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RESEARCH ARTICLE

Numerical Optimization of Heat Transfer Parameters in a Pipe with Decaying Swirl Flow Generators Using Response Surface Methodology

Faruk YEŞİLDAL[1,*]

[1] *Atatürk University, Faculty of Engineering, Department of Mechanical Engineering, 25240, Erzurum, TURKEY*

** Corresponding author E-mail: fyesildal@atauni.edu.tr*

HIGHLIGHTS

> Heat transfer characteristics of decaying swirl flow are investigated.

> The heat transfer parameters of the axial vortex generator fixed to the pipe inlet were numerically optimized by the Response Surface Method.

> A mathematical model is proposed for the heat transfer coefficient determined as the response variable.

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ABSTRACT

In this study; the heat transfer parameters (Reynolds number, helix angle and pitch) of an axial swirl flow generator attached to the pipe inlet were numerically optimized. The Response Surface Method Central Composite Design Face Centered (CCDFC) was used for this purpose. Three different parameters were examined at 3 levels with 20 analyzes performed in Fluent. The heat transfer coefficient (h) was determined as the objective function. As a result of the analysis, the square effects of Reynolds number and the combined effect of Reynolds number and swirl angle (α) were found to be statistically significant. Optimum results were obtained for the Reynolds number of 15000, for 15° the swirl angle with the pitch being 2mm. In addition, a mathematical model is proposed for the heat transfer coefficient, which is determined as a response function.

Contents

1. Introduction

Generally, the convective heat transfer can be improvement by the implementation of either passive or active methods. In active methods there always is an external power use that induce bring on the improvement, passive methods, therefore, are preferred in engineering systems over active methods due to their advantages such as non-electric operation, low cost, and low maintenance requirements. Passive swirl flow generators create turbulence and thus increase the total flow length. Swirl flow is of great importance in improving heat transfer as is in many engineering applications. In heat and mass transfer mechanisms, remarkable improvements can be achieved by mere implementation of swirl flows. A variety of swirl generators such as helical wires, twisted tapes, axial blades, short length helical inserts, tangential injectors, tangential fins and radial blade arrays can be incorporated into the system to created swirl flow. In a swirl fluid flow, the

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tangential component of the mainstream velocity is significantly effective on the resulting velocity [1]. Swirl flows are, therefore, desired in numerous chemical and mechanical systems where improved heat and mass transfer is of great importance [2].

Heat transfer and pressure drop characteristics in a horizontal pipe was investigated by Bali and Sarac [3] in the case of decaying swirl flow, focusing on comparative analysis of one or two propeller-type swirl generators. The effects of the number of local swirls and Reynolds number on stable and unstable heat transfer were investigated, by Chen et al. [4], in a pipe flow. In the study, the local heat transfer coefficient in the axial direction was observed to have been affected by the presence of the jet effect near the exit of the swirl vane. They concluded that for 30° vane angle (α) the heat transfer coefficient increases to a maximum after z = 0mm before decreasing non-linearly, whereas for 45° and 60° fin angle, that the heat transfer coefficient decreased non-linearly starting from the fin.

In another study, Aydin et al. [5], using air as their working fluid, experimentally investigated the decaying swirl flow in a pipe flow at Reynolds numbers ranging from 20,000 to 56,000, keeping the pipe surface at constant temperature. They examined the effects of helical swirl generators on heat transfer and pressure drop at different pipe lengths (h = 15, 20, 25 and 30 mm) and pipe length to diameter ratios (L / D = 10, 20, 30 and 40). They reported that the introduction of swirl to the flow resulted in significant improvements in heat transfer, 348% for a given test case. They concluded that the Re, h, and L/D effects were critically interdependent. In another study [6], the effect of swirl generators, with different swirl angles (0◦, 22.5◦, 41◦ and 50◦), fixed at the pipe inlet on heat transfer and fluid flow properties in a pipe flow was examined experimentally and numerically. In another study, Kurtbaş et al. [7] experimentally investigated the effect of conical injector type swirl generator inserts at the turbulent flow regime on heat and exergy transfer in a tube receiving uniform heat flux.

Rotational flow created by the implementation of a vane type swirl generator was examined by Rocha et al. [8] numerically in the Computational Fluid Dynamics (CFD) environment as well as experimentally on a test setup, comprising a 3m pipe with an inner diameter of 5cm. At Reynolds numbers less than 2000, the pressure drop, tangential and axial velocity components, and swirl density were computed in the CFD analysis. In another simulation study conducted by Saqr and Wahid [9], turbulence in compressible non-isothermal pipe flow was examined in order to reveal the effect of inlet swirl density and downstream decaying of swirl on heat transfer and local entropy generation.

