Fuzzy Logic to Model the Free Convection Heat Transfer from Horizontal Isothermal Cylinders Arranged in Vertical and Inclined Arrays

Ehsan Rezaei, Alimohammad Karami, Tooraj Yousefi, Masood Aghakhani, and Maziar Mahdipour Jalilian

***Abstract*—This paper highlights the application of fuzzy logic to predict the free convection heat transfer from horizontal isothermal cylinders arranged in vertical and inclined arrays. Experiments included cylinder spacing (center-to-center) varying from 2 to 5 times the cylinder diameter and horizontal spacing ranging from 0 to 2 times the cylinder diameter in inclined array. Also, Rayleigh number based on the cylinder diameter varied from 10^3 to 3×10^3. It was observed that the increase of cylinder spacing in vertical and inclined array and horizontal spacing in inclined array results in heat transfer increase from the array. Moreover, it was shown that, fuzzy logic is a powerful technique used for predicting the heat transfer due to its low error rate. The average error of fuzzy technique as compared with experimental data was found to be 0.081 % for this study.**

***Index Terms*—Free convection, Heat transfer, Isothermal cylinders, Inclined Arrays, Modeling, Fuzzy logic.**

I. Introduction

A. Free Convection Heat Transfer from Array of Cylinders

Free convection heat transfer from the arrays of parallel horizontal cylinders are encountered in many engineering applications including space heating, the cooling of electronic devices, the heating and cooling of fluids, process plants, oil heating, as well as the cooling of refrigerator condensers. The heat transfer from a cylinder in an array is quite different from a single cylinder due to the interaction of the temperature and flow fields around neighboring cylinders. This interaction is owing to the buoyant plume that is generated by each cylinder and which may impinge on other cylinders. This impingement may either increase or decrease the heat transfer relative to that for a single horizontal cylinder, depending on the positioning of the cylinders relative to each other. In many of the previous investigations the cylinders were arranged in a vertical array or in few studies in an inclined array. Yousefi et al. [1] studied the free convection heat transfer from a vertical array of isothermal horizontal elliptic cylinders confined between two adiabatic walls. The aim of the paper was to investigate the effects of the Rayleigh number and wall spacing to major diameter ratio (t/b) on the average heat transfer from the vertical array. It was found that, there was an optimum wall spacing in which the Nusselt number is maximum. Yousefi et al. [2] studied the free convection from a vertical array of isothermal horizontal elliptical cylinders. The investigation was devoted to evaluate the effect of cylinder spacing on the free convection from the vertical array. Yousefi et al. [3] investigated the free convection heat transfer from a vertical array of isothermal horizontal cylinders consisting of diverters with different inclination angles. The experimental study included flow diverters with the width of three times the cylinder diameter placed parallel and midway between the cylinders at the inclination angle of 30°, 45°, and 60°. The cylinders vertical spacing (centre to centre) was kept constant to three times the cylinder diameter. Also, the Rayleigh number, were varied from 10^3 to 2.5×10^3. It was shown that, the enhancement in heat transfer decreased as the flow diverter angle deviated from 45° and increased as the Rayleigh number increased. Corcione [4] studied numerically the laminar free convection heat transfer from a vertical array of horizontal isothermal cylinders. Numerical simulations were performed for the arrays of 2–6 circular cylinders, for center-to-center separation distances from 2 to up to more than 50 times the cylinder diameters, and for the values of the Rayleigh number based on the cylinder diameter ranging from 5×10^2 and 5×10^5. It was shown that the heat transfer rate at the bottom cylinder remained the same as a single cylinder. In contrast, the downstream cylinders may exhibit either enhanced or reduced Nusselt numbers depending on their location in the array and on the geometry of the array. Corcione [5] performed a numerical study on the free convection from a pair of vertical arrays consisting of 1–4 equally-spaced horizontal isothermal circular cylinders set in free air, for center-to-center horizontal and vertical spacings ranging from 1.4 to 24 and 2 to 12 times the cylinder diameters respectively. The Rayleigh number based on the cylinder diameter was in the moderate range of 10^2 to 10^4. It was found that at each investigated Rayleigh number, there was an optimum horizontal center-to-center separation distance to diameter ratio S_h/D in which the Nusselt number of the array reaches a

