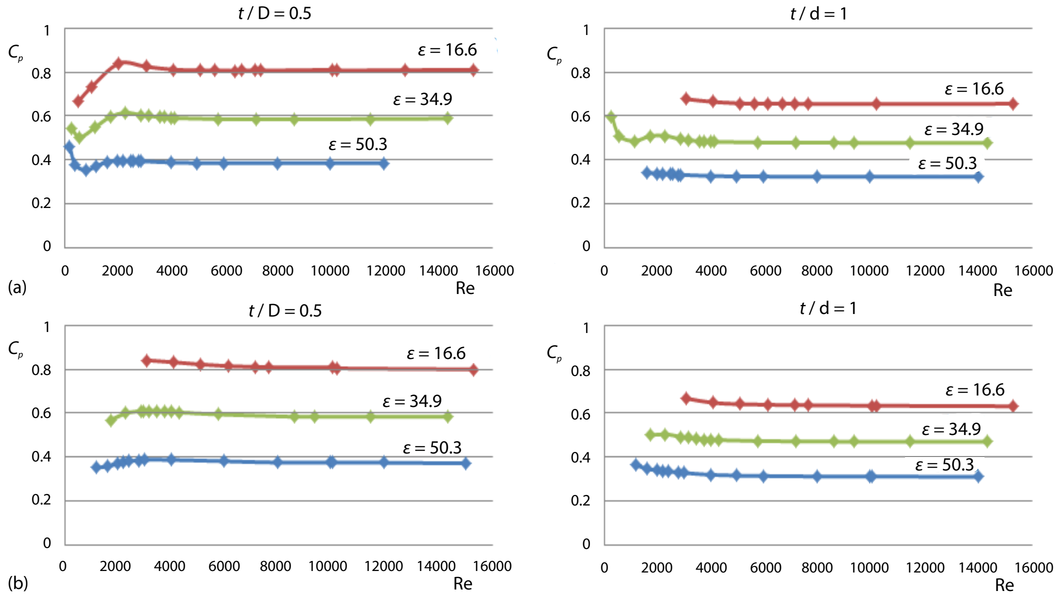

Figure 3. Numerical results for the pressure drop *vs.* Reynolds number [9]; (a) perforates in square array, (b) perforates in staggered array

Taguchi analysis

In the Taguchi method, process parameters which influence the products are separated into two main groups: control factors and noise factors. Control factors are those which are set by the researcher and cannot be directly changed by anyone. Noise factors are those over which the researcher has no direct control and may vary with the nature of the application [6, 7]. The control factors are used to select the best combination of independent variables which satisfies the minimization condition for the pressure drop.

The Taguchi method enables the researcher to perform an investigation with the use of orthogonal arrays. The optimal process parameters can be determined by employing these arrays [6, 8]. The greatest benefit of this method is the reduced number of numerical simulations required to study the entire parameter space. The orthogonal arrays that are relevant to the method can be found in the literature [11]. Small arrays can be derived mathematically; in contrast, large arrays are derived from deterministic algorithms. The arrays employed here include the independent parameters (variables) and their levels (states). Analysis of variance (ANOVA) of the collected outcomes from the Taguchi method can be used to select new parameter values to optimize the aforementioned performance requirement. The method of data analysis was conducted by using the ANOVA statistical method. A qualitative display of the outcomes was prepared by plotting the values of the focus variable (pressure drop, C_p) as a function of the run number of the simulations.

For the determination of the fluid flow characteristics, the aforementioned numerical simulations [9] were implemented for Reynolds numbers between 3000 and 15000, perforated-plate porosities, 19.6 and 50.3%, dimensionless plate thicknesses of t/D = 0.5 and 1, and staggered and square hole deployment patterns. The control parameters and their levels are listed in tab. 1.

Table 1. Control factors used in the experiments

Factors	Symbol	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	Level 8
Reynolds number	A	3000	4000	5000	7000	9000	11000	13000	15000
Porosity, ε	B	19.6	50.3	–	–	–	–	–	–
Thickness, t / D	C	0.5	1	–	–	–	–	–	–
Hole pattern	D	ST	SQ	–	–	–	–	–	–

Table 2. The L_{16} orthogonal array

Experiment No.	Control factors				S/N ratio (η)
	A	B	C	D	ΔP
1	1	1	1	1	1.494
2	1	2	2	2	9.564
3	2	1	1	1	1.587
4	2	2	2	2	9.698
5	3	1	1	2	1.849
6	3	2	2	1	10.01
7	4	1	1	2	1.864
8	4	2	2	1	10.12
9	5	1	2	1	3.945
10	5	2	1	2	8.268
11	6	1	2	1	3.945
12	6	2	1	2	8.268
13	7	1	2	2	3.670
14	7	2	1	1	8.519
15	8	1	2	2	3.662
16	8	2	1	1	8.589

* By taking the average of the S/N values in tab. 2. As an example, parameter A from tab. 2 is averaged to get the S/N value (1.494+9.561)/2 = 5.529

These all shown parameters are organized according to the Taguchi quality design concept, and an L16 orthogonal array with 16 rows (corresponding to the numerical simulation sequence descriptors) is constructed and presented in tab. 2.

