Fuzzy Logic Modeling of Heat Transfer in an Air Cooler Equipped with Butterfly Insert

A. Karami, E. Rezaei, M. Shahhosseni, and S. Feiz Jafari

***Abstract*—This paper highlights the use of fuzzy logic to model and predict the experimental results of heat transfer in an air cooled heat exchanger equipped with the butterfly inserts. Experiments included Reynolds number ranging from 4021 to 16118 and the inclined angle of the butterfly inserts from 45◦ to 90◦. Experimental results showed that, the maximum heat transfer by the use of butterfly insert was obtained with the inclined angle of 90◦. A fuzzy inference system named Mamdani was used to expect the output membership functions to be fuzzy sets. It has been also shown that, fuzzy logic is a powerful instrument for predicting the experiments due to its low error. The average error of fuzzy with respect to experimental data was found to be 0.41% for this study.**

***Index Terms*—Air cooled heat exchanger, Fuzzy logic, Heat transfer, Mamdani inference system, Butterfly inserts.**

I. Introduction

A. Heat Transfer Enhancement in Heat Exchangers

It has been commonly known that the heat transfer rate of heat exchangers especially for single-phase flows can be improved through many enhancement techniques. In general, heat transfer enhancement (HTE) techniques can be divided into two categories: (1) active techniques which need external power source and (2) passive techniques which do not need to external power source. Some examples of passive HTE methods include: insertion of twisted stripes and tapes [1,2], insertion of coil wire and helical wire coil [3, 4] and mounting of turbulent decaying swirl flow devices [5,6]. Despite of the high pressure drop caused by insert in embedded tubes, the use of tube insert in heat exchangers has received a lot of attention during the last two decades [2,7]. The increase in turbulence intensity and swirling flow may be the main reasons for HTE induced by tube inserts. An experimental study was carried out on heat transfer in a round tube equipped with propeller type swirl generators by Eiamsa-ard et al. [8]. The effects of the blade angle, pitch ratio and number of blades on Nusselt number and pressure loss were also studied. Chang et al. [9, 10] studied the heat transfer enhancement in a tube fitted with the serrated twisted tapes and broken twisted tapes. Saha [11] studied the heat transfer and pressure loss behaviors in rectangular and square ducts with combined internal axial corrugations and twisted-tapes with and without oblique teeth. Many studies have been carried out on porous media insert as a kind of satisfying inserts for enhancing heat transfer in the tube flow.

Recently Shabanian et al. [12] studied the heat transfer enhancement in an air cooler equipped with different tube inserts. They showed that using the different tube inserts (butterfly, jagged and classic twisted tape inserts), increase the heat transfer from the air cooler. They showed that by using the butterfly insert with an inclined angle of 90°, maximum heat transfer is obtained. Also, their results have revealed that the difference between the heat transfer rates obtained from employing the classic and jagged inserts reduces by decreasing twist ratio. The aim of the present study is to use fuzzy logic to model the heat transfer from the air cooler equipped with the butterfly insert.

Manuscript received June 3, 2011; revised August 8, 2011.

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B. Fuzzy Logic

Fuzzy logic is a method which can be used to model the experiments, and it has been introduced for the first time in 1965 by Zadeh [13]. Modeling of experiments can be helpful to reduce its costs. By using the models, we can predict results of experiments, which have not performed, or are not possible to perform due to some restrictions. In this study, the fuzzy logic methodology has been used in order to model and predict the experimental results. A simple fuzzy logic as it can be seen from Figure. 1, consists from four major parts: Fuzzification interface, Fuzzy rule base, Fuzzy inference engine, and defuzzification interface. A fuzzification operator has the effect of transforming crisp data into fuzzy sets. A fuzzy rule represents a fuzzy relation between two fuzzy sets. It takes a form such as; *if x is A then y is B*. Each fuzzy set is characterized by suitable membership functions. A fuzzy rule base contains a set of fuzzy rules, where each rule may have multiple inputs and multiple outputs. Fuzzy inferencing can be realized by utilizing a set of fuzzy operations. The defuzzification interface mixes and converts fuzzy membership functions into significant numerical outputs. Depending on the types of inference operations upon *if-then* rules, 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, fuzzifying the inputs and applying the fuzzy operator, are exactly the same. The main difference between Mamdani and Sugeno is that the Sugeno output membership functions are either linear or constant [16]. Other properties of these models can be found in reference [17]. The fuzzy system which has been used here is Mamdani which is the most commonly seen fuzzy methodology. After parameters classification, the rules for fuzzy systems must be defined. For example: if Ra is α, and θ is β, then Nu is γ. Where α, β and γ are arbitrary parameters.