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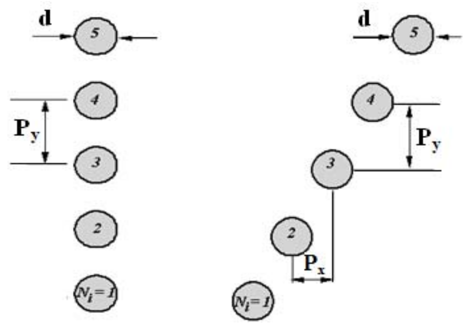
maximum value. In very large horizontal distances, the average Nusselt number of any cylinder was the same as that for the single cylinder, but as the S_h/D ratio was decreased, the heat transfer rate increased up to a peak due to a "chimney effect" between the cylinders. Decreasing this ratio below an optimum value, resulted in a dramatic degradation of the heat transfer performance of the array due to the merging of the two boundary layers. Liberman and Gebhart [6] experimentally investigated the interaction of heated wires under condition of uniform heat flux. They used a flat array of 10 wires of 0.127mm diameter with six spacing from 37.5 to 225 diameters and four equally orientation angles from 0° to 90°, for Grashof numbers of the orders of 10^{-1}. It was reported that there was an optimum spacing at each array angle for a maximum Nusselt number to result. The highest average Nusselt number occurred at a spacing of 75 times the cylinder diameter for the array at 60°. Ashjaee et al. [7] studied the free convection heat transfer from a single array of horizontal cylinders. They inserted flow diverters of one, two, and three cylinder-diameter widths, and of 45^o inclination angle midway between the cylinders in a vertical array of five horizontal tubes. The investigated range of Rayleigh number was between 10^3 and 2.5×10^3. The results indicated that by increasing the diverter width and the Rayleigh number, the average Nusselt numbers of individual cylinders and the whole array were increased. It was also reported that the flow diverters enhanced the heat transfer rate of the array from 10% up to 27%, depending on their width. This accomplishment was an incentive for applying the same technique on pairs of interacting tube-arrays, which has never been considered before, to the authors' knowledge. It is expected that in some horizontal spacings between the two arrays, the diverters could induce an enhanced chimney effect in the centerline and thus increase the rate of heat transfer from the whole array. D'Orazio and Fontana [8] studied the free convection from a pair of vertical arrays of five uniformly heated horizontal cylinders, for center-to-center horizontal and vertical spacing ranging from 2 to 145 and from 4 to 12 times the cylinder diameters respectively. The examined range of Rayleigh numbers was very low, specifically between 2.4 and 11.9. They obtained similar results, indicating that any cylinder may exhibit either enhanced or reduced Nusselt numbers with respect to the case of single array, depending on its location in the array, on the geometry of the array, as well as on the Rayleigh number. Rezvantalab et al. [9] studied the free convection heat transfer from a pair of vertical arrays of isothermal cylinders experimentally. The aim of the paper was to investigate the effects of horizontal center-to-center spacing (S_h/D) and Rayleigh number on the heat transfer from the pair of vertical arrays of isothermal cylinders. It was found that higher values of S_h/D lead to increased average Nusselt number for each individual cylinder in the array. In addition, for small S_h/D ratios, the flow diverters had a negative effect on heat transfer. Ashjaee and Yousefi [10] studied the free convection heat transfer from vertical and inclined arrays of five isothermal horizontal cylinders. The aim of the paper was to investigate the effects of cylinder spacing and Rayleigh number on the free convection from the vertical and inclined arrays. It was found that free convection heat transfer from the vertical array had an increasing trend with respect to vertical separation distance. Also in the inclined array, heat transfer increased by increasing the horizontal separation distance and decreased by increasing the vertical separation distance. In the present work, the effects of the Rayleigh number, vertical spacing ratio and horizontal spacing ratio on free convection heat transfer from horizontal isothermal cylinders arranged in vertical and inclined arrays were modeled based on experimental data collected by Ashjaee and Yousefi [10]. A schematic representation of the problem is shown in figure1. The cylinder diameter d, vertical and horizontal center-to-center separation distance P_y and P_x, the ordinal number of the cylinders N_i, and the height of the array H, are shown in figure.1.



(a) (b)

Fig. 1. Schematic representation of (a) the vertical array (b) the inclined array [10]

B. Fuzzy Logic (FL)

Fuzzy logic (FL) is a method introduced for the first time in 1965 by Zadeh [11] and has been used to model the experiments. In research works, modeling of experiments can be helpful in order to reduce the cost of experimentation and at the same time to predict the results of which are not possible to be performed due to some restrictions. Fuzzy logic starts with the concept of a fuzzy set. A fuzzy set is a set without a crisp, clearly defined boundary. It can contain elements with only a partial degree of membership. In other words, a fuzzy set is an extension of a classical set. If X is the universe of discourse and its elements are denoted by x, then a fuzzy set A in X is defined as a set of ordered pairs.