In the Taguchi method, a loss function is used to calculate the deviation between the experimental values (pressure drop for each experiment run) and the optimum output values. These ideal output values are defined by the Taguchi method [6]. If a design is sought that would minimize a targeted performance characteristic, the method defines the optimum output value as zero. In the analysis stage, this loss function is transformed into a signal-to-noise (S/N) ratio. There are several S/N ratio definitions available: for the problem in question, lower is best (LB). Here, it has already been noted that the least pressure drop for a given flow rate is the target, so that the LB for the pressure drop is selected to obtain optimum-performance characteristics.

For the LB relevant to the pressure drop, the definition of the loss function, L, for performance results y_i of n repeated number of simulations is shown in eq. (2), where y_i is the pressure drop for each experiment run:

$$L_{\mathrm{LB}} = \frac{1}{n}\sum_{i=1}^{n} y_i^2 \tag{2}$$

The S/N ratio η_{ij} for the i^{th} performance characteristics of the j^{th} experiment or simulation run output can be expressed:

$$\eta_{ij} = \log(L_{ij})^{-10} \tag{3}$$

A greater η value corresponds to a better performance. Therefore, the optimal levels of the design parameters are the levels with the greatest η value. By applying eqs. (2) and (3), the η values for each experiment of the L_{16} array (tab. 2) are calculated and exhibited in tab. 3.

Table 3. The η values for pressure drop as the targeted outcome

Factors	Symbol	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	Level 8
Reynolds number	A	5.529	5.643	5.927	5.990	6.106	6.106	6.095	6.126*
Porosity	B	2.752	9.129*	–	–	–	–		
t/D	C	5.055	6.826*	–	–	–	–		
Pattern	D	6.025*	5.855	–	–	–	–		

* Optimum level. Overall mean = 5.940 dB (base on average of all η values in tab. 3)

Based on the analysis of S/N ratio, the η values of the Reynolds number, porosity, thickness of the plate, and the pattern of the holes are found to be 6.126 (Level 8-A8), 9.129 (Level 2-B2), 6.826 (Level 2-C2), and 6.025 (Level 1-D1), respectively. In other words, if the levels A8B2C2D1 are considered, the optimal pressure drop value is obtained. This comparison between parameters using the S/N ratio is shown in fig. 4.

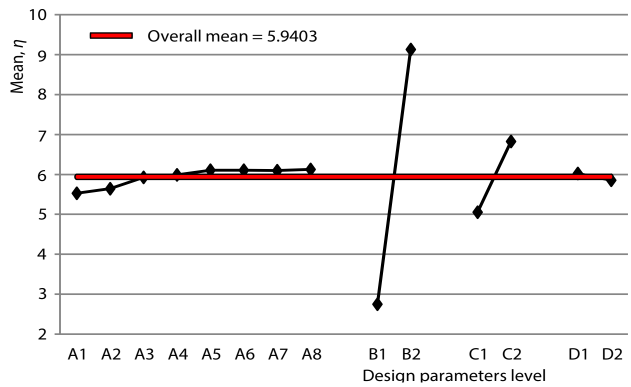

Figure 4. Effect of design parameters on pressure drop

The ANOVA confirmation

A more accurate result for the relative effects of the different numerical-simulation parameters on pressure drop is obtained by variance decomposition, which is referred to in the literature as the ANOVA. By the use of this method, the noise within the simulation results is evaluated, and the effects of various factors are resolved. The equations of the ANOVA analysis are:

$$SS_m = \frac{\left(\sum n_i\right)^2}{n} \tag{4}$$

$$SS_{\mathrm{factor}} = \frac{\sum \eta^2_{\mathrm{factor},i}}{N} - SS_m \tag{5}$$

$$SS_T = \sum \eta_i^2 - SS_m \tag{6}$$

$$SS_e = SS_T - \sum SS_{\text{factor}} \tag{7}$$

$$df_{\text{total}} = n - 1 \tag{8}$$

$$df_{\text{factor}} = k - 1 \tag{9}$$

$$V_{\text{factor}} = \frac{SS_{\text{factor}}}{df_{\text{factor}}} \tag{10}$$

$$F_{\text{factor}} = \frac{V_{\text{factor}}}{V_{\text{error}}} \tag{11}$$

where SS_m is the sum of squares due to the mean, n – the number of the experiments, SS_{factor} – the sum of squares due to inputs which are also referred to as parameters, SS_T – the total sum of squares, $\eta_{\text{factor},i}$ – the sum of i^{th} level of the factor, N – the repeating number of each level of factors, SS_e – the sum of squares due to error, d_f – the number of degrees of freedom, k – the number of the factor's level, V_{factor} – the variance of the factor, and F_{factor} – the F-test value of the factor. The results of the ANOVA analysis are presented in tab. 4.

