IJE TRANSACTIONS B: Applications Vol. 30, No. 8, (August 2017) 1253-1259

International Journal of Engineering

Journal Homepage: www.ije.ir

Enhancement of Heat Transfer over a Double Forward Facing Step with Square Obstacle through Taguchi's Optimization Technique

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PAPER INFO

Paper history:
Received 20 April 2017
Received in revised form 22 June 2017
Accepted 07 July 2017

Keywords:
Double Forward Facing Step Flow
Square Obstacle
Taguchi's S/N Ratio Analysis
Response Surface Methodology Technique
ANOVA
Numerical Simulation

ABSTRACT

In this paper, the heat transfer to the fluid, passing through the double forward facing step (FFS) channel with square obstacle is enhanced by Taguchi's S/N ratio analysis. Flow through the forward facing step channel has a wide range of applications in thermal systems due to its flow separation and subsequent reattachment, which in turn enhances the heat transfer. Flow separation and reattachment mainly depends on the channel geometry, obstacle and flow parameters. Hence, in this study, step height in the channel, obstacle size, Reynold's number and gap between the obstacle and step are included as control paramters in the S/N ratio analysis for maximizing the heat transfer. These parameters are varied through three levels of values and L9 orthogonal array is employed. Numerical simulation technique is applied to analyze the L9 cases through computational fluid dynamics code. From the simulation, the rise in temperature at the channel exit with reference to the inlet is predicted. The best values for the identified control parameters conclude to a temperature raise of about 2.86°C. The optimum result obtained from the S/N ratio analysis is also compared with response surface methodology technique. Finally, analysis of variance (ANOVA) is conducted and identified that step height and flow Reynold's number affect the heat transfer by about 79 and 19%, respectively.

***doi**: 10.5829/ije.2017.30.08b.19*

NOMENCLATURE

ρ	Density	w	Obstacle side width generalized with channel inlet diameter
g	Gravity	h*	Step height
μ_e	Effective viscosity	Re	Reynolds number
P	Pressure	g*	Gap between obstacle from the forward facing step generalized with channel inlet diameter
Cp	Specific heat	S/N	Signal to noise
K	Thermal conductivity	y	Output response
ΔT	Temperature rise	n	Number of trials

1. INTRODUCTION[1]

Flow through a forward facing step (FFS) channel is characterized by sudden contraction, flow separation and subsequent reattachment. This flow separation and reattachment are used widely in cooling and heating applications. Even though separation of flow is undesirable due to unwanted pressure drop and energy loss in some applications, it plays a significanct role in the enhancement of heat transfer. The applications of heat transfer appears in combustion chambers, environmental control systems, cooling systems for electronic equipment, chimerical process and energy system equipment, high performance heat exchangers, cooling passages in turbine blades, and flow through valves. Flow through the forward facing step channel is more complicated than backward facing step in which only one flow separation occurs behind the step. However, one or more separating region can be found in FFS depending on the boundary layer thickness and Reynold's number [1]. Also, the reattachment length in

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Please cite this article as: M. Janani, D. Prakash, E. Harini, T. Harish, Enhancement of Heat Transfer over a Double Forward Facing Step with Square Obstacle through Taguchi's Optimization Technique, International Journal of Engineering (IJE), TRANSACTIONS B: Applications Vol. 30, No. 8, (August 2017) 1253-1259

the FFS channel strongly depends on the geometry used to induce separation, and on the parameters such as Reynolds number based on the step height and free stream velocity, free stream turbulence level, relative boundary layer thickness, aspect ratio (*W*/*h*) and blockage ratio (Upstream rough-combined). Scheit et al. [2] analyzed the flow over a forward facing step through the direct numerical simulation method and observed that region of highest turbulent pressure fluctuations corresponds to the region of acoustic source. Kherbeet et al. [3] studied the effect of step height of microscale backward facing step on heat transfer characteristics and found that Nusselt number and skin friction coefficient increases with the increase of the step height, while the Reynolds number and pressure drop were found to decrease. Oztop et al. [4] observed that the aspect ratio of rectangular obstacle increases the rate of heat transfer and also reduces the pressure drop. Xie and Xi [5] studied the heat transfer characteristics in the backward and forward facing step with transitional flow and noticed that periodic flow fluctuation has a positive effect on the heat transfer enhancement and the fundamental fluctuation frequency decreases with the increase in step height. Nassab et al. [6] studied the turbulent forced convection flow adjacent to inclined forward step in a duct and reported that the heat transfer coefficient and hydrodynamic behavior of flow are strongly dependent on step height and inclination angle. Sanyılmaz et al. [7] stated that the reattachment length is affected significantly by an increase in Reynold's number due to the velocity gradient in the boundary layer. From this review, it is clearly observed that in the FFS channel, step height, Reynolds number and aspect ratio are the factors that affect the turbulence flow heat transfer. In continuation of the available research works, this study is focused to identify the optimal values of the control parameters that affect the turbulent heat transfer through Taguchi's S/N ratio optimization techniques. Furthermore, a statistical analysis "Analysis of Variance" (ANOVA) is also conducted to identify the significance of control parameters on the output response.