$$A = \{x, \mu A(x) \mid x \in X\} \quad (1)$$

where $\mu A(x)$ is called the membership function (or MF) of x in A. The membership function maps each element of X to a membership value between 0 and 1. In other words, a membership function (MF) is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. The input space is sometimes referred to as the universe of discourse, a fancy name for a simple concept. The membership functions are of many types such as trapezoidal, generalized bell, Gaussian, bell, sigmoidal, pi shaped, z- shaped s-shaped and etc. More information about the membership functions and their properties can be found in [12]. The most commonly simple used membership function is triangular membership function [12],[13] defined as

$$y = \text{trimf}(x, \text{parameters}) \tag{2}$$

$$y = \text{trimf}(x, [a\ b\ c]) \tag{3}$$

The triangular curve is a function of a vector x, and depends on three scalar parameters a, b, and c, as given by

$$\mu_A(x) = \begin{cases} 0, & x \le a_i \\ \dfrac{x-a_i}{b_i-a_i}, & a_i \le x \le b_i \\ \dfrac{c_i-x}{c_i-b_i}, & b_i \le x \le c_i \\ 0, & c_i \le x \end{cases} \tag{4}$$

or, more compactly, by

$$f(x\ ; a_i,\ b_i,\ c_i) = \max\left(\min\left(\frac{x-a_i}{b_i-a_i}, \frac{c_i-x}{c_i-b_i}\right), 0\right) \tag{5}$$

As it can be observed in figure2, the parameters a and b locate the "feet" of the triangle and the parameter c locates the peak.

To start with the fuzzy logic, following steps must be considered:

1) Choosing a Fuzzy Inference System (FIS)

The first step is to choose a fuzzy inference system (FIS) which its duty is to map an input space to an output space. Two types of fuzzy inference systems have been widely employed in various applications such as automatic control, data classification, decision analysis, expert systems, and computer vision: Mamdani fuzzy models [14] and Sugeno fuzzy models [15], which is similar to the Mamdani model in many respects. The first two parts of the fuzzy inference process, including the fuzzification of the inputs and applying the fuzzy operator, are exactly the same. The main difference between Mamdani and Sugeno inference systems is that the Sugeno output membership functions are either linear or constant [13].

2) Fuzzifying Inputs

The second step is to take the input values and fuzzifying them through fuzzification operators. A fuzzification operator has the duty of transforming crisp numerical value, limited to the universe of discourse of the input variable into fuzzy sets through the generation of membership values (always the interval between 0 and 1) for a fuzzy variable using membership functions.

3) Applying Fuzzy Operators

In case we have more than one input, the use of fuzzy operators will be inevitable. Because, initial parts of each fuzzy rule must be connected to each other through the necessary fuzzy operators in order to determine the output values between 0 and 1. The first operation is AND operation being equivalent to min (A, B), where A and B are membership values limited to the range (0, 1). AND operation is of two types, min (minimum) and prod (product) AND method. Using the same reasoning, we can replace the OR operation with the max function, so that A OR B becomes equivalent to max (A, B). OR operation is also of two types, max (maximum), and probor (probabilistic OR) method [13]. The probabilistic OR method is calculated according to the equation

probor(A,B) = A+B-AB (6)

For example, consider a fuzzy rule which is consist of two initial parts as given below:

if input1 is mf6 and input2 is mf13, then output is mf48

The two different parts of the above rule (*input1 is mf6 and input2 is mf13*) yielded the fuzzy membership values 0.8 and 0.5 respectively. The fuzzy OR operator simply selects the maximum of the two values, 0.8, and the fuzzy operation for this rule is complete. If we used the probabilistic OR method, the result would be 0.9. Finally, the operation NOT A becomes equivalent to the operation 1-A.

4) Applying Implication Method

After fuzzifying the input and applying any necessary fuzzy operators, that result must be applied to the consequent. This process is called Implication. A consequent is a fuzzy set represented by a membership function, which assigns an entire fuzzy set to the output. The consequent is reshaped using a single number associated with the initial part of the fuzzy rule. The input for the implication process is a single number given by the initial part of the fuzzy rule, and the output is a fuzzy set. Implication is implemented for each rule. There are two methods for applying the implication process, used by the AND method: min (minimum), which truncates the output fuzzy set, and prod (product), which scales the output fuzzy set [13].

5) Aggregating All Outputs

After applying implication Method, the aggregation process takes place. Aggregation is a process which the fuzzy sets that represent the outputs of each rule are combined into a single fuzzy set. Aggregation only occurs once for each output variable, just prior to the final step, defuzzification. The output of the aggregation process is one fuzzy set for each output variable. Aggregation methods are of three types, maximum (max), probabilistic OR (probor), and sum method [13].