The ANOVA uses the F-test to determine whether the variability between group means is larger than the variability of the observations within the groups. If that ratio is sufficiently large, you can conclude that not all the means are equal. In other words, the F-test is used for quantifying the magnitude of the results of the analyses. The calculated F values are compared to appropriate standard confidence tables which are presented in [5]. If the F values calculated in this analysis are larger than the F values in the standard confidence tables, the analysis is concluded to be at that assumed confidence level.

Table 4. Results of ANOVA

Factor	Degree of freedom, d_f	Sum of square, SS	Variance, V	F-test	F.05	Contribution [%]
A	7	0.747	0.107	9.75*	4.88	0.38
B	1	162.7	162.7	14843*	6.61	92.24
C	1	12.55	12.55	1145*	6.61	7.11
D	1	0.115	0.115	10.49*	6.61	0.059
Error	5	0.055	0.0110			0.211
Total		176.1				

* At least 95% confidence level

As known, in statistical testing problems, one usually is not interested in the component vectors themselves, but rather in their squared lengths, or sum of squares. The degrees of freedom associated with a sum-of-squares are the degrees of freedom of the corresponding component vectors.

Analysis of the results displayed in tab. 4 shows that the most effective parameter with respect to pressure drop is the porosity, followed by the thickness of the plate, whereas the effects of the hole deployment pattern and the Reynolds number on the pressure drop were insignificant. The percent contribution column in tab. 4 indicates that the relative influence of a factor to reduce variance. For a factor with a high percentage of contribution, a small variation will have a great influence on the performance. According to tab. 4, the porosity was found to be the major factor affecting the pressure drop with 92% of the contribution, followed by the thickness of the plate with 7.1%. The Reynolds number is found to be the third-ranking factor at 0.38%. Finally, the parameter which has the least effect on the pressure drop is found to be the hole deployment pattern of the plate, with a value of 0.059%.

Confirmation experiment or simulation run output

The confirmation simulation is the final step in the first iteration of the Taguchi based DOE process. The purpose of the confirmation simulation is to validate the conclusions drawn during the analysis phase. This validation is performed by conducting a simulation with a specific combination of factors and levels previously evaluated. In this study, after determining the optimum conditions and predicting the response corresponding to these conditions, a new simulation is designed and conducted with the newest optimum levels of the design parameters. The final step is to predict and verify the improvement of the performance characteristics. The predicted *S*/*N* ratio using the optimal levels of design parameters can be calculated as:

$$\hat{\eta} = \eta_m + \sum_{i=1}^{p}\left(\overline{\eta}_i - \eta_m\right) \tag{12}$$

where η_m is total mean of *S*/*N* ratio, η_i – the mean of *S*/*N* ratio at the optimal level, and p – the number of main design parameters that significantly affect the performance. As seen in tab. 4, all parameters have significant effects on the performance, hence p is equal to 4 in this study.

The results of the simulation confirmation using the optimal design parameters are shown in fig. 5. This figure shows the comparison of the predicted pressure drop with the pressure drop using the optimum design parameters. It is clear from the graph that the obtained and predicted values have an excellent agreement with each other.

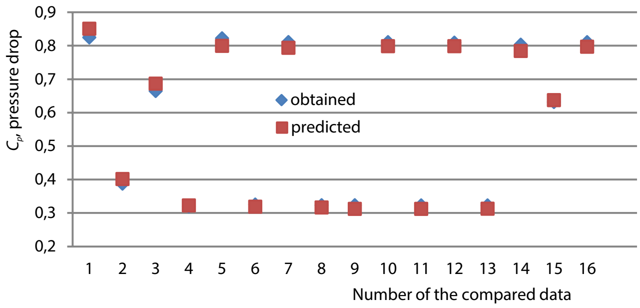

Figure 5. Results of the confirmation
(*for color image see journal web site*)

Conclusions

The research conveyed in this paper has revealed and documented a little-recognized feature of the Taguchi methodology. That feature is the capability to reduce the number of numerical simulations required to attain a specified target. In complex physical situations, the most demanding and time-sensitive phase of goal seeking is carrying out numerical simulations.

The physical situation treated here is a case in point. The underlying numerical simulations, performed in [9], were carried out for a parametric value of the independent variables without any guidance as to which of the variables deserved a denser array of parametric values.

A trio of dimensionless geometrical parameters was varied systematically, as was the Reynolds number to encompass turbulent flows. As a result, the thinner plate caused higher pressure drops as did the square-array hole pattern; also, the pressure drop was found to depend on the square of the Reynolds number, indicating the dominance of momentum-based losses. These trend reversals are attributable to the differences in separated-flow reattachment patterns for the different plate thicknesses.

In actuality, it was the Reynolds number that was accorded the largest number of parametric values. However, as demonstrated here, that treatment should have accorded to the porosity.

Nomenclature

C_p – pressure coefficient
D – diameter of the hole
P – distance between the origin of two hole
Δp – pressure diference
t – thickness of the plate
U – mean velocity

Greek symbol

ρ – density

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