2. DOUBLE FORWARD FACING STEP WITH SQUARE OBSTACLE

The double forward facing step channel investigated in this study has two steps in the upstream direction with square obstacle ahead of each step. The flow through the channel is analyzed by numerical simulation methodology and the flow is considered as 2-dimensional, steady state and incompressible. The diameter of the channel opening at the inlet is taken as 0.1 m and the length of the channel is 1.6 m. The channel contains two obstacles (O_1 and O_2) located at a distance of "g"infront of the step. The top wall of the channel is perfectly insulated and the bottom wall along with steps are maintained at a constant temperature (T_w). The length of the channel for various step heights are 1, 0.2 and 0.4 m. In this geometry, the step height and gap between the obstacle and step are generalized with the channel inlet diameter (D) as h* (h_1/D=h_2/D) and g* (g/D), respectively. The geometry of the double FFS channel is shown in Figure 1.

3. NUMERICAL SIMULATION METHODOLOGY

The double forward facing channel model is created in the Gambit software as a two-dimensional approach with Cartesian coordinates. Air is the working fluid, having the properties listed in Table 1.

The flow is assumed to enter the channel perpendicular to the inlet and the fluid properties are assumed to be constant with reference to the temperature. The flow variables velocity, pressure and temperature are calculated from the continuity, pressure momentum and energy equation given by Equations (1) to (4), respectively [8]:

Continuity equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho v_x)}{\partial x}+\frac{\partial(\rho v_y)}{\partial y}=0 \tag{1}$$

X momentum equation:

$$\begin{aligned}&\frac{\partial \rho v_x}{\partial t}+\frac{\partial(\rho v_x v_x)}{\partial x}+\frac{\partial(\rho v_x v_y)}{\partial y}=\rho g_x-\frac{\partial P}{\partial x}+R_x\\&+\frac{\partial}{\partial x}\left(\mu_e\frac{\partial v_x}{\partial v_x}\right)+\frac{\partial}{\partial y}\left(\mu_e\frac{\partial v_x}{\partial y}\right)+\tau_x\end{aligned} \tag{2}$$

Y momentum equation:

$$\begin{aligned}&\frac{\partial \rho v_y}{\partial t}+\frac{\partial(\rho v_x v_y)}{\partial x}+\frac{\partial(\rho v_y v_y)}{\partial y}=\rho g_y-\frac{\partial P}{\partial y}+R_y\\&+\frac{\partial}{\partial x}\left(\mu_e\frac{\partial v_y}{\partial v_x}\right)+\frac{\partial}{\partial y}\left(\mu_e\frac{\partial v_y}{\partial y}\right)+\tau_y\end{aligned} \tag{3}$$

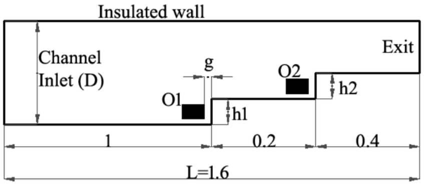

Figure 1. Double FFS channel with obstacle

TABLE 1. Properties of air

Property	Value
Density	1.225 kg/m^3
Specific heat	1006.43 J/kg.K
Thermal conductivity	0.0242W/mK

Energy equation:

$$\frac{\partial}{\partial t}\left(\rho C_p T_o\right)+\frac{\partial}{\partial x}\left(\rho v_x C_p T_o\right)+\frac{\partial}{\partial y}\left(\rho v_y C_p T_o\right)= \frac{\partial}{\partial x}\left(K\frac{\partial T_o}{\partial x}\right)+\frac{\partial}{\partial y}\left(K\frac{\partial T_o}{\partial y}\right)+W^v+E_k+Q_v+\phi+\frac{\partial P}{\partial t} \tag{4}$$

where v_x, v_y and v_z are the components of velocity in x, y and z directions, ρ is the density, t is the time, g is the gravity, μ_e is the effective viscosity, P is the pressure, R_i is the distributed resistance, suffix i is x, y and z, τ is the viscous loss. C_p is the specific heat, T_o is the total temperature, K is the thermal conductivity, W^v is the viscous work term, Q_v is the volumetric heat source, ϕ is the viscous heat generation term and E_k is the kinetic energy.