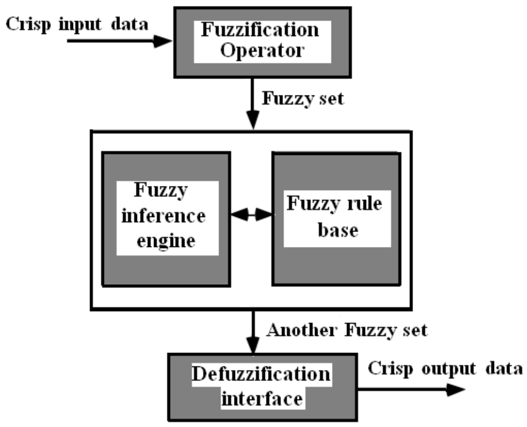
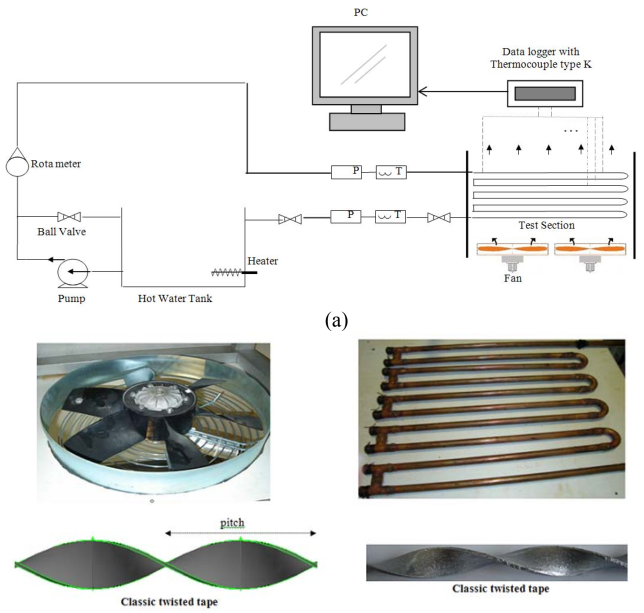


Fig. 1 Schematic view of the performance of a simple fuzzy model

II. Experimental Apparatus



(a)

(b)

Fig. 2. (a) Schematic diagram of the experimental rig and (b) the used tools in the experiment

A schematic view of the experimental rig [12] is shown in Figure2a. The rig consists of two fans and a set of copper tubes. The set of tubes has three sections including calming section, bent tube and outlet section. The fluid is entered the calming section which has a length of 2m to eliminate the entrance effect. The temperature and pressure are measured at the end of this section as the inlet of bent tube section. Then, the fluid passes through 9 bends in 6.5m length of the bent tube and reaches to the outlet section. The pressure and the temperature are measured at the outlet section. The 50 W fans with 1400 rpm rotation speed are placed in 20cm distance beneath the bent tube and whole of the assembly is enclosed in a 60×100×50 cm cubic channel. Hot water from a 100 liter reservoir equipped with heater enters the bent tube after passing through rotameter with 58°C temperature. Water volumetric flow rate varies from 100 lit/hr to 400 lit/hr which correspond to Reynolds numbers from 4021 to 16118. The tube inlet and outlet water pressure and temperature are measured through two pressure transmitters and copper-constantan thermocouple. Moreover, in order to determine the average Nusselt number, the temperatures at 20 different positions on the outer surface of the tube are measured. All twenty temperature sensing probes are connected to a data logger set. In the experiments, the butterfly insert, is placed in the bent tube. Figure 2b shows the bent tube, fan and tube inserts used in the experiment. The tube applied here has 17mm diameter and 1mm thickness. The butterfly inserts are made from aluminum sheet with 0.5mm thickness and consist of a holding rod with 1.9mm diameter. These inserts are used in three inclined angles of 45°, 90° and 135° between the butterfly piece and the rod with 6cm pitch length. In the butterfly arrangement, pieces are placed on the rod to increase the flow turbulence intensity in the tube. Also the pieces on the rod are twisted slightly in order to reduce the blocking effect.

III. Data Reduction

In order to express the experimental results in a more efficient way, the measured data are reduced using the following procedure [12]:

The heat transfer rate resulted from the hot fluid in the tubes is expressed as:

$$Q = mC_p(T_o - T_i) \tag{1}$$

On the other hand, the heat transfer rate to the air surrounded the tube is approximated by:

$$Q = hA(\overline{T}_w - T_b) \tag{2}$$

where,

$$T_b = (T_o + T_i)/2 \quad \text{and} \quad \overline{T}_w = (\sum T_w)/20 \tag{3}$$

T_w is the local wall temperature and is measured at the outer wall surface of the tubes. The relations used in calculation of the average heat transfer coefficient and the average Nusselt number are as follows:

$$h = mC_p(T_o - T_i)/A(\overline{T}_w - T_b) \tag{4}$$

$$Nu = hD_h/K \tag{5}$$

In addition, the Reynolds number is obtained according to the following equation:

$$\mathrm{Re} = UD_h/v \tag{6}$$

In the present work, the uncertainties of experimental measurements are determined based on ANSI/ASME [18]. The maximum uncertainties for Nu and Re are estimated 7% and 5.2%, respectively.

