**ROMANIAN JOURNAL OF INFORMATION SCIENCE AND TECHNOLOGY**
Volume **21**, Number 4, 2018, 406–428

# Fuzzy logic approach for temperature analysis in multi-jet air impingement investigation

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**Abstract.** In the present work, an experimental investigation was carried out to study the influence of design parameters of impinging air jets on heat transfer, temperature and Nusselt number in a multi-jet air impingement system. Studies have been conducted to see the effect of parameters such as type of nozzle, area of nozzle, Reynolds number and H/D ratio on the heat transfer characteristics. Square, triangle and circular type nozzles with area 8, 10 and 12 mm$^2$ were used for the analysis considering Reynolds number 18000, 20000 and 22000. The H/D ratio used was 2D, 4D and 6D. Taguchi based design of experiment approach with $L_{27}$ orthogonal array was used to design the experiments. Grey relational analysis is used to optimize the multiple responses and the uncertainty in the experimental data is handled using fuzzy logic technique. The complexity, vagueness and softness in the experimental data are eradicated using fuzzy rules and hence the deductive inference based on rules is used for effective decision making. The investigation reveals that the type of nozzle contributes the most towards overall performance with contribution of 86% followed by area of nozzle, H/D ratio and Reynolds number respectively. A significant improvement in experimental data is observed with the application of fuzzy logic technique.

**Key-words:** Multi-jet air impingement, heat transfer, Fuzzy logic, Grey relational analysis.

## 1. Introduction

Air-jet impingement is an effective heat transfer technology, used to improve the heat transfer efficiency in engineering applications and industries significantly. Air-jet impingement heat transfer is extensively used for cooling electronic components, drying paper, cooling critical machinery structures, annealing metal plates, and numerous industrial processes [1]. In recent years, numerous methods were developed to improve convective heat transfer ratio to the problem of heat flux escalation from electronic devices, *e.g.* pin fins, rib turbulators, dimpled surfaces, jet impingement cooling, etc. Out of all the above methods, jet impingement techniques are used extensively in industries due to its high rates of heat transfer. It is therefore used for cooling turbine blades and combustion chamber walls in gas turbine engines, glass processing industries, cooling of electronic circuits and equipment's and surface treatment of metals [2–5]. In jet impingement, high velocity jet is released from a nozzle towards the object. Jet impingement heat transfer is advantageous when high local and surface heat transfer coefficients were to be higher. Increase in the heat transfer rate by high velocity jet is due to the destruction of the boundary layer. In jet impingement, another important feature is the ability to perform arbitrary heat flux distribution by varying the number of nozzles, location of nozzles and flow rate through them [6, 7]. The rate of heat transfer by jet impingement depends on various parameters such as *Reynolds number* (Re) , the distance of nozzle exit from surface of impingement (jet to plate spacing), the radial distance of nozzle from stagnation point (r/d), nature of jet (conventional or swirling), geometry of the surface of target plate, the nature of surface plate, Prandtl number, target plate inclination, confinement of the jet, nozzle geometry, cross- flow, curvature of target plate, etc. [8, 9].

## 2. Literature Review

Many researchers had studied the flow characteristics and heat transfer analysis of impinging jets and extensive analysis had been carried out by Goldstein [10], Martin [11], Zuckerman and Lior [12], summarizing the natural of work investigated and results obtained from the different flow of impinging jets. Kinsella et al [13] studied the local heat transfer coefficient by introducing swirl and reported that heat transfer coefficient is less at the stagnation point when swirl is introduced. But it increases when we move away from the stagnation point. Without swirl, the heat transfers at location closer to 0.5D is high and remains higher till 2D. Beyond a distance of 2D from the stagnation point, the value is almost the same as that without swirl. Nirmalkumar and Katti [14] studied the influence of Reynolds number based on the slot widths (Re) of 4200–12,000 as well as the non-dimensional nozzle-to-plate spacing (H/W) of 0.5–12 on jet impingement heat transfer. They found that at the region of H/W= 0.5–2, secondary peaks formed when x/W was approximately 5 for different Re; however, these are not distinctly observed for lower Re (4200–7800) and larger H/W (2–12).

Yang *et al.* [15] investigated the transient conjugate heat transfer model with high turbulence using the low-Re k-$\omega$x turbulence model for the Reynolds numbers (Re) of 16,100–29,600.

Their study indicated that heat transfer rate can remain constant at the end of heat transfer, and the time required to reach the steady-state condition decreases as the Reynolds number increases. However, the heat transfer coefficient distribution of the impinging plate was not provided Aldabbagh and Mohamad [16] studied the influence of jet-to-jet spacing in heat transfer and flow characteristics for a five in-line array jets, with spaces varied from 2 to 20 times the width, with a Reynolds number of 200. From long straight pipes, kinetic energy, turbulent shear stress and turbulence intensity were given at the initial region of the jet.

Chiang *et al.* [17] evaluated and optimized the heat sink design parameters made by pin fin arrangement considering with multiple outputs of thermal characteristics as thermal resistance, pressure drop and average convective heat transfer coefficient using hybrid grey-fuzzy logic approach based on standard orthogonal arrays. Different input parameters chosen and explored are; height of fin, diameter of pin-fin and width of pitch between the fins. Analysis of variance was also applied to determine the influence of the selected design parameters on heat sink thermal performance characteristics. Aghaie et al. [18] optimized geometry of angled ribs for enhancing the thermo-hydraulic behaviour of a solar air heated channel using Taguchi approach. The results concluded that the rib relative pitch, rib height, rib tip width and rib front projection have the most influence on thermo-hydraulic performance of the solar air flow channel.

Chauhan *et al.* [19] investigated and optimized design parameters of impinging jet used in solar thermal collector by Taguchi method. The heat transfer and fluid friction behaviour have been studied along with the thermo-hydraulic performance by determining the performance index which plays simultaneously on both these criteria. The results obtained show that the geometric variations significantly affect the performance of impinging jet solar thermal collector and investigation reveals that the jet diameter ratio contributes the most towards overall performance with contribution ratio of 48.86% followed by span wise pitch ratio and stream wise pitch ratio with contribution ratio of 41.61% and 9.53% respectively.

From the above literature review, most of the researchers had coupled Taguchi with grey relational analysis [31] and grey relational analysis with principal component analysis [20, 21]. Only few researchers had attempted the optimization of design parameter by DoE based fuzzy logic technique. The novelty of the present approach is to eliminate the vagueness or fuzziness in the obtained experimental data with the application of a popular technique, fuzzy logic approach, the recent optimization technique which does not require any algorithm-specific parameter that needs to be tuned, thereby making the technique much simpler in adoption. Apart from this, fuzzy logic control is a range-to-point or range-to-range control when compared with classical control strategy, which makes it much suitable for these kind of experimental investigation.

With the optimum condition reached from the fuzzy logic approach, the output responses that can be obtained will be better than the other combination of input parameters, which is proved by other researchers also. Apart from temperature analysis, fuzzy rule based system has been applied in other areas of research such as wireless sensor networks [43] and pattern classification [44] and in other areas. Hence the application of the Fuzzy logic coupled with GRA for multi objective optimization multi-jet air impingement is considered in this paper.

## 3. Experimental Setup and Methodology

The photographic view of the experimental setup is shown in Figure 1. A rectangular heating foil of size 150 $\times$ 100 mm, heating capacity 600 Watts is sandwiched between two steel plates of same dimension and thickness of 18 mm. A dimmer stat is used to vary the heat supplied to the heating element. K-type thermocouples are used to measure the surface temperature of the top plate which is exposed to the jets. Agilent 34972A and a personal computer with required software [Bench link data logger-3] are used, which can simultaneously record air temperature, airflow rate, and the temperature at the target plate. Except the top surface, all the faces of the plate area are covered with ceramic fiber of sufficient thickness to avoid hearing loss. The hot plates consisting of heating coils are placed over a stand, in order to vary the H/D ratio, height is varied using a lead screw mechanism. Centrifugal blower with plenum chamber was used to supply air to the jet. The purpose of the plenum chamber is to make the flow stable and free from fluctuations. A hot wire anemometer is used to measure the velocity of air in the main duct which takes air from the blower exit to the plenum chamber.