6) Defuzzification

The final step is defuzzification. The process of converting a Fuzzy set into a single value is called defuzzification. Defuzzification methods are of five types, centroid, bisector, middle of maximum, largest of maximum, and smallest of maximum. The most commonly used method of defuzzification is centroid method which returns the center of area under the curve. More information on the defuzzification methods is available elsewhere [13].

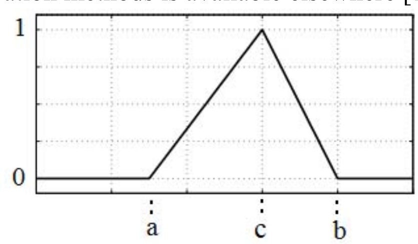


Fig. 2. A schematic representation of a triangular membership function

II. EXPERIMENTAL SETUP

A. Interferometer

A Mach-Zehnder Interferometer (MZI) was used in the experimental study. The interferometer consists of a light source, a micro lens, a pinhole, two doublets, three mirrors and two beam splitters. Figure 3 shows the interferometer setup. Beam splitters BS_1 and BS_2, along with plane mirrors M_1 and M_2 constituted the basic MZI. Further information about MZI can be found in [16-18]. The light source which was used is a 10mW Helium-Neon laser, with λ=632.8nm. All the interferograms were digitized with a "Panasonic WV-CP410" 1/3" CCD camera with 440000 pixel. To acquire the Interferogram the camera was connected to a video recorder through a PC. Local Nusselt numbers at each cylinder surface were obtained using infinite fringe mode, where the fringes correspond directly to isotherms in the flow field.

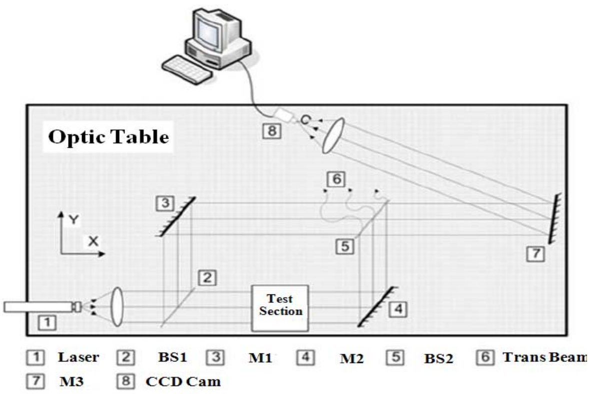


Fig. 3. Schematic of (MZI) setup [10]

B. Experiment Test Section

The details of 10 mm diameter aluminum cylinder used in the array with the heating circuit are shown schematically in figure 4 [10]. The length of each cylinder was chosen as 160 mm which caused the induced flow to have two dimensions. In addition, wooden end caps with thermal conductivity of 0.05 W/m.K [19] were installed on each cylinder bases to minimize the end effects. A 70Ω heater was installed inside each cylinder which was filled with magnesium oxide powder. To reduce the effect of radiation heat transfer and achieve the desired surface smoothness, the cylinders were highly polished using grinding process which resulted in a surface roughness of 0.2 μm. By passing electricity through each heater by a 20V-2A DC power supply and considering relatively thick wall aluminum tubes, constant surface temperature could be achieved. Also, in order to achieve constant surface temperature at the steady state condition, a calibrated hand held digital thermometer was used to measure the temperature at 10 different locations both in the circumferential and axial directions. It is worth mentioning that the maximum variation between temperatures did not exceed 0.1°C [10]. The electrical power supplied to each heater was controlled by a variable transformer in order to obtain different cylinder surface temperatures. The supplied electrical power was measured by a digital wattmeter. Our need for such uniformity allowed us to use a variable resistor of 35Ω for each cylinder. These resistors were connected to the cylinder heaters in series. The surface temperature of each heated cylinder was recorded by two K-type thermocouples, placed axially in the cylinder wall at locations 30 mm and 80 mm from its base. Two K-type thermocouples were also used for measuring the ambient and reference temperatures [10]. The room air temperature was measured at two different vertical locations about 70 cm away from our test section indicating the same temperature and no variation with time. Also the air conditioning fans in the laboratory were switched off during the experiments. A calibrated four-channel data logger ″TESTO 177″ was connected to a PC, in order to monitoring all the temperatures continuously. The laboratory pressure and relative humidity were recorded during all the experiments. Each cylinder was held using two 0.7 mm diameter holding rods, attached to the wooden end caps. The rods were connected to an adjustable stand to providing the parallelism of cylinders with the laser beam and the cylinder vertical and horizontal movement. The stand and mechanisms for horizontal and vertical movements are shown schematically in figure 5. A horizontal adjustment screw and a spring were used in each holding plate in order to move the holding rod horizontally. Two vertical adjustment nuts were also used for vertical movement of each holding plate with the help of four guiding rods.