IV. Results and Discussion

Before undertaking the experiments using the tube equipped with tube inserts, the Nusselt number is measured in a plain tube. In order to evaluate the validity of measured value of the plain tube, the experimental data are compared with the results obtained with well-known correlations under similar condition. The comparisons for Nusselt number is shown in Figure. 3. According to this figure, the present results are in good agreement with the Gnielinski's Nusselt numbers [19] with tolerances of ±5.9%. The butterfly insert is used in this study, and its effect on heat transfer from the air cooled heat exchanger was investigated. The aim of this study is to consider the effect of two main factors, Reynolds number and the inclined angle of the butterfly insert, on heat transfer from the air cooled heat exchanger by using fuzzy logic. In order to perform fuzzy logic, input and output variables and their levels must be determined. Reynolds number (Re) in seven levels ranging from 4021 to 16118, inclined angle (θ) of butterfly inserts in three levels from 45° to 135°, as input variables and average Nusselt number as output variable were chosen. After data reduction, the values of average Nusselt number for twenty one different tests were determined. The Mamdani inference system used in this study is shown in Figure. 4. Symmetric triangular membership functions [20] for output and input variables were defined. Figures 5 and 6, show membership functions for input variables, i.e. Reynolds number, and inclined angle of the butterfly inserts. The membership functions of average Nusselt number are brought in Figure. 7. Some parts of twenty one rules, which were chosen for the fuzzy model, are shown in Table 1. The values of average Nusselt number obtained from Eq. (5) where Heat Transfer coefficient, h is calculated from Eq. (4) and also the errors of fuzzy predictions with respect to experimental results are shown in Table 2. The errors of Fuzzy predictions with respect to experimental Nusselt numbers in table 2 are calculated as given below:

$$Error\% = \left| Predicted\ Nusselt - Exprimental\ Nusselt / Exprimental\ Nusselt \right| \% \quad (7)$$

As it can be seen from this Table and Figure 8, the average error is 0.41%. Therefore experimental results are in good agreement with predicted one by fuzzy model, which shows that, the fuzzy logic is a reliable method to predict the average Nusselt number. According to Figure9 from fuzzy logic, with increasing Reynolds number, the average Nusselt number increases. As it can be seen from Figure.9, the tube fitted with butterfly insert with inclined of 90° has higher Nusselt number compared with other two inclined angles. This result may be explained by the generation of stronger turbulence intensity and more rapid mixing of flow created by this insert.

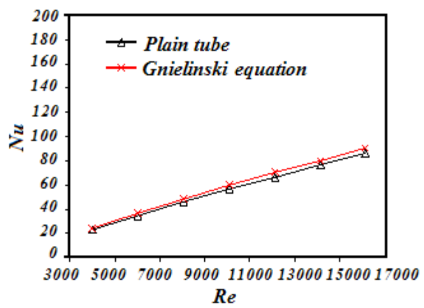


Fig. 3. Comparison of experimental Nusselt number for the plain tube with the results of Gnielinski [19]