Energy and entropy equations are solved with Shih's viable Reynolds Averaged Navier Stokes Equations k-ε turbulence model. According to Yan et al. [10], the decreasing rotational flow properties on a multi-lobed swirl generator (MLSG) were investigated using Reynolds stress turbulence model and CFD. They observed the effects of different lobe numbers (n) and pitch to length ratios (P/D) on swirl density, pressure drop, friction factor coefficient and decay rate in the range of Reynolds numbers from 50,000 to 125,000. They evaluated the efficiency of swirl induction with pressure loss using a swirl efficiency (SE) criterion. In a study by [11], the swirl flow produced by a three-lobed helical tube mounted on a lab-scale pneumatic conveying rig was examined, having measured the strength of induced swirl formations in the turbulent flow regime at a set of Reynolds numbers, where the decay rates of the downstream swirl flows were measured. The swirl decaying rate was found to be inversely proportional to the Reynolds number of the upstream flow, the swirl tube, on the other hand, was observed to have created a redistribution of the downstream velocity field from axial to tangential, and a momentum transfer from axial to angular was also observed.

In another study, Banerjee et al. [12] numerically studied the mechanism of the rotational flow between two concentric cylinders using FLUENT finite volume platform to understand the decaying nature of turbulent swirl flow by simulation. They applied RSM to evaluate the phenomenological properties of the 3D flow field distribution. Ultimately, based on the results obtained from the analysis, they reported that there was a relative difference in swirl density in the flow inlet region of the ring, but that the results of turbulent kinetic energy differed slightly compared to the experimental results they cited.

Yilmaz et al. [13], in their experimental study, examined the heat transfer and frictional properties of the decaying swirl in the rotational flow induced by the use of guide vanes attached at different angles, i.e. 15, 30, 45, 60 and 75. As a result, they proposed a correlation of Reynolds number, Prandtl number and Nusselt number as a function of vane angle. In another study, Helgadóttir et al. [14] studied the shape of a guide vane for laminar swirl flow by numerical simulation in OpenFOAM. They worked on the mesh technique, in which a predefined blade shape is created by mesh twisting or morphing. In order to determine the desired shape of the guide vanes, they employed the velocity profile previously obtained for optimal swirl reduction and laminar swirl flow.

In the light of the findings and recommendations reported in the literature, a total of 20 numerical analyzes were carried out in this study as per the RSM experiment design to determine the optimum values of the Reynolds number, swirl angle and pitch parameters that are predicted to affect the heat transfer in decaying swirl flow generators.

2. Material and Method

A constant heat flux of 1000 W/m^2 was applied to the40 mm diameter pipe for the test area. Air flow was defined from the inlet area at a constant velocity of 11,625 m/s and at a temperature of 295 K. The render image of the geometry employed in the study is given in Figure 1.

RSM, utilizing from combination of statistical and mathematical techniques in process modeling and optimizing, is a useful method used to reveal the relationship between the process variables and responses [15]. RSM helps to determine optimum conditions by evaluating a large number of variables and the interactions between these variables by making fewer experiments thanks to the design approaches it uses [16]. RSM successfully combines mathematical and statistical techniques to improve, develop and optimize processes [17].

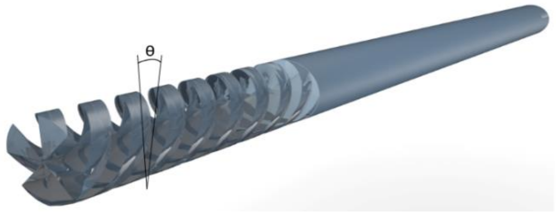

Figure 1 Render image of pipe with decaying swirl generator

The factors, parameters investigated in the study, and their levels are as given in Table 1. In Table 2 is the experimental plan obtained with the Minitab 18 utility software. Face Centered Central Composite Design (FCCCD), consisting of axial points placed at the face centers of a cube, was used in the method. As all parameters investigated in the study has three levels, the design consisted of a combination of the parameter values at all levels, thus seven center points and eight star points were on the face of the cube [18]. CCD is generally used when the design plan requires sequential testing. These designs contain information from a properly planned factorial experiment [19].