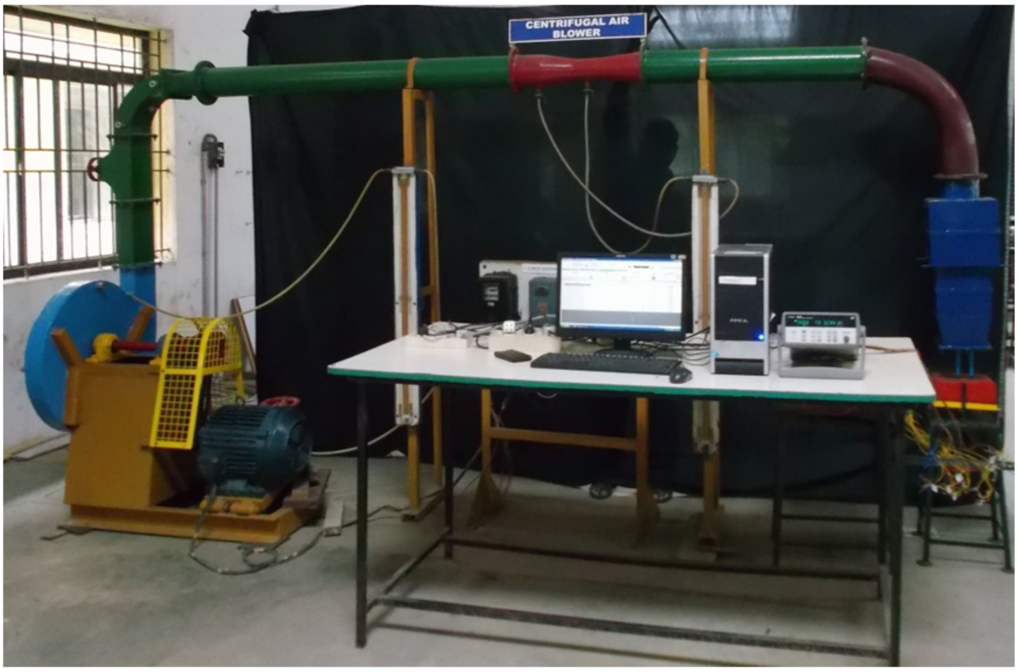


**Fig. 1.** Photographic view of experimental setup (color online).

# 4. Experimental Procedure

After fixing a particular nozzle assembly to the plenum chamber the blower is switched on. Simultaneously, the power is supplied to the heating coil through the regulator (dimmer stat) such that a constant heat flux (7666.67 w/m$^2$) is supplied to the heater. By adjusting the gate valve, the rate of air flow is controlled until the required Reynolds number is attained. The temperatures at the fifteen points were observed periodically from a personal computer which is connected to the data acquisition system and the final readings are noted for further calculation after steady state is attained. Reynolds number and D/D ratio were varied according to the required values.

## 4.1. Taguchi's Technique

For studying many factors economically and simultaneously, a statistical technique known as Taguchi's Design of Experiments (DoE) is used [40, 32]. In quality optimization Taguchi's technique is a most versatile and powerful tool. The best level of factor combination can be identified by understanding the effects of individual factors. When this technique is applied to a design, it will bring out the best design among the different alternatives available [24]. A special orthogonal array is used in Taguchi's technique to analyze the output responses from a minimal experiment [39].

In order to analyze the heat transfer analysis of multi-jet air impingement setup, a L27 Orthogonal Array is formulated to conduct experiments for varying combinations of heat transfer parameters. The input parameters such as type of nozzle, area of nozzle, Reynolds no. and H/D ratio are analysis to obtained the multi-performance optimization of heat transfer coefficient, temperature and Nusselt no. Table 1 shows the level values selected for multi-jet air impingement analysis.

**Table 1.** Level values of control parameters

| Parameter / Level | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Type of Nozzle | Square | Triangle | Circle |
| Area of Nozzle (mm2) | 8 | 10 | 12 |
| Reynolds No. | 18000 | 20000 | 22000 |
| H/D ratio | 2D | 4D | 6D |

Using Minitab-16 for the selected input parameters and their value range, a $L_{27}$ is selected from the array selector for three parameters three levels. Orthogonal array from Taguchi's DoE for varying combinations of heat analysis is given in Table 2.

**Table 2.** $L_{27}$ Orthogonal array

| Exp. No | Input Parameters | | | |
|---|---|---|---|---|
| | Type of Nozzle | Area of Nozzle | Reynolds No. | H/D ratio |
| 1 | Square | 8 | 18000 | 2D |
| 2 | Square | 8 | 20000 | 4D |
| 3 | Square | 8 | 22000 | 6D |
| 4 | Square | 10 | 18000 | 2D |
| 5 | Square | 10 | 20000 | 4D |
| 6 | Square | 10 | 22000 | 6D |
| 7 | Square | 12 | 18000 | 2D |
| 8 | Square | 12 | 20000 | 4D |
| 9 | Square | 12 | 22000 | 6D |
| 10 | Triangle | 8 | 18000 | 6D |
| 11 | Triangle | 8 | 20000 | 2D |
| 12 | Triangle | 8 | 22000 | 4D |
| 13 | Triangle | 10 | 18000 | 6D |
| 14 | Triangle | 10 | 20000 | 2D |
| 15 | Triangle | 10 | 22000 | 4D |
| 16 | Triangle | 12 | 18000 | 6D |
| 17 | Triangle | 12 | 20000 | 2D |
| 18 | Triangle | 12 | 22000 | 4D |
| 19 | Circle | 8 | 18000 | 4D |
| 20 | Circle | 8 | 20000 | 6D |
| 21 | Circle | 8 | 22000 | 2D |
| 22 | Circle | 10 | 18000 | 4D |
| 23 | Circle | 10 | 20000 | 6D |
| 24 | Circle | 10 | 22000 | 2D |
| 25 | Circle | 12 | 18000 | 4D |
| 26 | Circle | 12 | 20000 | 6D |
| 27 | Circle | 12 | 22000 | 2D |

## 4.2. Grey Relational Analysis

*Grey Relational Analysis* (GRA) is used for multi-objective optimization problems, to determine the optimum condition to obtain the best level of input parameters considering single and multiple responses [23, 33]. With meagre information available, GRA has been broadly applied in evaluating or judging the performance of a complex system [34, 41]. However in GRA, data to be used must be pre-processed into quantitative indices for normalizing raw data for the subsequent analysis. Pre-processing raw data is a process of converting an original sequence into a decimal sequence between 0.00 and 1.00 for comparison. If the expected data sequence is of the form "Higher-the-better", then the original sequence can be normalized as,

$$x_i^*(k) = \frac{x_i^0(k) - min\, x_i^0(k)}{max\, x_i^0(k) - min\, x_i^0(k)} \tag{1}$$

where $x_i^0(k)$ is the original sequence, $x_i^*(k)$ the sequence after the data pre-processing, $max\, x_i^0(k)$ the largest value of $x_i^0(k)$, and $min\, x_i^0(k)$ implies the smallest value of $x_i^0(k)$.When the form "Smaller-the-better" becomes the expected value of the data sequence, the original sequence can be normalized as,

$$x_i^*(k) = \frac{max\, x_i^0(k) - x_i^0(k)}{max\, x_i^0(k) - min\, x_i^0(k)} \tag{2}$$

Following data pre-processing, a grey relational coefficient is calculated to express the relationship between the actual and ideal experimental results. The deviation sequence is determined by identifying maximum of the normalized values regardless of response variable. Let this maximum value be R, which is known as reference value which is given as,

$$R = Max(X_{ijk}) \tag{3}$$

Find the absolute difference between each normalized value and the reference value (R), regardless of the response variables, trials and replications. Let it be $\Delta_{ijk}$, where, i = 1,2,3,. . . ,p and j = 1, 2, 3, . . . , q and k =1,2,3,. . . , r.

$$\Delta_{ijk} = X_{ijk} - R \tag{4}$$

Then the grey relational coefficient can be expressed as,

$$\zeta_i(k) = \frac{\Delta_{min} + \zeta.\Delta_{max}}{\Delta_{0i}(k) + \zeta.\Delta_{max}} \tag{5}$$

where $\Delta_{0i}(k)$ is the deviation sequence of the reference sequence which is given by,

$$\Delta_{0i}(k) = \left\| x_0^*(k) - x_i^*(k) \right\| \tag{6}$$

$$\begin{aligned} \Delta_{max} &= \max_{\forall j \varepsilon i} \max_{\forall k} \left\| x_0^*(k) - x_j^*(k) \right\| \\ \Delta_{min} &= \min_{\forall j \varepsilon i} \min_{\forall k} \left\| x_0^*(k) - x_j^*(k) \right\| \end{aligned} \tag{7}$$

$\zeta$ is distinguishing or identification coefficient: $\zeta \in [0, 1]$.$\zeta$ = 0.5 is generally used. After obtaining the grey relational coefficient, we normally take the average of the grey relational coefficient as the grey relational grade. The grey relational grade is defined as,

$$\gamma = \frac{1}{n}\sum_{k=1}^{n} i\zeta i(k) \tag{8}$$

## 4.3. Fuzzy Interference system

The Fuzzy Logic tool is a mathematical tool introduced by Lotfi Zadeh in 1965, to deal with uncertainty, imprecision and information granularity. For representing linguistic constructs, fuzzy theory provides a mechanism viz. "many" "low" "medium" "often" and "few". Fuzzy logic provides a window of inference structure which enables appropriate human reasoning capabilities. The utility of fuzzy sets lies in their ability to model uncertain or ambiguous data as shown in Fig. 2. It is observed that, there is an intimate relationship between fuzziness and complexity. When the complexity of a problem of a system while performing that task, exceeds a certain threshold limit, the system will necessarily become fuzzy in nature [25].