3. 1. Boundary Conditions and Solution Methodology At the inlet of the channel, flow velocity and temperature are specified. At the exit of the channel atmospheric pressure is imposed. The top wall is perfectly insulated and hence the heat flux is set to zero. The bottom wall and steps are maintained at a constant temperature of 313K. No slip boundary condition is employed for all wall surfaces.

The governing equations for the specified boundary conditions are solved in Fluent 6.2 software. The geometry is meshed with tetrahedral T grid type cell and the result independent grid size is attained for the grid density of 128,320 cells. Standard k-ε turbulence model is employed and double precision pressure based solver is used. Semi implicit method for pressure linked solution (SIMPLE) algorithm is used to couple the pressure and velocity flow variables. The second order upwind scheme is employed for the discretization of flow variables and the numerical solution is iterated up to the convergence level of 10^{-6} for all the flow variables. This numerical simulation is validated with the results obtained from flow through the double forward flow channel conducted by Oztop et al. [4] and a comparison is made on the axial velocity across the channel at a distance of 0.97 m from the channel entry as shown in Figure 2.

4. MAXIMIZATION OF HEAT TRANSFER-TAGUCHI'S S-N RATIO ANALYSIS

Taguchi method is one of the robust design and optimization methods, widely used to determine the values of control factors discretely to obtain the optimal value of objectives. The Taguchi method is an experimental design technique, useful in reducing the number of experiments drastically by using orthogonal arrays and also minimizing the effects of the factors out of control. The basic philosophy of the Taguchi method is to ensure quality in the design phase.

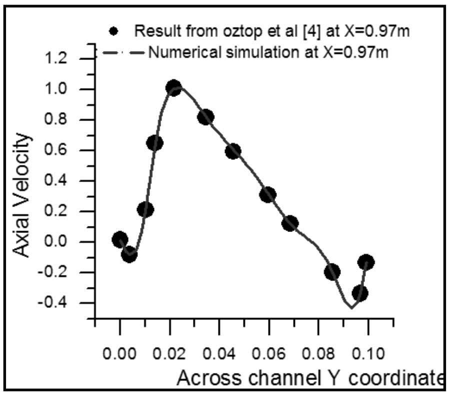

Figure 2. Validation of numerical simulation

This technique is based on the following concepts; the quality losses must be determined as deviations from the goals and the quality must be designed into the product. The full factorial experimental design is costly because it has many runs. So the alternative is to use the Taguchi method to save resources, expenses and time [9-11]. The greatest advantages of the Taguchi method are to decrease the experimental time, to reduce the cost and to find out significant factors in a shorter time period [12]. This technique is employed in this study to maximize the heat transfer to the fluid flow through a double forward facing channel with square obstacle. Square obstacle width, step height, Reynold's number and gap between the obstacle from the step are the parameters considered in this Singal to Noise ratio (S/N ratio) optimization analysis. The four parameters are varied through three levels of values and are given in Table 2.

4. 1. Orthogonal Array Selection of orthogonal array is a vital part in the Taguchi's optimization method. Orthogonal array can drastically reduce the number of experimental runs in comparison with the full factorial test or trial and error method. The general expression for orthogonal array is Ld(ak), where d is the total number of experiments in Taguchi's method, a and k represent the number of levels of variation of each factor and number of factors considered in the optimization, respectively. In this study, four parameters are varied through three levels of values and hence L9 orthogonal array is employed and given in Table 3.

TABLE 2. Parameters and their values at three levels

Parameter	Level 1	Level 2	Level 3
Obstacle side width in (%) of h1 (w)	25	50	75
Step height h1=h2 (h*)	0.025	0.05	0.075
Reynolds's number (Re)	10,000	20,000	30,000
Gap between obstacle from the forward facing step (g*)	0.02	0.04	0.06

Since the orthogonal array has the property of orthogonality, it is fair to compare the effects of each factor by main effects plot.