Table 1 Parameters and Levels

Parameter	Level 1	Level 2	Level 3
Reynolds Number	5,000	10,000	15,000
Swirl angle (°)	15	20	25
Pitch (mm)	2	3	4

In this study, 20 numerical analyzes in which 3 different parameters were examined at 3 levels were done with the Fluent software. Statistical analyzes for the obtained outputs were carried out with the Minitab 18 utility software.

Table 2 Experimental Layout

Exp. No.	Parameters			Response variable
	Reynolds Number (A)	Swirl angle (B)	Pitch (C)	h
1	5,000	25	4	100.961
2	5,000	25	2	102.252
3	5,000	15	2	102.848
4	10,000	20	3	102.561
5	10,000	20	3	102.561
6	5,000	20	3	101.993
7	15,000	15	4	107.074
8	10,000	20	3	102.561
9	15,000	15	2	107.791
10	10,000	25	3	102.402
11	10,000	20	3	102.561
12	15,000	25	4	103.967
13	10,000	20	4	101.67
14	10,000	20	3	102.561
15	5,000	15	4	102.214
16	15,000	20	3	105.887
17	10,000	20	3	102.561
18	10000	20	2	103.111
19	15000	25	2	105.436
20	10000	15	3	102.76

When the response of interest is affected by various variables [21], the implementation of RSM, a widely used mathematical and statistical method for modeling and analyzing, can provide a proper experimental design, where all independent variables are integrated, and a set of equations by which a theoretical value of an output is found can be obtained by using the input data of an experiment. Outputs are obtained by well-designed regression analyses and results from the mathematical model [20].

2.1. CFD Procedure

Using the k-ε turbulence model, the heat transfer was aimed to be increased without using any element in the test region by giving memory to the flow with the flow generator added from the outside. For the optimum geometries obtained, the meshes created to be used in the analysis were gradually improved starting from 500,000 and solutions were achieved with the mesh number of 941,000 for this geometry. It has been seen that upgrading the mesh geometry and dimensions by improving the mesh did not cause any change in the results, and the solutions obtained with 941,000 mesh number gave results very close to the actual solution. In the numerical analysis, the boundary conditions and assumptions were as below:

- Air, used as the fluid, with incompressible properties (Ma < 0.3).
- The test zone and the rotational flow generators are stable and continuous.
- The air flow defined at the inlet area has a constant velocity of 11,625 m/s and a temperature of 295 K.
- 1000 W/m^2 heat flux was applied to the pipe.
- Gravitational effects are neglected.

3. Results and Discussions

RSM defines the functional relationship between the parameters under consideration and the objective function, and a well definition is needed for a good fit. Therefore, a fit test is designed to determine whether the chosen model is sufficient to explain the observed data.

Table 3 Analysis of variance table

Source	DF	Adj. SS	Adj. MS	F Value	P Value
Model	9	61.8654	6.87393	70.74	0.000
Linear	3	0.5050	0.16834	1.73	0.223
A	1	0.4547	0.45472	4.68	0.056
B	1	0.0037	0.00372	0.04	0.849
C	1	0.0253	0.02531	0.26	0.621
Square	3	11.4639	3.82129	39.33	0,000
A*A	1	6,0255	6,02545	62.01	0,000
B*B	1	0.0404	0.04041	0.42	0.533
C*C	1	0.0132	0.01320	0.14	0.720
2-way Interaction	3	1.8884	0.62947	6.48	0.010
A*B	1	1.6317	1.63172	16.79	0.002
A*C	1	0.0085	0.00852	0.09	0.773
B*C	1	0.2482	0.24816	2.55	0.141
Error	10	0.9717	0.09717		
Lack-of-Fit	5	0.9717	0.19433	*	*
Pure Error	5	0.0000	0.00000		
Total	19	62.8370			

The interaction of the model with the experimental data is determined by comparing the P value with the significance level, which, in this study, was selected to be $\alpha = 0.05$. This suggests that any P value greater than 0.05 is statistically significant, whereas those less than 0.05 are deemed to have an effect that is insignificant. The ANOVA table for the heat transfer coefficient (h), which was determined here as the objective function, is shown in Table 3.