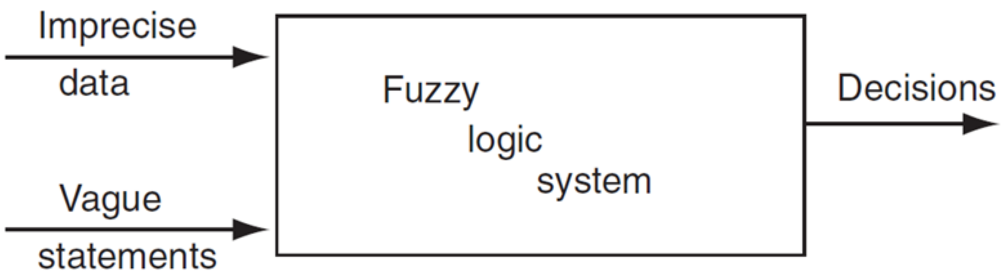


**Fig. 2.** A fuzzy logic system.

Fuzzy rule based system or fuzzy inference system consists of a fuzzification interface, a rule base and database, a decision making unit and a defuzzification interface [27]. The database defining the membership functions of the fuzzy sets were used in the fuzzy rules, decision making unit performs the inference operations on the rules [26, 45], fuzzification interface converts the crisp inputs into degrees of match with linguistic values and defuzzification interface converts the fuzzy results of the Inference into a crisp output [28]. The fuzzy rule base consists of a group of if-then control rules with the two inputs, $x_1$ and $x_2$, and one put $y$, *i.e.*,

- Rule 1: if $x_1$ is $A_1$ and $x_2$ is $B_1$ then $y$ is $C_1$ else
- Rule 2: if $x_1$ is $A_2$ and $x_2$ is $B_2$ then $y$ is $C_1$ else
- ............................................................
- ............................................................
- Rule n: if $x_1$ is $A_n$ and $x_2$ is $B_n$ then $y$ is $C_2$.

$A_i, B_i$ and $C_i$ are fuzzy subsets defined by the corresponding membership functions, *i.e.*, $\mu_{Ai}$, $\mu_{Bi}$ and $\mu_{Ci}$. Figure 3 shows the illustration of the FIS using which prediction is carried out [22].

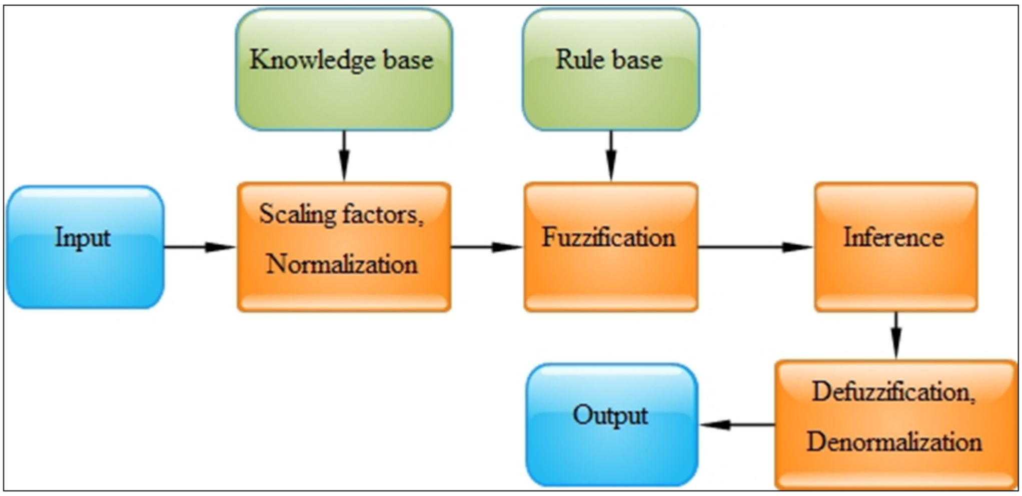


**Fig. 3.** Fuzzy inference systems (color online).

## 4.4. Multiple Regression Model and Analysis of Variance

Regression is a mathematical tool to investigate the functional relationship between the input and output decision variables, useful for parameter estimation and its control of a manufacturing process data [29]. In simple linear regression model, by minimizing the sum of squares of residuals ($S_r$), the best line is fitted between the measured response and the predicted data's from regression model. The linear regression model fit is expressed as,

$$y = a_0 + a_1 x \tag{9}$$

where $y$ is the measured response and x is the input variable value. An extension of simple linear regression is the multiple linear regressions models when the response is dependent of two or more independent variables. Normally, y is related to $k$ regressor variables. The model in Equ. (10), is called a multiple linear regression model with $k$ regressor variables.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \varepsilon \tag{10}$$

The parameters $\beta_j, j = 0, 1, ., k$ are called regression coefficients. In predicting the outputs using the chosen input parameters, these kinds of regression models are particularly useful. *Analysis of Variance* (ANOVA) is a statistical tool, which allows us to divide the total measured variance in the study into its component parts. The total variance measured is the variance of scores obtained from the measured quantities of the dependent input variables [30]. ANOVA is applied to analyze the individual effect on the categorical factors on the measured response. ANOVA determines, which input parameter has a significant effect on the output response, and how much of variability is attributable to each factor.

# 5. Results and Discussions

With the designed $L_{27}$ array, experiments were conducted and Table 3 shows the measured output responses. Heat transfer coefficient, temperature variation and Nusselt number for all the 27 trial runs were determined. Two replications ($R_1$ and $R_2$) or runs are carried out and the average of the value is considered for analysis.

Observations made from the experimental results show that when the nozzle type changed from square to triangle, the heat transfer coefficient decreased 3.15%, temperature increased by 2.31% and Nusselt number decreased by 12.85%. While changing the nozzle type from triangle to circle, the heat transfer coefficient of the system increased by 89.61%, temperature decreased by 26.11% and Nusselt number increased by 119.47%. When we increased the area of nozzle from 8 to 10mm, the heat transfer coefficient, temperature and Nusselt number increased by 7.00, 0.76 and 35.95% respectively. Again increasing the area from 10 to 12mm, the heat transfer coefficient increased by 4.60%, temperature decreased by 5.08% and Nusselt number increased by 19.37%. During the increase of Reynolds number from 18000 to 20000, the heat transfer coefficient, temperature and Nusselt number increased by 1.40, 1.36 and 11.12% respectively.