4. 2. S-N Ratio Analysis The output responses obtained from the numerical simulation are transformed to S/N ratio based on logarithmic data transformation. The signals indicate that the effect on the average responses and noises are calculated by the influence on the deviations from the average responses, which will disclose the sensitiveness of the experimental output to the noise factors [13]. For the objective of maximization and minimization, "larger is the better" and "smaller is the better" equations are used, respectively. In this study, the heat transfer in terms of temperature difference is maximized and hence "larger is the best" equation is used as given in Equation (5) [14].

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y^2}\right) \qquad (5)$$

The temperature rise plot across the double forward facing step channel with square obstacle is shown in Figure 3 and for the nine cases is represented in Table 3. The predicted rise in temperature (ΔT) at the channel exit and the corresponding S/N ratio for the nine experiments are given in Table 4.

The main effect plots for the S/N ratios are calculated and shown in Figure 4. From this figure, the optimal values for the identified design parameters are w= 75%; h*= 0.075; Re=10000 and g*=0.04.

TABLE 3. L9 orthogonal array

Case no	w	h*	Re	g*
1	25	0.025	10000	0.02
2	25	0.05	20000	0.04
3	25	0.075	30000	0.06
4	50	0.025	20000	0.06
5	50	0.05	30000	0.02
6	50	0.075	10000	0.04
7	75	0.025	30000	0.04
8	75	0.05	10000	0.06
9	75	0.075	20000	0.02

TABLE 4. Predicted output response and S/N ratio values

Case no	ΔT	S/N ratio
1	1.77155	4.96707
2	1.80872	5.14743
3	2.29572	7.21838
4	1.51328	3.59839
5	1.71228	4.67150
6	2.84427	9.07942
7	1.43597	3.14291
8	2.24246	7.01449
9	2.57239	8.20674

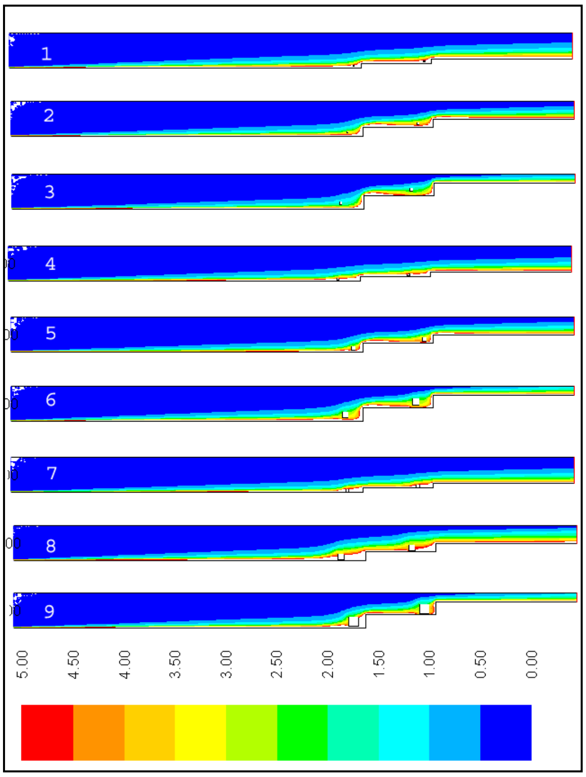

Figure 3. Temperature rise ((ΔT) plot in double FFS channel

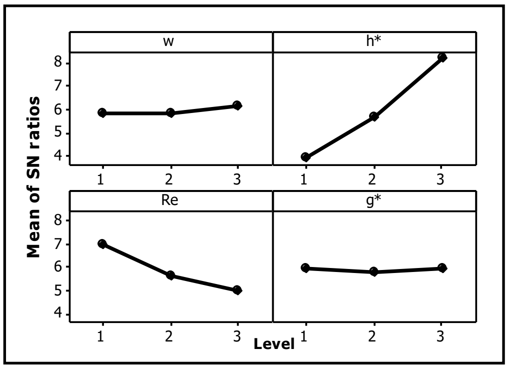

Figure 4. Main effect plots on S/N ratio

5.COMPARISON WITH RESPONSE SURFACE METHODOLOGY TECHNIQUE

The best values identified from the Taguchi's S/N ratio analysis are compared with the response surface methodology technique. Response surface methodology (RSM) is a collection of mathematical and statistical techniques useful for analyzing the problems in which several independent variables influence a response [15]. RSM technique additionally provides the relationship between the parameters and the response. The objective and typical applications of RSM are: (1) mapping a response over a particular region of interest, (2) optimization of response, and (3) selection of operating conditions to achieve specifications [16]. In this study, the identified parameters are varied for 5 levels of values with the same upper and lower limits as given in Table 5. The design matrix for RSM technique is given in Table 6 along with the predicted rise in temperature.