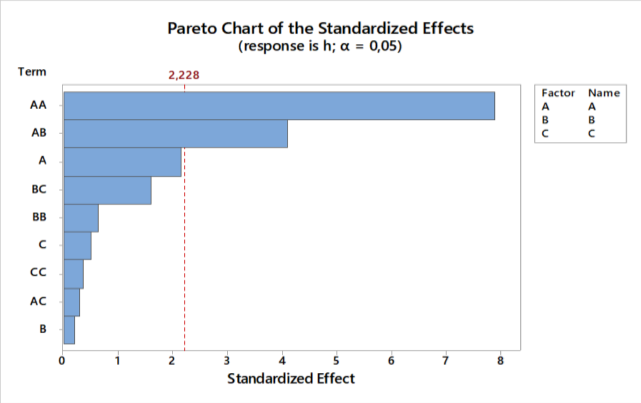

Figure 2 Pareto Chart

In Figure 2, is the Pareto chart that can help compare the relative magnitude of the key, square, and interaction effects and their statistical significance based on their extent with respect to the baseline (red dotted vertical line). Any effect that crosses the baseline is considered statistically significant. Accordingly, the square effects of the Reynolds number (AA) and the combined effects of the Reynolds number and the swirl angle (AB) are statistically significant.

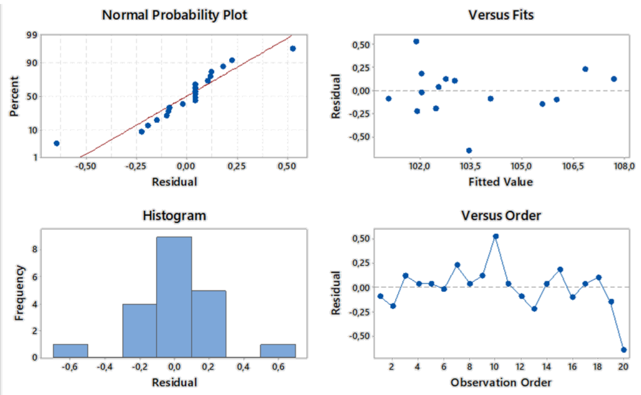

Figure 3 Residual Plots for response variable (h)

In Figure 3, the residual plots for the heat transfer coefficient, h, is given. Moving away from the orthogonal line in the normal probability plot, which represents the points where the numerical analysis results and the values taken from the model overlap, means that there is a difference between the model and the numerical analysis. It is seen that the results of the model created for the maximum heat transfer coefficient and the results of the numerical analysis are in good agreement. According to the graph showing the order of observations versus the residuals, residual values are shown for the 20 analyzes that show the difference between the model and the numerical analysis. While a negative residual value denotes experimental values smaller than that given by the model, its being positive means the value given by the model and the numerical analysis value are close to each other.

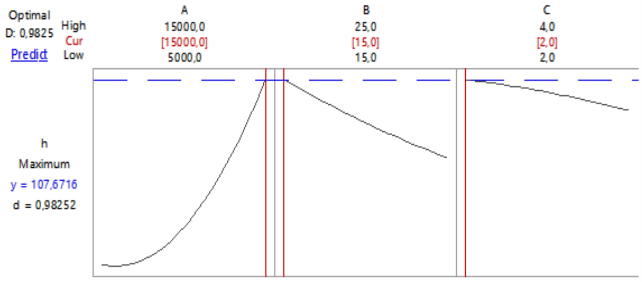

Figure 4 Optimization Graphs

The model used the D-optimality criterion to determine the optimized transport coefficient based on the three factors considered in the study. As shown in Figure 4, with a heat transfer coefficient of 107.6716 W/m^2, a D-optimality of 0.9825 was obtained as the highest optimization result. The D-optimality value, is the ratio of the optimum value of the objective function to the maximum value that the model can provide. Figure 5 shows the intersection of parameters and optimally calculated values [22].

Optimum values are given in Table 4.

Table 4 Optimum results

Parameter	Optimum value
Reynolds number	15000
Swirl angle (°)	15
Pitch (mm)	2

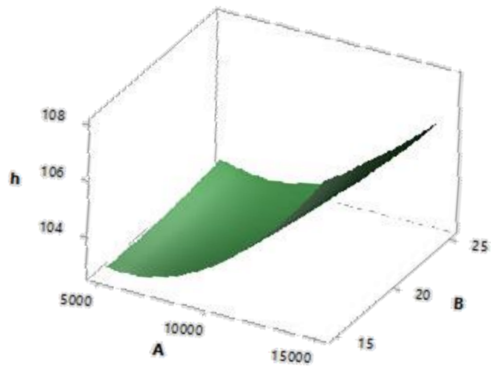

Figure 5 Three-dimensional interaction Response Surface Plot of h versus B; A

The three-dimensional response plot of the objective function (the heat transfer coefficient), Reynolds number (A) and helix angle (B) is given in Figure 5.