**Table 3.** Output responses

| Exp. | Heat Transfer Coefficient | | | Temperature | | | Nusselt No. | | |
|---|---|---|---|---|---|---|---|---|---|
| No | $R_1$ | $R_2$ | Average | $R_1$ | $R_2$ | Average | $R_1$ | $R_2$ | Average |
| 1 | 157.53 | 157.45 | 157.49 | 77.64 | 77.72 | 77.68 | 44.98 | 45.02 | 45.00 |
| 2 | 149.33 | 149.29 | 149.31 | 84.34 | 84.36 | 84.35 | 42.67 | 42.65 | 42.66 |
| 3 | 152.71 | 152.73 | 152.72 | 80.22 | 80.18 | 80.2 | 43.66 | 43.62 | 43.64 |
| 4 | 161.14 | 161.06 | 161.1 | 76.6 | 76.58 | 76.59 | 57.52 | 57.56 | 57.54 |
| 5 | 155.62 | 155.62 | 155.62 | 82.25 | 82.29 | 82.27 | 55.59 | 55.57 | 55.58 |
| 6 | 156.57 | 156.61 | 156.59 | 78.95 | 78.97 | 78.96 | 55.91 | 55.95 | 55.93 |
| 7 | 167.68 | 167.62 | 167.65 | 74.76 | 74.7 | 74.73 | 65.87 | 65.85 | 65.86 |
| 8 | 162.64 | 162.66 | 162.65 | 74.74 | 85.54 | 80.14 | 63.92 | 63.88 | 63.9 |
| 9 | 163.42 | 163.46 | 163.44 | 76.89 | 76.93 | 76.91 | 64.23 | 64.19 | 64.21 |
| 10 | 134.99 | 134.97 | 134.98 | 85.79 | 85.81 | 85.8 | 33.54 | 33.56 | 33.55 |
| 11 | 158.97 | 159.01 | 158.99 | 81.25 | 81.19 | 81.22 | 39.54 | 39.5 | 39.52 |
| 12 | 152.3 | 152.24 | 152.27 | 80.36 | 80.34 | 80.35 | 37.83 | 37.87 | 37.85 |
| 13 | 138.16 | 138.12 | 138.14 | 84.52 | 84.48 | 84.5 | 45.79 | 45.77 | 45.78 |
| 14 | 166.28 | 166.26 | 166.27 | 79.13 | 79.09 | 79.11 | 55.13 | 55.09 | 55.11 |
| 15 | 154.52 | 154.56 | 154.54 | 79.58 | 79.64 | 79.61 | 51.21 | 51.23 | 51.22 |
| 16 | 143.24 | 143.26 | 143.25 | 82.49 | 82.55 | 82.52 | 50.44 | 50.44 | 50.44 |
| 17 | 172.62 | 172.56 | 172.59 | 77.41 | 77.43 | 77.42 | 60.79 | 60.77 | 60.78 |
| 18 | 160.55 | 160.57 | 160.56 | 77.76 | 77.74 | 77.75 | 56.52 | 56.56 | 56.54 |
| 19 | 253.11 | 253.15 | 253.13 | 58.29 | 58.29 | 58.29 | 72.33 | 72.31 | 72.32 |
| 20 | 235.42 | 235.4 | 235.41 | 64.58 | 64.56 | 64.57 | 67.28 | 67.24 | 67.26 |
| 21 | 307.67 | 307.61 | 307.64 | 54.93 | 54.91 | 54.92 | 87.92 | 87.88 | 87.9 |
| 22 | 280.13 | 280.17 | 280.15 | 65.35 | 65.39 | 65.37 | 100.09 | 100.01 | 100.05 |
| 23 | 268.99 | 268.93 | 268.96 | 65.52 | 65.48 | 65.5 | 96.04 | 96.08 | 96.06 |
| 24 | 339.64 | 339.68 | 339.66 | 60.56 | 60.58 | 60.57 | 121.34 | 121.28 | 121.31 |
| 25 | 289.38 | 289.42 | 289.4 | 57.53 | 57.45 | 57.49 | 124.01 | 124.05 | 124.03 |
| 26 | 279.59 | 279.61 | 279.6 | 57.41 | 57.43 | 57.42 | 119.84 | 119.82 | 119.83 |
| 27 | 365.66 | 365.66 | 365.66 | 53.95 | 53.99 | 53.97 | 156.72 | 156.7 | 156.71 |

Again increasing the Reynolds number from 20000 to 22000, the heat transfer coefficient increased by 11.64%, temperature decreased by 4.28% and Nusselt number increased by 12.42%. When we increased the H/D ration from 2D to 4D, the heat transfer coefficient decreased by 11.99%, temperature increased by 4.62% and Nusselt number decreased by 12.41%. Again increasing H/D ration from 4D to 6D, the heat transfer coefficient decreased by 4.81%, temperature increased by 1.62% and Nusselt number decreased by 4.54%.

The GRA technique is applied to identify the optimal design and flow parameters of an impinging jet system. For normalizing the Eq. (1) and Eq. (2) is used based on Larger-the-better and Smaller-the-better condition of output responses. Table 4 shows the normalizing and deviation sequence values of the individual responses using grey relational technique.

**Table 4.** Normalizing and Deviation sequence

| Exp. No | Normalizing Sequence | | | Deviation Sequence | | |
|---|---|---|---|---|---|---|
| | Heat Transfer Coefficient | Temperature | Nusselt No. | Heat Transfer Coefficient | Temperature | Nusselt No. |
| 1 | 0.098 | 0.255 | 0.093 | 0.902 | 0.745 | 0.907 |
| 2 | 0.062 | 0.046 | 0.074 | 0.938 | 0.954 | 0.926 |
| 3 | 0.077 | 0.176 | 0.082 | 0.923 | 0.824 | 0.918 |
| 4 | 0.113 | 0.289 | 0.195 | 0.887 | 0.711 | 0.805 |
| 5 | 0.089 | 0.111 | 0.179 | 0.911 | 0.889 | 0.821 |
| 6 | 0.094 | 0.215 | 0.182 | 0.906 | 0.785 | 0.818 |
| 7 | 0.142 | 0.348 | 0.262 | 0.858 | 0.652 | 0.738 |
| 8 | 0.120 | 0.178 | 0.246 | 0.880 | 0.822 | 0.754 |
| 9 | 0.123 | 0.279 | 0.249 | 0.877 | 0.721 | 0.751 |
| 10 | 0.000 | 0.000 | 0.000 | 1.000 | 1.000 | 1.000 |
| 11 | 0.104 | 0.144 | 0.048 | 0.896 | 0.856 | 0.952 |
| 12 | 0.075 | 0.171 | 0.035 | 0.925 | 0.829 | 0.965 |
| 13 | 0.014 | 0.041 | 0.099 | 0.986 | 0.959 | 0.901 |
| 14 | 0.136 | 0.210 | 0.175 | 0.864 | 0.790 | 0.825 |
| 15 | 0.085 | 0.194 | 0.143 | 0.915 | 0.806 | 0.857 |
| 16 | 0.036 | 0.103 | 0.137 | 0.964 | 0.897 | 0.863 |
| 17 | 0.163 | 0.263 | 0.221 | 0.837 | 0.737 | 0.779 |
| 18 | 0.111 | 0.253 | 0.187 | 0.889 | 0.747 | 0.813 |
| 19 | 0.512 | 0.864 | 0.315 | 0.488 | 0.136 | 0.685 |
| 20 | 0.435 | 0.667 | 0.274 | 0.565 | 0.333 | 0.726 |
| 21 | 0.748 | 0.970 | 0.441 | 0.252 | 0.030 | 0.559 |
| 22 | 0.629 | 0.642 | 0.540 | 0.371 | 0.358 | 0.460 |
| 23 | 0.581 | 0.638 | 0.508 | 0.419 | 0.362 | 0.492 |
| 24 | 0.887 | 0.793 | 0.713 | 0.113 | 0.207 | 0.287 |
| 25 | 0.669 | 0.889 | 0.735 | 0.331 | 0.111 | 0.265 |
| 26 | 0.627 | 0.892 | 0.701 | 0.373 | 0.108 | 0.299 |
| 27 | 1.000 | 1.000 | 1.000 | 0.000 | 0.000 | 0.000 |

For individual responses, grey relational coefficient is calculated following the normalizing process of data and deviation sequence. Grey relational grade is calculated by considering the average values of grey relational coefficient [42] that corresponds to the input parameter level value as shown in Table 5. In calculating the grey relational grade, equal weightage is considered for all responses.

GRG (100%) = [GRC of (heat transfer coefficient + temperature + Nusselt number)]/3. For trial no. 2, the grey relational grade can be calculated as
GRG (100%) = [(0.348) + (0.344) + (0.351)]/3 = 0.347

The value of grey relational grade lies in the range from 0 to 1, for this ranking is given in the order of higher to smaller value. The $27^{th}$ experimental run has the maximum value and is ranked 1, which provides the best combination for the multi-objective characteristics of all experiment.