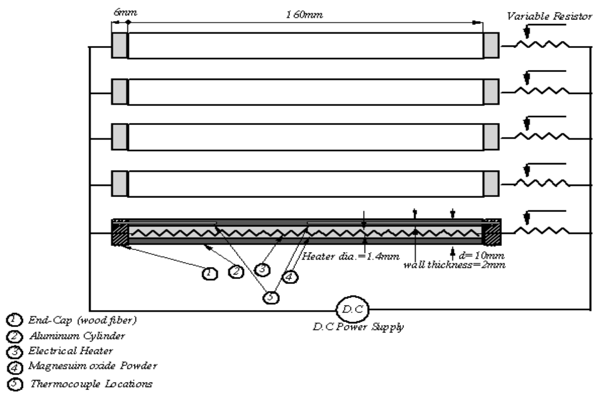


Fig. 4. Details of the cylinder used in the array with the heating circuit [10]

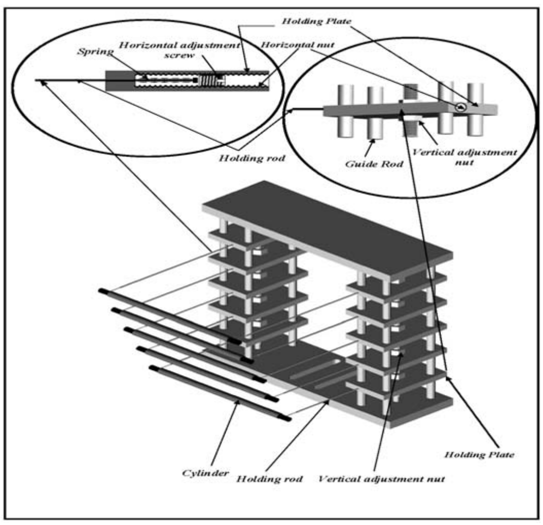


Fig. 5. Schematic of the holding stand of the cylinders and mechanisms for horizontal and vertical movement [10]

III. RESULTS AND DISCUSSION

In order to predict the effects of Rayleigh number, vertical and horizontal separation distances on the free convection heat transfer from horizontal isothermal cylinders arranged in vertical and inclined arrays, a fuzzy logic model was used. The aim of current study was to determine the effect of three main factors, such as Rayleigh number, vertical spacing ratio and horizontal spacing ratio on heat transfer from the arrays using fuzzy logic. The selected structure of the fuzzy model used in this study is shown in Table1. In order to perform fuzzy logic, input and output variables with their corresponding levels were determined. Moreover, the following levels for different input variables were considered. Rayleigh number (Ra) in five levels ranging from 10^3 to 3×10^3, vertical spacing ratio (P_y/d) in four levels from 2 to 5 and horizontal spacing ratio (P_x/d) in five levels from 0 (vertical position) to 2, and finally average Nusselt number of the arrays, as output variable were considered for experimentation. After data reduction, the values of average Nusselt number for each individual cylinder in the arrays ($\overline{Nu_i}$) for five hundred different tests was obtained. Subsequently, the average Nusselt number of the arrays $\overline{Nu_a}$ is obtained as the arithmetic mean value of the average Nusselt number of the individual cylinder $\overline{Nu_i}$ in the arrays:

$$\overline{Nu_a} = \frac{1}{5}\sum_{i=1}^{5}\overline{Nu_i} \tag{7}$$

Using the above equation, one hundred values for average Nusselt number of vertical and inclined arrays ($\overline{Nu_a}$), were obtained.