The regression equation obtained from the results of the Minitab analysis of variance is given in Equation 1.

$$h = 104.04 + 0.000398A - 0.1534B - 0.555C \qquad (1)$$

The images obtained in CFD analyses using the optimum parameters obtained by the RSM are given in Figure 6, Figure 7 and Figure 8.

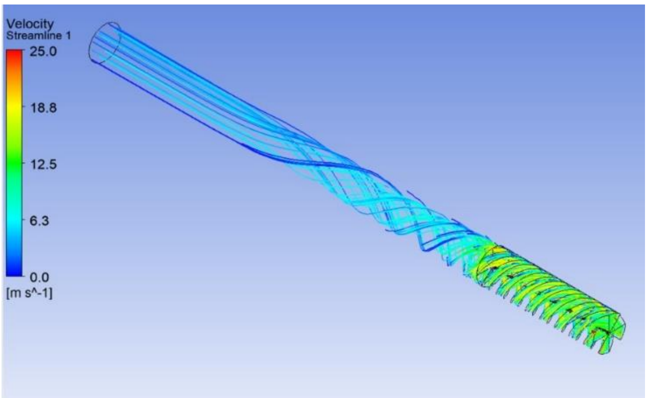

Figure 6 Velocity streamlines

As seen in Figure 6, the swirl memory imparted to the flow moves along the pipe, decreasing until halfway through the pipe.

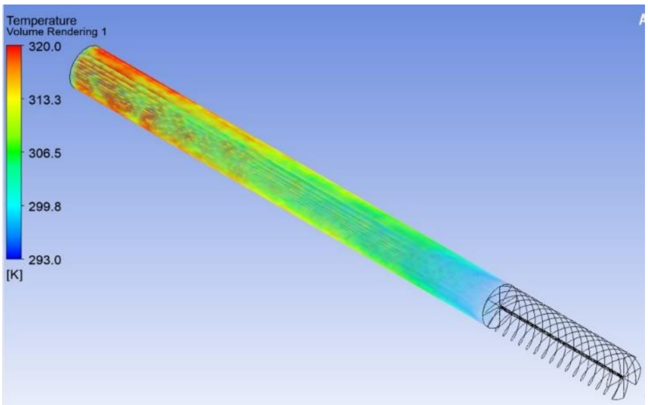

Figure 7 Temperature Volume Rendering

The increase in the heat imparted to the air due to the heat flux at the exit shows itself up in the temperature distribution in Figure 7.

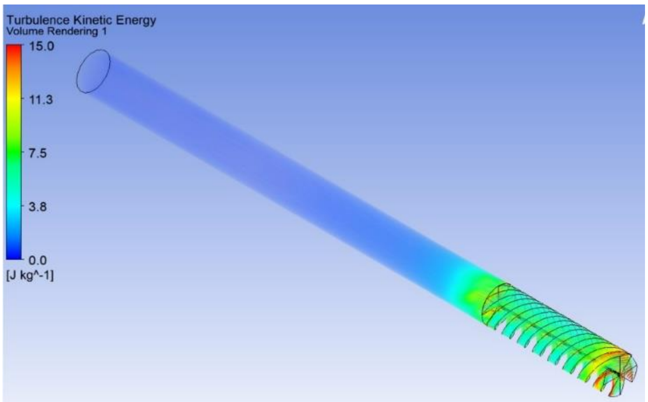

Figure 8 Turbulence kinetic energy

The turbulence kinetic energy is relatively higher at the pipe inlet due to the swirl memory imparted to the flow (Figure 8).

Analysis was also performed for a pipe with no swirl generators for comparison purposes. The heat transfer coefficient was obtained as 54.638 W/m^2 K. When it is compared with that of the decaying swirl flow generator at the optimum Reynolds number, a decrease in heat transfer by roughly 50% was observed.

4. Conclusion

The effects of axial swirl generators added to the pipe inlet, which are intended to impart a swirl memory to the flow, on heat transfer were investigated. Numerical optimization was done with the RSM. The square effects of Reynolds number (AA) and the combined effects of Reynolds number and swirl angle (AB) were found to be statistically significant. Optimum results were obtained for the Reynolds number of 15,000, for 15° swirl angle and 2mm pitch. A mathematical model is proposed for the heat transfer coefficient determined as the response function. Confirmation analyzes were performed for optimum results. Numerical analysis results for optimum parameters were visualized with velocity streamlines, temperature volume rendering and turbulence kinetic energy outputs.

Declaration of Conflict of Interest

The authors declare no conflict of interest.