**Table 5.** Grey relational coefficient and grey relational grade

| Exp. No | Grey Relational Coefficient | | | Grey Relational Grade |
|---|---|---|---|---|
| | Heat Transfer Coefficient | Temperature | Nusselt No. | |
| 1 | 0.357 | 0.402 | 0.355 | 0.371 |
| 2 | 0.348 | 0.344 | 0.351 | 0.347 |
| 3 | 0.351 | 0.378 | 0.353 | 0.361 |
| 4 | 0.361 | 0.413 | 0.383 | 0.386 |
| 5 | 0.354 | 0.360 | 0.378 | 0.364 |
| 6 | 0.356 | 0.389 | 0.379 | 0.375 |
| 7 | 0.368 | 0.434 | 0.404 | 0.402 |
| 8 | 0.362 | 0.378 | 0.399 | 0.380 |
| 9 | 0.363 | 0.410 | 0.400 | 0.391 |
| 10 | 0.333 | 0.333 | 0.333 | 0.333 |
| 11 | 0.358 | 0.369 | 0.344 | 0.357 |
| 12 | 0.351 | 0.376 | 0.341 | 0.356 |
| 13 | 0.336 | 0.343 | 0.357 | 0.345 |
| 14 | 0.366 | 0.388 | 0.377 | 0.377 |
| 15 | 0.353 | 0.383 | 0.369 | 0.368 |
| 16 | 0.341 | 0.358 | 0.367 | 0.355 |
| 17 | 0.374 | 0.404 | 0.391 | 0.390 |
| 18 | 0.360 | 0.401 | 0.381 | 0.381 |
| 19 | 0.506 | 0.787 | 0.422 | 0.572 |
| 20 | 0.470 | 0.600 | 0.408 | 0.493 |
| 21 | 0.665 | 0.944 | 0.472 | 0.694 |
| 22 | 0.574 | 0.583 | 0.521 | 0.559 |
| 23 | 0.544 | 0.580 | 0.504 | 0.543 |
| 24 | 0.816 | 0.707 | 0.635 | 0.719 |
| 25 | 0.602 | 0.819 | 0.653 | 0.691 |
| 26 | 0.573 | 0.822 | 0.625 | 0.673 |
| 27 | 1.000 | 1.000 | 1.000 | 1.000 |

Table 6 shows the ANOVA for the grey relational grade before Fuzzy technique. This table shows that type of nozzle is the most influential parameter having higher contribution of 73%, followed by H/D ratio, area of nozzle and Reynolds number. The 'S' value of ANOVA is 0.06272 and $R^2$ value is 89.84%. Since the 95% confidence interval is considered, and as the $R^2$ values of the analysis are low, in order to bring the result closer to 100%, Fuzzy technique is adopted here.

**Table 6.** Grey relational coefficient and grey relational grade

| Source | DoF | Seq SS | Adj MS | F | P | % Contribution |
|---|---|---|---|---|---|---|
| Type of Nozzle | 2 | 0.510726 | 0.255363 | 64.94 | 0.000 | 73.30 |
| Area of Nozzle | 2 | 0.037918 | 0.018959 | 4.82 | 0.021 | 5.44 |
| Reynolds No. | 2 | 0.034167 | 0.017083 | 4.34 | 0.029 | 4.90 |
| H/D ratio | 2 | 0.043172 | 0.021586 | 5.49 | 0.014 | 6.20 |
| Error | 18 | 0.070778 | 0.021586 | | | 10.16 |
| Total | 26 | 0.696761 | 0.003932 | | | 0.003932 |

The uncertainties in the outputs such as vague and incomplete information and imprecision in the problem statement are identified using the fuzzy logic technique [22,35]. By developing a fuzzy reasoning grade from fuzzy logic tool, the uncertainty present in the data's are reduced [36,37]. Instead of considering multiple outputs of complicated nature, fuzzy logic approach is aimed to obtain a grey-fuzzy reasoning grade. Input output data's and the defuzzified output values are compared to achieve good prediction accuracy. An expert system uses these fuzzified data's to answer the questions that are imprecise and vague in nature and it also describes the different methods of assigning membership functions to fuzzy variables. Mamdani's method of inference is selected among the different options available for developing the membership function values using fuzzy implication operations, known as max-min reference method which is applied for obtaining the aggregation of fuzzy rules. Triangular membership functions and a set of fuzzy rules are framed for fuzzifying the grey relational coefficient of selected responses and three subsets such as low, medium and high are assigned for each grey relational grade of outputs as shown in Fig. 4. Centroid method of defuzzification is carried out in this analysis [38], which is more prevalent and most appealing of other available methods. Triangular membership function for heat transfer coefficient, temperature and Nusselt no. are shown in Fig. 5. The output of Grey-fuzzy reasoning grade is divided into six number of membership functions as shown in Fig. 6.