The fuzzy inference system, Mamdani, was used in this study as shown in Figure. 6. Symmetric triangular [13] membership functions for output and input variables were defined. To build up the Rayleigh membership functions, five symmetric triangles where the peak of each triangle is the main values in experiments were used [10]. The membership functions of vertical spacing ratio and horizontal spacing ratio is established using four and five triangles, respectively, similar to those of Rayleigh number. To establish the output membership functions, one hundred triangular symmetric membership functions were used in the range of zero to 99, where 0,1,…,99 indicate locations of triangle peaks. Subsequently, the range of zero to 99 was marked as 1.9737 to 4.2064 respectively. Having this sort of replacement, therefore, one hundred triangular membership functions for the average Nusselt number were obtained. Figures 7 to 9 show membership functions for input variables including Rayleigh number, vertical spacing ratio and horizontal spacing ratio. In addition, the average Nusselt number membership functions are also shown in Figure. 10. Some parts of one hundred rules, which were taken for the fuzzy model, are shown in Table 2. The results of proposed fuzzy model are shown in figure11. The comparison between average Nusselt numbers obtained from experimental results of Ashjaee and Yousefi [10] and predicted one obtained by the fuzzy model for the vertical array as a function of vertical spacing ratio for some arbitrary Rayleigh numbers is shown in figure12. Moreover, a similar comparison for the inclined array as a function of horizontal spacing ratios for some arbitrary Rayleigh numbers, and vertical spacing ratios is shown in figure13. According to these figures and also the results shown in figure11, the maximum errors of the proposed fuzzy model in predicting the Nusselt number for the data is 0.5983%. Also the mean relative error for the data is 0.081%. Therefore, the error values are low and it can be concluded that there is a good consistency between the experimental and predicted data. Therefore, the fuzzy results can be applied to precisely model the experiments. According to Figure12, in the vertical array, by increasing the vertical separation distance, heat transfer increases. This phenomenon is predictable since the plume from lower cylinders influences the heat transfer characteristics in two different ways. First, it behaves as a forced convection field for the upper cylinder, and second, it causes a lower temperature difference between the cylinder surface and the incoming air. The first effect tends to increase and the second to decrease heat transfer from the upper cylinders. The relative strength of each of these effects finally determines the net effect of the lower cylinders on the heat transfer from the upper cylinders. The second effect, which tends to decrease the heat transfer rate at the downstream cylinders, is of major importance at close spacing, which can be observed from the decrease of number of isotherms. This may be explained through the theoretical results obtained by Gebhart et al. [20] for a plume above the horizontal line source. In fact, they demonstrated that the centerline temperature of the plume decreases as the inverse of the three-fifths power of the distance above the source, while the centerline velocity of the plume increases as the fifth power of the distance above the source. Therefore as the distance above the source increases, the velocity effect must outweigh the effect of the increased fluid temperature. As it can be observed from the figures13a and 13b, in the inclined array, for small vertical separation distances, with increasing the horizontal separation distance, heat transfer from each cylinder in the array and consequently heat transfer from the array increases. This can be explained by considering that for small vertical spacing when the downstream cylinders are given a transverse offset, the effect of the hot air buoyant flow impingement, is lessened, and the heat transfer from the each individual cylinder increases. But, as it could be observed in figures13c and13d, for large vertical separation distances, the variations of P_x/d have no effect on the heat transfer from the cylinders. This is due to the weakness of thermal interference between the cylinders.