TABLE 5. Parameter values for RSM method

Parameter	-2	-1	0	1	2
w %	25	37.5	50	62.5	75
h*	0.025	0.0375	0.05	0.0625	0.075
Re	10000	15000	20000	25000	30000
g*	0.02	0.03	0.04	0.05	0.06

TABLE 6. Design matrix with response surfaces

Std Ord	Run Ord	Pt Type	Blocks	w	h*	Re	g*	ΔT
21	1	-1	1	0	0	-2	0	2.24
17	2	-1	1	-2	0	0	0	1.89
7	3	1	1	-1	1	1	-1	2.03
30	4	0	1	0	0	0	0	1.98
18	5	-1	1	2	0	0	0	2.08
19	6	-1	1	0	-2	0	0	1.53
11	7	1	1	-1	1	-1	1	2.27
28	8	0	1	0	0	0	0	1.98
24	9	-1	1	0	0	0	2	1.96
1	10	1	1	-1	-1	-1	-1	1.87
29	11	0	1	0	0	0	0	1.98
5	12	1	1	-1	-1	1	-1	1.61
26	13	0	1	0	0	0	0	1.98
2	14	1	1	1	-1	-1	-1	1.94
25	15	0	1	0	0	0	0	1.98
15	16	1	1	-1	1	1	1	2.01
27	17	0	1	0	0	0	0	1.98
14	18	1	1	1	-1	1	1	1.65
12	19	1	1	1	1	-1	1	2.39
9	20	1	1	-1	-1	-1	1	1.84
23	21	-1	1	0	0	0	-2	2.01
31	22	0	1	0	0	0	0	1.98
8	23	1	1	1	1	1	-1	2.15
13	24	1	1	-1	-1	1	1	1.58
16	25	1	1	1	1	1	1	2.13
20	26	-1	1	0	2	0	0	2.44
6	27	1	1	1	-1	1	-1	1.68
3	28	1	1	-1	1	-1	-1	2.29
22	29	-1	1	0	0	2	0	1.72
4	30	1	1	1	1	-1	-1	2.41
10	31	1	1	1	-1	-1	1	1.91

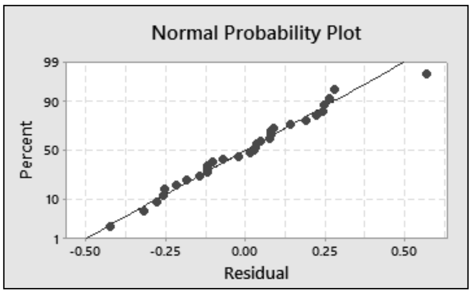

Figure 5. Normal probability plot residue

The normal percentage probability vs residual plots for a rise in temperature are shown in Figure 5 which reveals that the residuals are falling in a straight line, which means the errors are distributed normally.

The optimisation in RSM technique is performed by using the Minitab Response Optimizer and the optimum parameters are found from Figure 6 as w= 75%; h*= 0.075; Re=10000 and g*=0. 02 as same from the Taguchi's S/N ratio analysis.

6. CONFIRMATION TEST

A confirmation test is conducted for the best level values of parameters. Obstacle side width in (%) of h1 (w) = 75; step height h1=h2 =(h)*= 0.075; Reynolds number =10000 and the gap between obstacle from the forward facing step (g*)=0.02 are set and the rise in temperature is found to be 2.86°C which is within the confidence level.