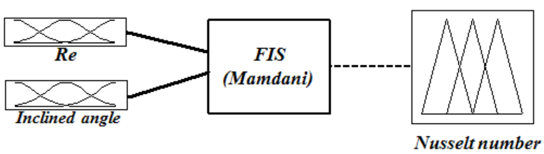


Fig.4. Mamdani system used

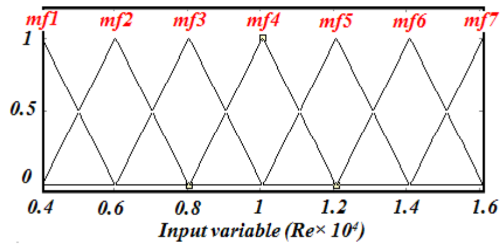


Fig. 5. Membership functions for Reynolds number

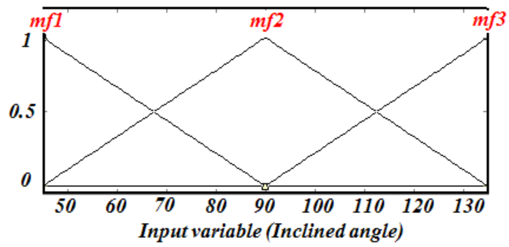


Fig. 6. Membership functions for the inclined angles of butterfly inserts

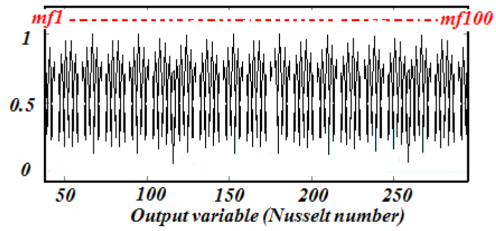


Fig. 7. Membership functions for average Nusselt number

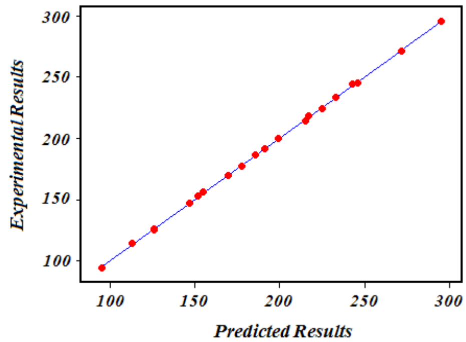


Fig. 8. Experimental results versus predicted results from fuzzy logic

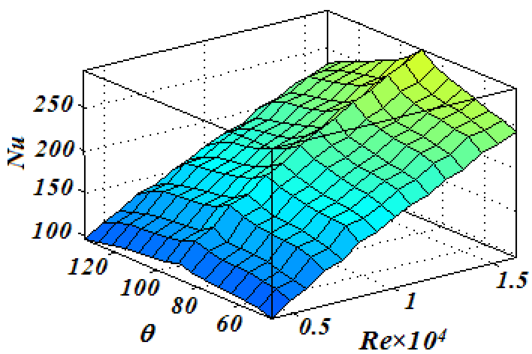


Fig. 9. Average Nusselt number of an air cooler equipped with butterfly inserts versus Reynolds number and inclined angle

TABLE I. PARTS OF RULES INVOLVED IN FUZZY MODEL

No	Rules	No	Rules
1	If (Re is mf1) and (θ is mf2) then (Nu is mf30)	4	If (Re is mf3) and (θ is mf1) then (Nu is mf45)
2	If (Re is mf4) and (θ is mf2) then (Nu is mf70)	5	If (Re is mf5) and (θ is mf1) then (Nu is mf63)
3	If (Re is mf7) and (θ is mf2) then (Nu is mf100)	6	If (Re is mf1) and (θ is mf3) then (Nu is mf23)

TABLE II. COMPARISON OF AVERAGE NUSSLET NUMBER BETWEEN FUZZY RESULTS AND EXPERIMENTS

No	Experiments	Fuzzy logic predictions	Error %	No	Experiments	Fuzzy logic predictions	Error %
1	94.280	95.0000	0.75	12	245.000	246.000	0.40
2	125.714	126.000	0.22	13	271.100	272.000	0.33
3	152.857	152.000	0.56	14	295.000	295.000	0.00
4	177.142	178.000	0.48	15	94.2840	95.0000	0.75
5	200.000	199.000	0.50	16	125.011	126.000	0.22
6	224.285	225.000	0.31	17	147.140	147.000	0.09
7	244.286	243.000	0.52	18	169.721	170.000	0.16
8	114.44	113.000	1.25	19	191.421	191.000	0.22
9	156.020	155.000	0.65	20	214.281	215.000	0.29
10	186.660	186.000	0.35	21	232.861	233.000	0.05
11	218.050	217.000	0.48				

V. CONCLUSIONS

The prediction of experimental results of heat transfer from an air cooler equipped with butterfly insert, placed in a bent tube of the air cooled heat exchanger, was studied by the use of fuzzy logic. This method was used to gain relationship between two input parameters namely Rayleigh number and inclined angles of butterfly inserts, and the average Nusselt number as output variable.

The following results were obtained:

1. Average Nusselt number will increase with the increase of Reynolds number.

2. Maximum heat transfer value by employing the butterfly insert is obtained with inclined angle of 90° in Reynolds number of 16118.

3. Fuzzy logic is a reliable method for the prediction of results due to its high accuracy and can be used to model the experiments precisely.

VI. NOMENCLATURE

A	heat transfer area (m^2)
Q	heat transfer rate (W)
C_p	specific heat capacity (kJ/kg·K)
D	diameter of the smooth tube (m)
D_h	hydraulic diameter (m)
h	heat transfer coefficient ($W/m^2 \cdot K$)
K	thermal conductivity (W/m·K)
mf	membership function
m	mass flow rate (kg/s)
Nu	Nusselt number
P	static pressure (Pa)
Re	Reynolds number
T	temperature (K)
U	mean velocity (m/s)

Greek letters

ν	kinematic viscosity (m^2/s)
θ	inclined angle

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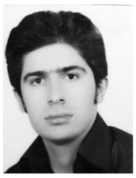

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