References

[1] Siddique H, Hoque MSB, Ali M. Effect of swirl flow on heat transfer characteristics in a circular pipe. In: *AIP Conference Proceedings*: AIP Publishing LLC. p. 50028.

[2] Liu S, Sakr M. A comprehensive review on passive heat transfer enhancements in pipe exchangers. *Renewable and sustainable energy reviews* (2013) **19**:64–81.

[3] Bali T, Sarac BA. Experimental investigation of decaying swirl flow through a circular pipe for binary combination of vortex generators. *International Communications in Heat and Mass Transfer* (2014) **53**:174–179.

[4] Chen B, Ho K, Xiao H, Abakr YA, Chan A. The effects of swirling decaying flow towards pipe entry length and heat transfer in an annular pipe. *International Journal of Heat and Mass Transfer* (2018) **123**:668–677.

[5] Aydin O, Avci M, Markal B, Yazici MY. An experimental study on the decaying swirl flow in a tube. *International Communications in Heat and Mass Transfer* (2014) **55**:22–28.

[6] Bilen K, Tokgoz N, Solmaz İ, Balta T. Thermo-hydraulic performance of tube with decaying swirl flow generators. *Applied Thermal Engineering* (2022) **200**:117643.

[7] Kurtbaş İ, Gülçimen F, Kılıçarslan A, Kaya M. Effect of swirl generator inserted into a tube on exergy transfer: decaying flow. *Experimental Heat Transfer* (2014) **27**(5):472–487.

[8] Rocha AD, Bannwart AC, Ganzarolli MM. Numerical and experimental study of an axially induced swirling pipe flow. *International journal of heat and fluid flow* (2015) **53**:81–90.

[9] Saqr KM, Wahid MA. Effects of swirl intensity on heat transfer and entropy generation in turbulent decaying swirl flow. *Applied Thermal Engineering* (2014) **70**(1):486–493.

[10] Yan T, Qu J, Sun X, Chen Y, Hu Q, Li W. Numerical evaluation on the decaying swirling flow in a multi-lobed swirl generator. *Engineering Applications of Computational Fluid Mechanics* (2020) **14**(1):1198–1214.

[11] Fokeer S, Lowndes I, Kingman S. An experimental investigation of pneumatic swirl flow induced by a three lobed helical pipe. *International journal of heat and fluid flow* (2009) **30**(2):369–379.

[12] Banerjee C, Urankar S, Raikar S, Suresh D. Numerical Study of Decaying Swirling Flow in an Annulus.

[13] Yilmaz M, Çomakli Ö, Yapici S. Enhancement of heat transfer by turbulent decaying swirl flow. *Energy conversion and management* (1999) **40**(13):1365–1376.

[14] Helgadóttir Á, Lalot S, Beaubert F, Pálsson H. Mesh Twisting Technique for Swirl Induced Laminar Flow Used to Determine a Desired Blade Shape. *Applied Sciences* (2018) **8**(10):1865.

[15] Myers RH, Montgomery DC, Anderson-Cook CM. *Response surface methodology: process and product optimization using designed experiments*: John Wiley & Sons (2016).

[16] Yoğurtçu H. Optimization of microwave apple drying using response surface method. *Journal of the Faculty of Engineering and*

Architecture of Gazi University, Accepted Manuscript (2019) **34**(3):1365–1376.

[17] Sabreena AN, Azma Y, Mohamad O. response surface methodology for optimisation of parameters for extraction of *Stevia rebaudiana* using water, H_2O. *IIOAB* (2017) **47**:459–466.

[18] Balachandran M, Devanathan S, Muraleekrishnan R, Bhagawan SS. Optimizing properties of nanoclay–nitrile rubber (NBR) composites using face centred central composite design. *Materials & Design* (2012) **35**:854–862.

[19] Akers MD. *Exploring, Analysing and Interpeting Data with Minitab 18*: Compass Publishing (2018).

[20] Gelis K, Akyurek EF. Entropy generation of different panel radiator types: Design of experiments using response surface methodology (RSM). *Journal of Building Engineering* (2021) **41**:102369.

[21] Aydar AY. Utilization of response surface methodology in optimization of extraction of plant materials. *Statistical approaches with emphasis on design of experiments applied to chemical processes* (2018):157–169.

[22] Yesildal F, Ozakin AN, Yakut K. Optimization of operational parameters for a photovoltaic panel cooled by spray cooling. *Engineering Science and Technology, an International Journal* (2021).