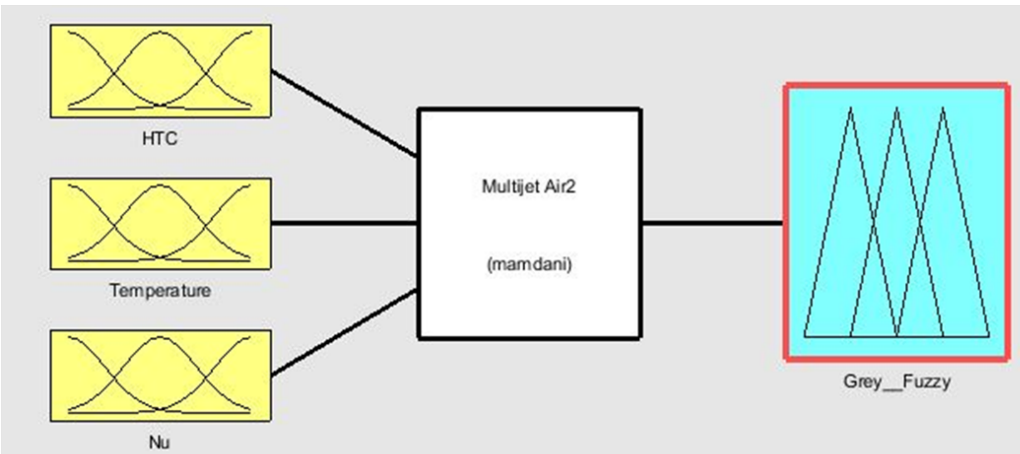


**Fig. 4.** Fuzzy inference system (color online).

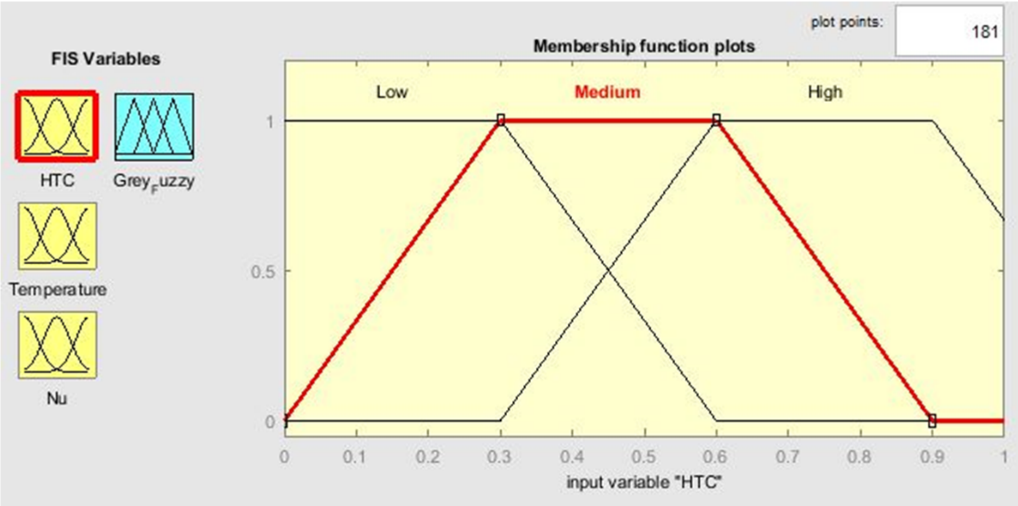


**Fig. 5.** Triangular membership function applied in FIS (color online).

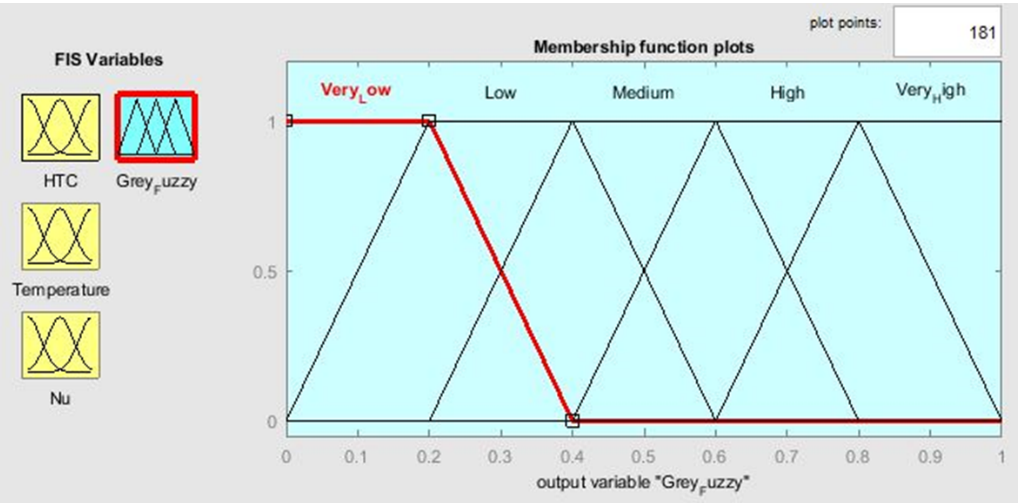


**Fig. 6.** Membership function of output grey fuzzy grade (color online).

Based on the framed rules, a surface plot between heat transfer coefficient and temperature and grey-fuzzy reasoning grade is drawn as shown in Fig. 7, between heat transfer coefficient and Nusselt no. and grey-fuzzy grade, and also between temperature and Nusselt no and grey-fuzzy grade.

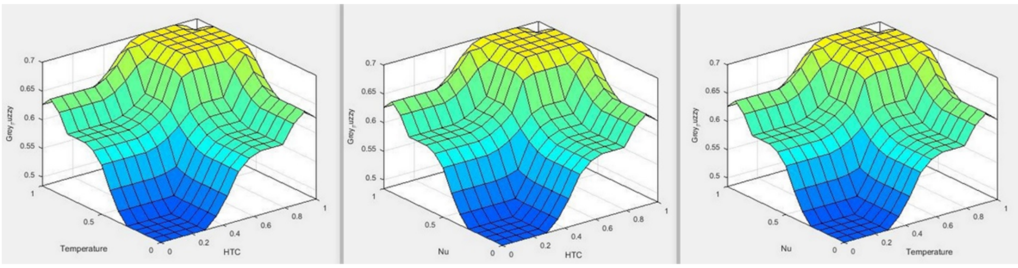

**Fig. 7.** Surface plot of input parameters and grey-fuzzy grade (color online).

Fuzzy logic technique uses If-Then rule to formulate prediction statements, an in this work, it has three grey relational coefficients; heat transfer coefficient, temperature and Nusselt number with output as grey-fuzzy reasoning grade. For performing the fuzzy logic technique, fuzzy logic tool in MATLAB software is used. A set of rules are framed, for activating the fuzzy inference system (FIS) and for predicting the grey-fuzzy reasoning grade for all 27 experiments, FIS is evaluated. The rule editor, shown in Fig. 8 in fuzzy environment is used for predicting the grey-fuzzy reasoning grade, for a set of given input values of heat transfer coefficient, temperature and Nusselt number.

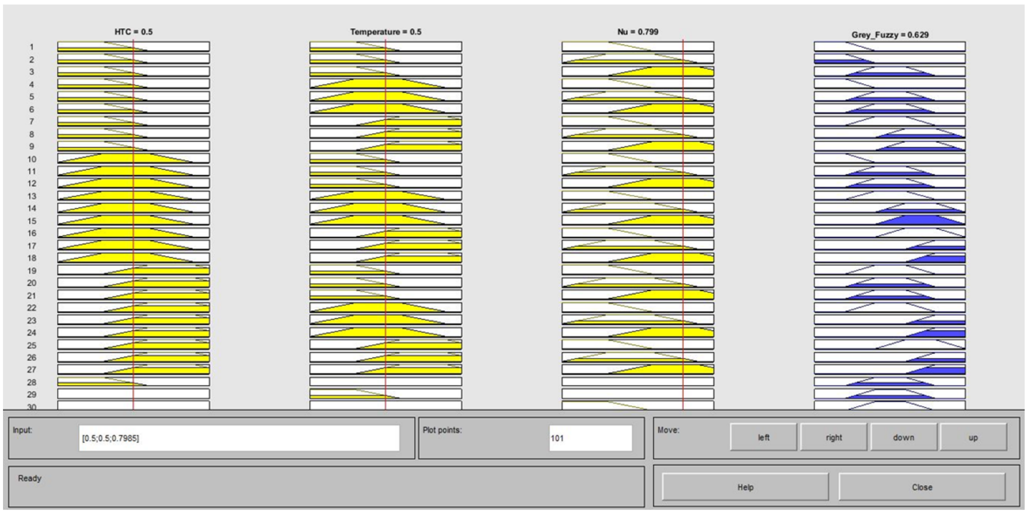

**Fig. 8.** Computation of Grey-Fuzzy reasoning grade (color online).

From the framed rules, for corresponding grey relational coefficient of heat transfer coefficient, temperature and Nusselt no., the corresponding Grey-fuzzy reasoning grade is obtained and Table 7 shows the results obtained and percentile improvement from the previously obtained grey relational grade. It is observed that experiment no. 10 corresponds to the maximum improvement of 40.844% and experiment no. 27 corresponds to the reduced grade value of -16.605%. The average percentile improvement of the Taguchi-grey relational grade obtained from fuzzy approach is 24.28%, which is a better one for analysis and this shows the reduction in fuzziness of the values obtained for analysis.

**Table 7.** Grey-fuzzy reasoning grade and % improvement

| Exp. No | Grey Relational Grade | Grey Fuzzy Grade | % improvement |
|---|---|---|---|
| 1 | 0.371 | 0.485 | 30.73% |
| 2 | 0.347 | 0.475 | 36.89% |
| 3 | 0.361 | 0.48 | 32.96% |
| 4 | 0.386 | 0.497 | 28.76% |
| 5 | 0.364 | 0.483 | 32.69% |
| 6 | 0.375 | 0.492 | 31.20% |
| 7 | 0.402 | 0.51 | 26.87% |
| 8 | 0.380 | 0.493 | 29.74% |
| 9 | 0.391 | 0.504 | 28.90% |
| 10 | 0.333 | 0.469 | 40.84% |
| 11 | 0.357 | 0.481 | 34.73% |
| 12 | 0.356 | 0.479 | 34.55% |
| 13 | 0.345 | 0.474 | 37.39% |
| 14 | 0.377 | 0.491 | 30.24% |
| 15 | 0.368 | 0.481 | 30.71% |
| 16 | 0.355 | 0.48 | 35.21% |
| 17 | 0.390 | 0.499 | 27.95% |
| 18 | 0.381 | 0.494 | 29.66% |
| 19 | 0.572 | 0.615 | 7.52% |
| 20 | 0.493 | 0.591 | 19.88% |
| 21 | 0.694 | 0.69 | -0.58% |
| 22 | 0.559 | 0.685 | 22.54% |
| 23 | 0.543 | 0.656 | 20.81% |
| 24 | 0.719 | 0.752 | 4.59% |
| 25 | 0.691 | 0.749 | 8.39% |
| 26 | 0.673 | 0.734 | 9.06% |
| 27 | 1.000 | 0.834 | -16.60% |

Figure 9 shows the comparison bar chart of grey relational grade before and after fuzzy logic approach. It is observed that, s significant improvement in the Taguchi grey relational grade is obtained after implementing fuzzy logic approach thereby reducing the fuzziness in the data's, the fuzziness is reduced towards the reference value 1.

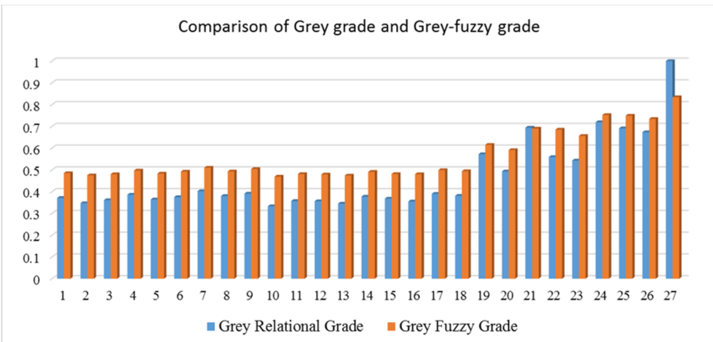


**Fig. 9.** Comparison of grey relational grade before and after fuzzy (color online).

By determining the average values of grey-fuzzy reasoning grade, the best levels are identified, corresponding to each and every level of parameters and are consolidated in Table 8.