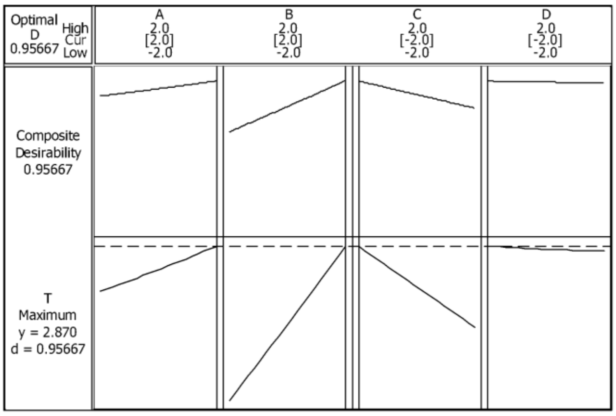

Figure 6. Optimal values from RSM method

7. ANALYSIS OF VARIANCE (ANOVA)

ANOVA is a collection of statistical models used to analyze the differences among group means and their associated procedures (such as "variation" among and between groups), developed by statistician and evolutionary biologist Ronald Fisher [17]. ANOVA is performed to judge the statistical significant process parameters affecting the responses [18, 19]. Table 7 shows the ANOVA analysis of the model. From this table, it is identified that, step height and Reynolds number are the significant factors that affect about 80 and 18% of the temperature rise of air and the other two factors are insignificant.

TABLE 7. ANOVA table

Parameter	Degree of freedom	Sum of squares	Mean square	F Value	SS'	Contribution (%)
w	2	0.01423	0.00714	0.00714	0.0142	0.782
h*	2	1.4417	0.72085	0.72085	1.441	79.28
Re	2	0.35988	0.17993	0.17993	0.3598	19.79
G*	2	0.00257	0.00128	0.00128	0.0025	0.14
Error	0				0	0

8. CONCLUSION

Flow through double forward facing step channel has a wide range of applications in the area of heat transfer. The magnitude of heat transfer depends on many geometrical parameters and flow parameters, since it strongly affects the flow separation and reattachment. However a defined value for the geometry and flow parameters to enhance the heat transfer is limited. Hence, in this study, a best set of values is identified for maximum heat transfer through Taguchi's S/N ratio analysis and also compared to RSM technique. The experimetal cases planned for both techniques are numerically simulated by computational fluid dynamics technique and the same is validated. For the channel diameter of unit diameter and length of 1.6 times of channel diameter, the best values for the obstacle side width w = 75% of step height; generalized step height (h*) = 0.075; Reynold's number=10000 and the generalized gap between step and obstacle (g*) = 0.02 are identified. The identified best value raises the temperature of air by 2.86 °C with reference to the temperature of air at the channel inlet. Finally, the most influencing factor on heat transfer are identified as step height (h*) and Reynold's number through ANOVA technique.

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Paper history:
Received 20 April 2017
Received in revised form 22 June 2017
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Numerical Simulation

چکیده

در این مقاله، انتقال حرارت به مایعی که از کانال دو طرفه رو به جلو (FFS) با مانع مربعی عبور می‌کند با آنالیز S/N تاگوچی افزایش داده می شود. جریان در کانال گام رو به جلو کاربرد گسترده ای در سیستم های حرارتی دارد چرا که جداسازی جریان و اتصال مجدد آن، به نوبه خود انتقال حرارت را افزایش می دهد. جداسازی جریان و اتصال مجدد به طور عمده به هندسه کانال، مانع و پارامترهای جریان بستگی دارد. از این رو، در این مطالعه، ارتفاع گام در کانال، اندازه مانع، عدد رینولدز و فاصله بین مانع و گام به عنوان پارامترهای کنترل در آنالیز نسبت S/N برای به حداکثر رساندن انتقال حرارت بررسی می شود. این پارامترها در سه سطح مقادیر تغییر داده شده و در آرایه افقی L9 استفاده می شوند. شبیه سازی عددی برای تحلیل موارد L9 از طریق کد دینامیک سیالات محاسباتی استفاده می شود. از شبیه سازی، افزایش دما در خروجی کانال با توجه به ورودی پیش بینی شده است. با استفاده از بهترین مقادیر برای پارامترهای کنترل، افزایش درجه حرارت در حدود ۲٫۸۶درجه سانتیگراد است. نتیجه مطلوب حاصل از آنالیز نسبت S/N با روش پاسخ سطح مقایسه شده است. در نهایت، آنالیز واریانس (ANOVA) انجام می شود و مشخص می شود که ارتفاع گام و عدد رینولدز روی انتقال حرارت به ترتیب به میزان ۷۹ و ۱۹٪ تاثیرگذار هستند.

doi: *10.5829/ije.2017.30.08b.19*