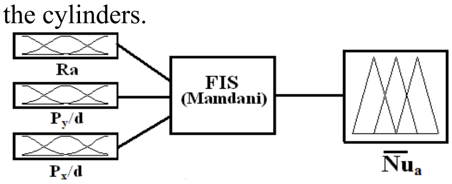


Fig. 6. Mamdani system used in this study

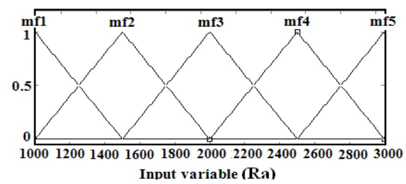


Fig. 7. Membership functions for Rayleigh number

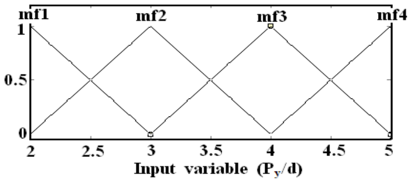


Fig. 8. Membership functions for the vertical separation distance

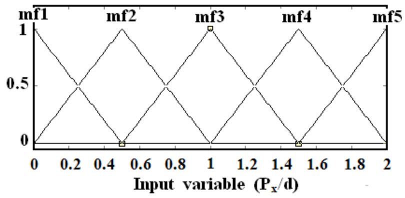


Fig. 9. Membership functions for the horizontal separation distance

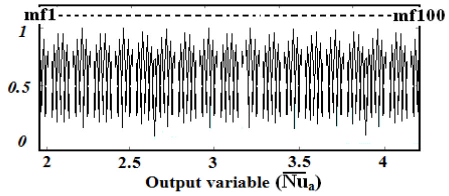


Fig. 10. Membership functions for Nusselt number

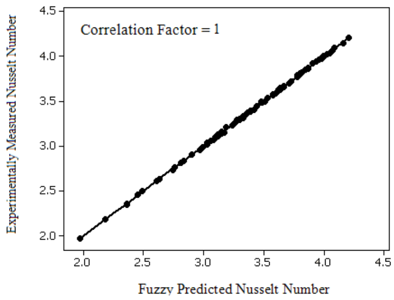
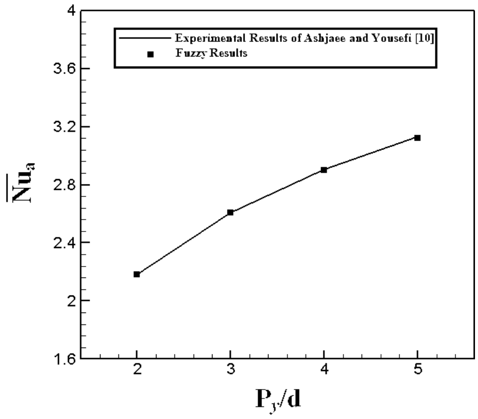
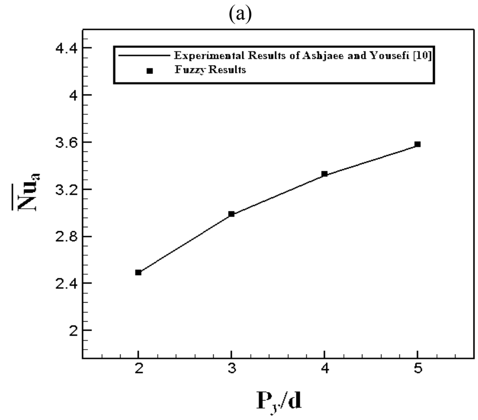


Fig. 11. The comparison between experimental and predicted values of average Nusselt number using fuzzy logic

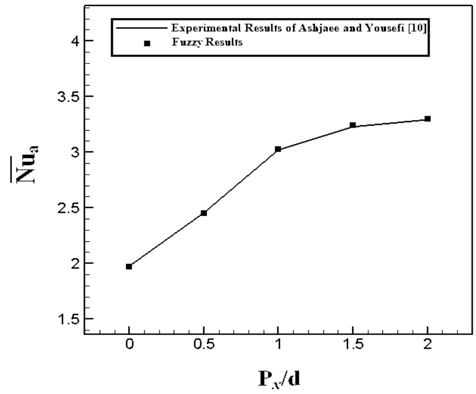


(a)

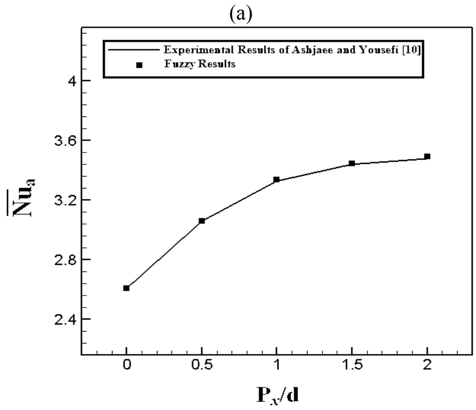


(b)

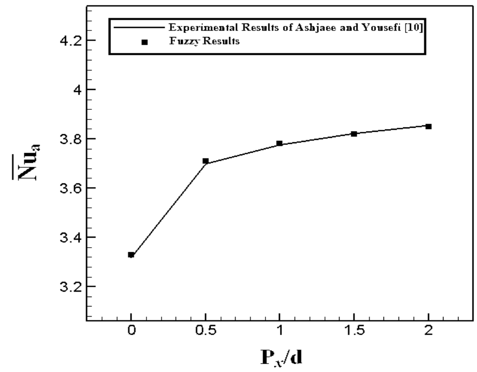
Fig. 12. Comparison between experimental and predicted values of average Nusselt number of the vertical array using ANFIS for a) Ra=1.5×10^3 b) Ra=2.5×10^3



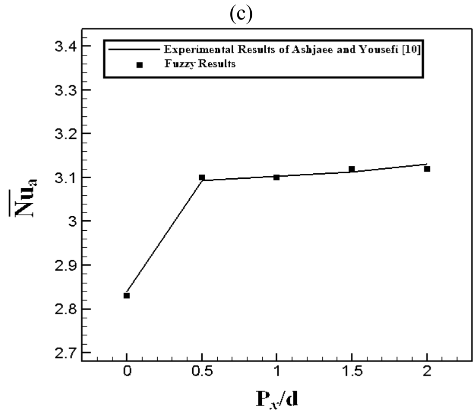
(a)