**Table 8.** Response table for Grey-fuzzy reasoning grade

| Level / Parameter | Shape of Nozzle | Area of Nozzle | Reynolds No. | H/D ratio |
|---|---|---|---|---|
| Level 1 | 0.491 | 0.529 | 0.552 | 0.582 |
| Level 2 | 0.483 | 0.557 | 0.545 | 0.550 |
| Level 3 | 0.701 | 0.589 | 0.578 | 0.542 |

Main effects plot is drawn from the response table of grey-fuzzy reasoning grade, as shown in Fig. 10 to determine the optimum conditions. It is found that circular nozzle with area of 12 $mm^2$ combined with 22000 Reynolds no and 2D H/D ratio is the best combination of inputs.

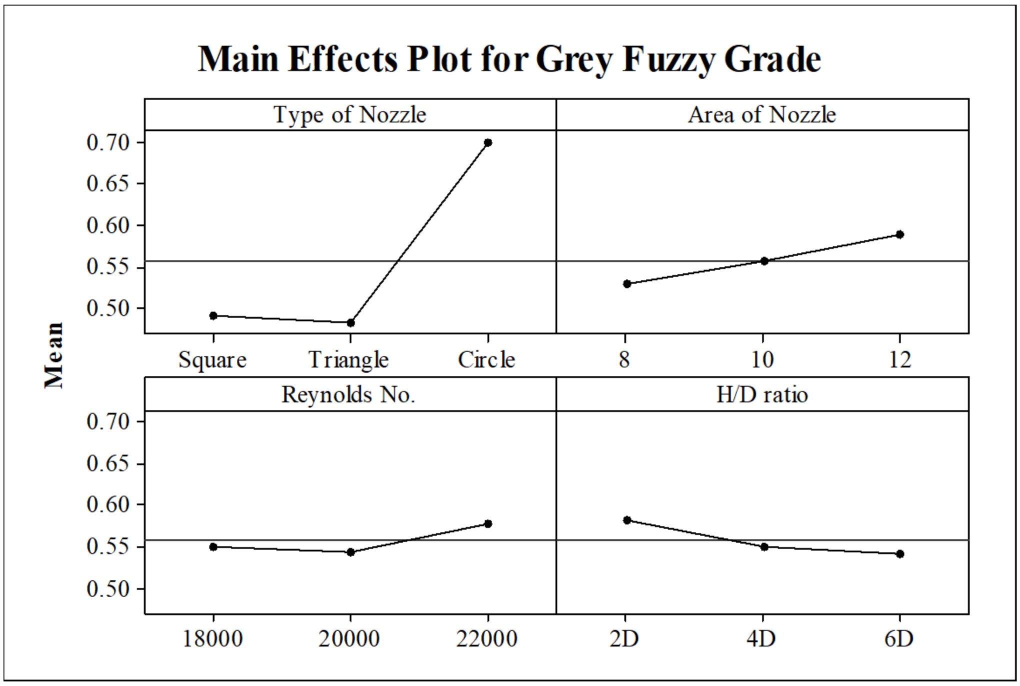


**Fig. 10.** Main Effects plot of grey-fuzzy reasoning grade (color online).

Interaction plot for Grey-fuzzy reasoning grade is given in Fig. 11. Parallel lines represent non-significant interaction effect and non-parallel lines represent a significant interaction effect between the chosen input parameters. Interaction plot is drawn between the input heat transfer parameters with respect to the grey-fuzzy grade. From the graph, it is observed that, a significant interaction effect is sensed between the Reynolds no. and H/D ratio and a moderated interaction exists between type of nozzle and Reynolds no. and also between the type of nozzle and H/D ratio. Interaction effect between the other input parameters is not observed.

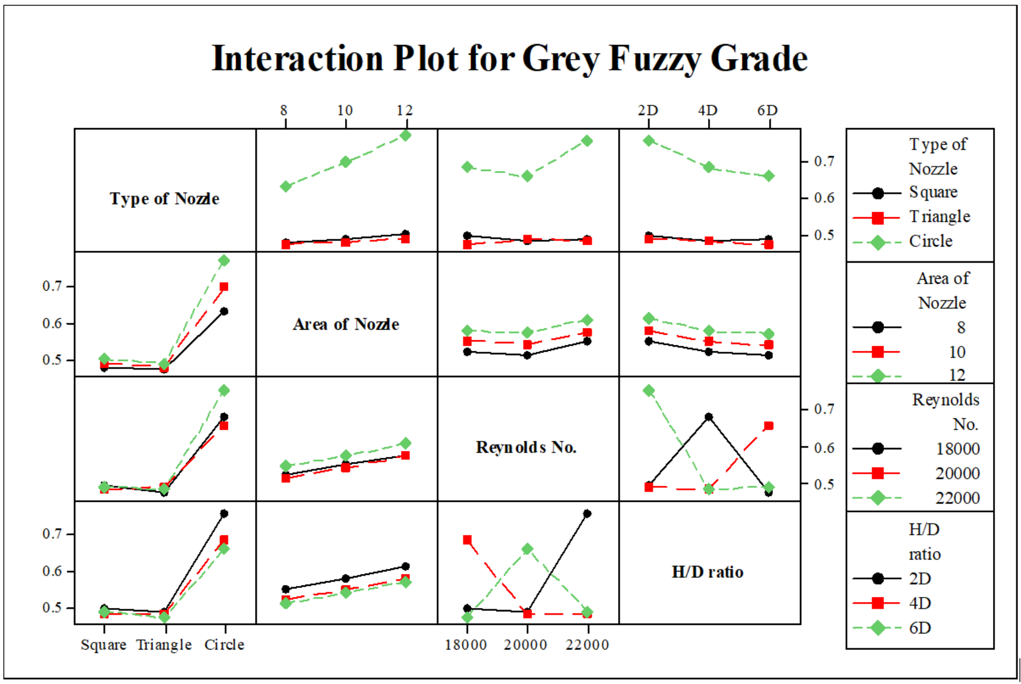


**Fig. 11.** Interaction plot for Fuzzy grey relational grade (color online).

Table 9 shows the ANOVA for the grey relational grade after Fuzzy technique. This table shows that type of nozzle is the most influential parameter having higher contribution of 85.26%, followed area of nozzle, H/D ratio and Reynolds number. The 'S' value of ANOVA is 0.0316 and $R^2$ value is 94.42% and adjusted $R^2$ value is 91.94%. As the $R^2$ values of the analysis are higher, the fuzziness in the data's is eliminated with the use of fuzzy logic approach.

**Table 9.** ANOVA after Fuzzy

| Source | DoF | Seq SS | Adj MS | F | P | % Contribution |
|---|---|---|---|---|---|---|
| Type of Nozzle | 2 | 0.274058 | 0.137029 | 137.53 | 0.000 | 85.26 |
| Area of Nozzle | 2 | 0.015753 | 0.007877 | 7.91 | 0.003 | 4.90 |
| Reynolds No. | 2 | 0.005707 | 0.002854 | 2.86 | 0.083 | 1.78 |
| H/D ratio | 2 | 0.007985 | 0.003992 | 4.01 | 0.036 | 2.48 |
| Error | 18 | 0.017934 | 0.000996 | | | 5.58 |
| Total | 26 | 0.321437 | | | | 100 |

Figure 12 shows the normal probability plot of Grey-fuzzy reasoning grade, which shows that the residuals follow a normal distribution as the points are very close to the straight line. No scatter of data's is seen as all data's align with the straight line indicating that no transformation is required for a better analysis. Graph of actual response values versus the predicted response values is shown in Fig. 13. This graph is useful in detecting values that are not easily predicted by the model developed during the analysis. As the data points split evenly along the straight line by 45 degrees, transformation is not required to improve the fit.