(b)



(c)



(d)

Fig. 13. Comparison between experimental and predicted values of average Nusselt number of the inclined array using ANFIS for a) Ra=10^3 and P_y/d=2 b) Ra=1.5×10^3 and P_y/d=3 c) Ra=2.5×10^3 and P_y/d=4 d) Ra=10^3 and P_y/d=5

TABLE I: SELECTED STRUCTURE OF THE PROPOSED FUZZY MODEL

Type of fuzzy inference system (FIS)	Mamdani
Inputs / Output	3/1
Input membership function types	Triangular
Output membership function types	Triangular
Number of input membership functions	5/4/5
Number of output membership function	100
Rules weight	1
Number of fuzzy rules	100
And method	Min
Implication method	Min
Aggregation method	Max
Defuzzification method	Centroid

TABLE II. PARTS OF RULES INVOLVED IN FUZZY MODEL

No	Rules	No	Rules
1	If (Ra is mf1) and (P_y/d is mf1) and (P_x/d is mf1) then (Nu is mf1)	8	If (Ra is mf3) and (P_y/d is mf4) and (P_x/d is mf3) then (Nu is mf82)
2	If (Ra is mf1) and (P_y/d is mf2) and (P_x/d is mf2) then (Nu is mf36)	9	If (Ra is mf4) and (P_y/d is mf2) and (P_x/d is mf4) then (Nu is mf85)
3	If (Ra is mf1) and (P_y/d is mf3) and (P_x/d is mf5) then (Nu is mf53)	10	If (Ra is mf4) and (P_y/d is mf4) and (P_x/d is mf1) then (Nu is mf72)
4	If (Ra is mf2) and (P_y/d is mf1) and (P_x/d is mf3) then (Nu is mf61)	11	If (Ra is mf5) and (P_y/d is mf2) and (P_x/d is mf2) then (Nu is mf75)
5	If (Ra is mf2) and (P_y/d is mf2) and (P_x/d is mf5) then (Nu is mf68)	12	If (Ra is mf5) and (P_y/d is mf3) and (P_x/d is mf1) then (Nu is mf68)
6	If (Ra is mf2) and (P_y/d is mf4) and (P_x/d is mf3) then (Nu is mf64)	13	If (Ra is mf5) and (P_y/d is mf4) and (P_x/d is mf5) then (Nu is mf91)
7	If (Ra is mf3) and (P_y/d is mf2) and (P_x/d is mf2) then (Nu is mf59)	14	If (Ra is mf5) and (P_y/d is mf3) and (P_x/d is mf4) then (Nu is mf91)

IV. CONCLUSION

The free convection heat transfer from vertical and inclined arrays of isothermal horizontal cylinders in the air was modeled using fuzzy logic. This model was used on the basis of obtaining relationship between thee input variables namely Rayleigh number, vertical spacing ratio and horizontal spacing ratio, and average Nusselt number. It was observed that, in the vertical array, by increasing the vertical separation distance, heat transfer increases. Also, in the inclined array, for small vertical separation distances, with increasing the horizontal separation distance, heat transfer from the array increases. For large vertical separation distances, the variations of horizontal spacing ratio have no effect on the heat transfer from the cylinders. In addition, Since fuzzy logic is a reliable technique for predicting the average Nusselt number of the arrays due to its high accuracy as indicated in this research work, therefore, it can be used to precisely model the experiments accordingly.

NOMENCLATURE

d diameter of the cylinders, (m)
g gravitational acceleration, (m/s^2)
l length of cylinder, (m)
N number of cylinders in the array, N =5
N_i ordinal number of the *ith* cylinder in the array
$\overline{Nu_a}$ average Nusselt number of the arrays
$\overline{Nu_i}$ average Nusselt number of the *ith* cylinder in the arrays
p pressure, (Pa)
P_x horizontal center-to-center separation distance, (*m*)
P_y vertical center-to-center separation distance, (*m*)
Ra Rayleigh number based on the cylinder diameter, $=g\beta(T_w - T_\infty)d^3/\nu\alpha$
T temperature, (K)

Greek symbols

α thermal diffusivity of air, (m^2/s)
β coefficient of volumetric thermal expansion of air, (1/K)
ε fringe shift
λ laser wave length=632.8 nm
ν kinematic viscosity of air, (m^2/s)
φ angle of flow diverter = 45^o

Subscripts

w referred to undisturbed air
∞ referred to the cylinder surface
ref referred to a fringe shift=0

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