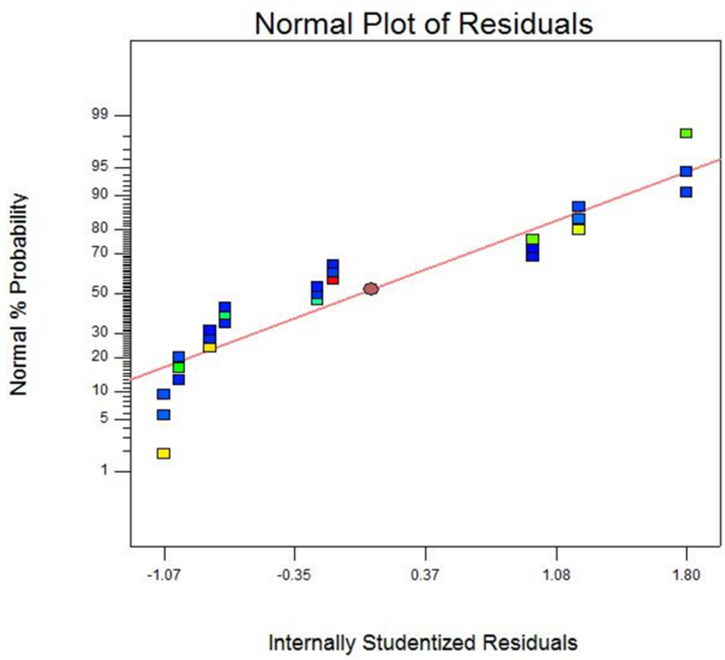


**Fig. 12.** Normal plot of residuals for Grey relational grade after Fuzzy (color online).

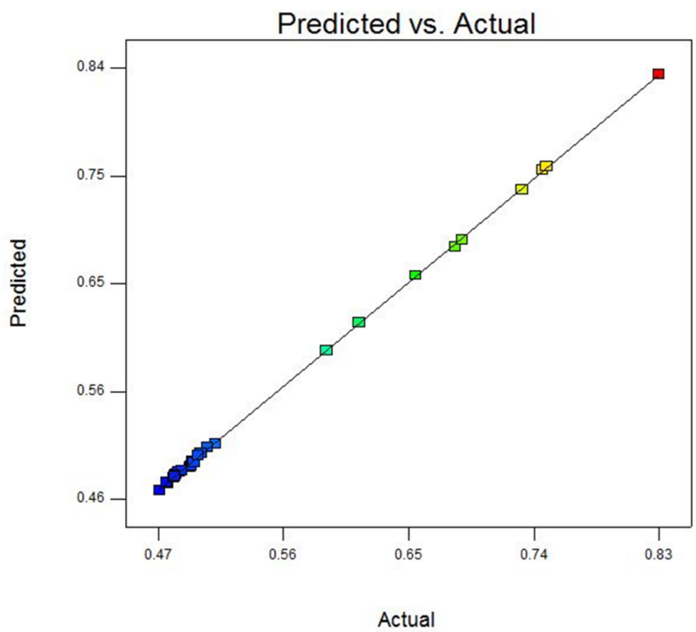


**Fig. 13.** Predicted vs. Actual Grey relational grade after Fuzzy (color online).

Figure 14 shows the influence of machining parameters of EDM machine setup over the Taguchi-grey-fuzzy reasoning grade. From the 3D surface plot, it is observed that, as the area of nozzle increases, grey-fuzzy grade increases, but for a moderate value of Reynolds no., grey fuzzy grade is higher. For lower Reynolds no. grey fuzzy grade is lower when compared to higher Reynolds no. value of 22000. A significant improvement in grey-fuzzy grade is obtained with change in shape of nozzle. Circular nozzle produced better heat transfer effect compared with other two shapes. Lower H/D ratio contributes to higher grey-fuzzy grade whereas higher H/D ratio has a moderate effect.

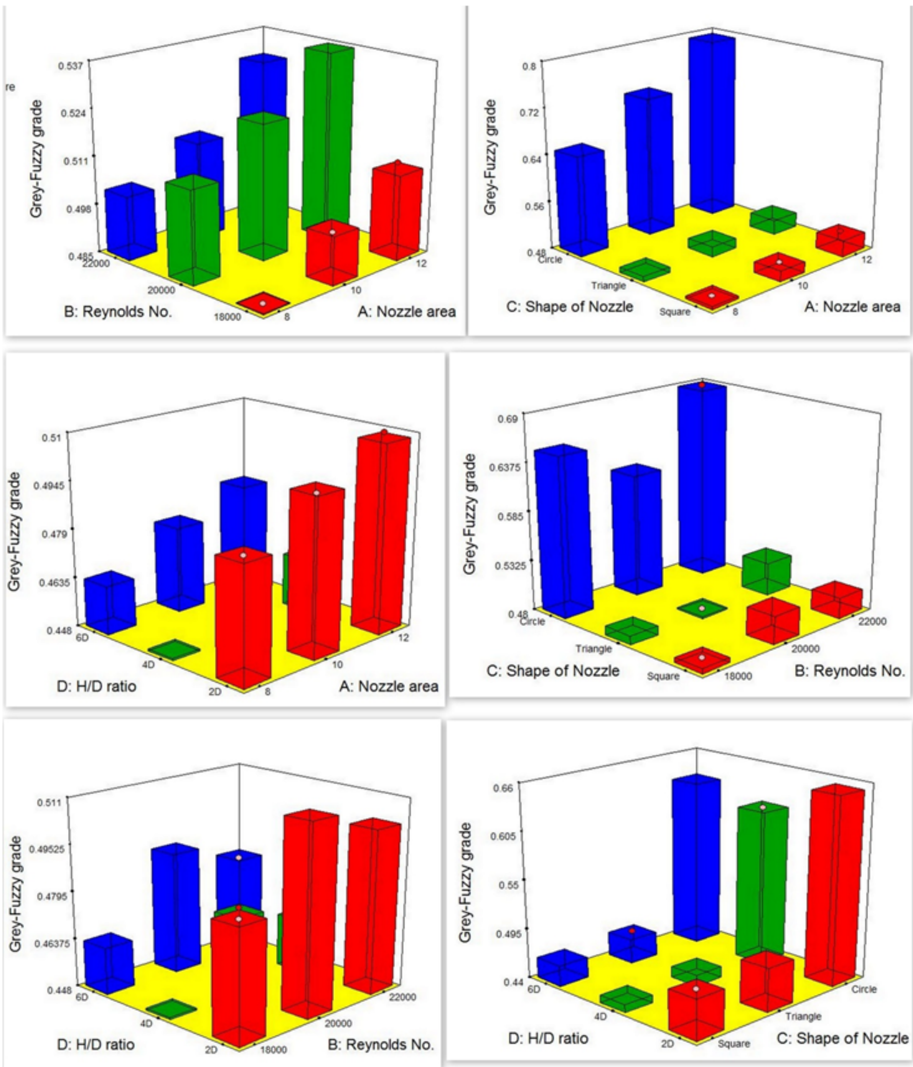


**Fig. 14.** Effect of Grey Fuzzy Reasoning Grade on Machining Parameters (color online).

# 6. Conclusions

Heat transfer analysis of multi-jet air impingement setup is carried out in this work, considering different shapes of nozzle, varying the area of nozzle, Reynolds no. and H/D ratio of nozzles. The experiment is designed with Taguchi's DoE considering $L_{27}$ OA and grey relational approach is used to analyze the outputs. The fuzziness in the data's is reduced by apply fuzzy logic approach. The conclusion derived from the analysis are:

1. Improvement in heat transfer analysis is observed with circular type nozzle with higher nozzle area. Reynolds no. of 22000 produces better heat transfer and lower H/D ratio produces better results and with increase in H/D ratio inverse effects are observed.
2. From grey relational analysis it is observed that, type of nozzle is the most influential parameter having higher contribution of 73%, followed by H/D ratio, area of nozzle and Reynolds number with $R^2$ value of 89.84%.
3. Triangular membership function is chosen in fuzzy approach and 3 conditions are selected for input and six membership function is considered for output.
4. From grey fuzzy reasoning grade, the optimum condition obtained is circular nozzle with area of 12 $mm^2$ combined with 22000 Reynolds no and 2D H/D ratio is the best combination of inputs.
5. A significant interaction effect exists between the Reynolds no. and H/D ratio and a moderated interaction exists between type of nozzle and Reynolds no. and also between the type of nozzle and H/D ratio.
6. From ANOVA result of grey fuzzy grade, type of nozzle is the most influential parameter having higher contribution of 85.26%, followed area of nozzle, H/D ratio and Reynolds number. The 'S' value of ANOVA is 0.0316 and $R^2$ value is 94.42% and adjusted R2 value is 91.94%.

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