Modeling the Free Convection Heat Transfer in a Horizontal Cavity with Flow Diverters Using Adaptive Neuro-Fuzzy Inference System

Alimohammad Karami, Tooraj Yousefi, Ehsan Rezaei, and Damoon Ghashghaei

***Abstract*—This paper highlights the application of adaptive neuro-fuzzy inference system (ANFIS) to model the free convection heat transfer in a horizontal cavity with adiabatic vertical and isothermally horizontal walls and adiabatic diverters. The main focus of the present paper is to consider the effects of diverter angle and Rayleigh number variation on average free convection heat transfer in the horizontal cavity. The training data for optimizing the ANFIS structure is obtained experimentally by a Mach-Zehnder interferometer. A hybrid learning algorithm consists of gradient descend method and least-squares method is used for ANFIS training. The proposed ANFIS developed using MATLAB functions. For the best ANFIS structure obtained in this study, the maximum errors of the train and test data were found to be 0.148% and 6.651%, respectively. Also, the mean relative errors of the train and test data were found to be 0.049% and 2.54%, respectively. The predicted results show that ANFIS can predict the experimental results precisely.**

***Index Terms*—Free convection; heat transfer; horizontal cavity; diverters; modeling; ANFIS.**

I. Introduction

Free convection heat transfer in a cavity consisting of diverters has been extensively studied using numerical simulations and experiments because of its importance in industrial applications. Some applications are solar collectors, fire research, electronic cooling, aeronautics, chemical apparatus, fenestration systems and construction engineering. Most of the papers in this field are substantially oriented toward the study of natural convection in enclosed squares or rectangular cavities. Safer et al. [1] modeled the air flow in a double-skin facade equipped with a horizontal venetian blind and forced ventilation. The study examined the effect of slat angle, blind position and air outlet position on the velocity profiles in the double-skin facade. Collins et al. [2] developed a two-dimensional steady free convection model of a window cavity with between-panes louvers (i.e., slats) by approximating the system as a vertical cavity with isothermal walls at different temperatures and with rotatable baffles located midway between the walls. They showed that the system is suited to a traditional one-dimensional analysis, and that the convective heat transfer is largely independent of the Rayleigh number for the conditions of practical interest. Dağtekin and Öztop [3] studied the natural convection heat transfer and fluid flow of two heated partitions attached to the lower adiabatic wall for Rayleigh numbers of 104–106. Enclosure is cooled from the left and top walls while the only heat source within the medium is due to the partitions whose length and positions were varied. They showed that the mean Nusselt number increases with the increase of the partition length. Tasnim and Collins [4] studied the natural convection in a square cavity with a thin baffle on the hot wall using finite volume method with collocated variable arrangement. They observed that the fin has a blocking effect on the fluid depending on the Rayleigh number, length of the baffle, and its position. Shi and Khodadadi [5] studied the almost perfectly conducting partition on the hot wall. Based on the obtained results, they proposed correlations to calculate Nusselt number as a function of relevant parameters. Yousefi et al. [6] studied the free convection heat transfer in a vertical cavity consisting of diverters. The aim of that study was to investigate the effect of confined diverters on free convection heat transfer in the vertical cavity. They found that, the maximum heat transfer occurs at the diverter angle of 150° and Rayleigh number of 12000. Bilgen [7] studied the free convection heat transfer in cavities with a thin fin on a hot wall. He found that Nusselt number increases with the increase of Rayleigh number, and decreases with the increase of fin length and relative conductivity ratio. Shahid and Naylor [8] studied the effects of the presence of a venetian blind on the thermal performance of single and double glazed windows, numerically. The blind was positioned adjacent to the indoor surface of either a single or a double glazed window and the coupled convection and radiation heat transfer problem was solved using a two-dimensional finite volume model. They showed that, the presence of a venetian blind can significantly improve the window energy performance. Also, it was shown that, the blind reduces the overall heat transfer rate through the window by reducing the thermal radiation from the indoor glazing. Yousefi et al. [9] studied the free convection heat transfer in a horizontal cavity consisting of diverters. The aim of that study was to investigate the effect of confined diverters on free convection heat transfer in a horizontal cavity. They found that, at each Rayleigh number the maximum and the minimum heat transfer occurs at the diverter angle of 30° and 90° respectively. The main focus of the present study is to utilize an adaptive neuro-fuzzy inference system (ANFIS), to model the free convection heat transfer in a horizontal cavity consisting of diverters. The experiments have been carried out using a Mach–Zehnder interferometer. A schematic

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representation of the problem is shown in figure 1. The diverter length L, diverter width H, thickness of each diverter t, pitch of the diverter p, cavity side length W, diverter angles θ, and also the boundary conditions are represented in this figure.

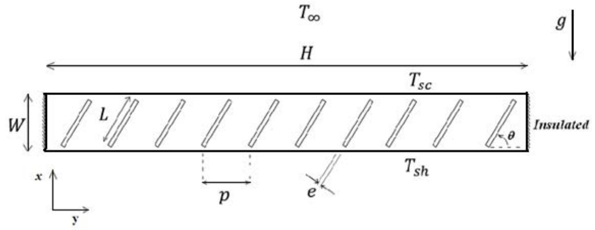


Fig. 1. Schematic representation of the problem.

II. Experimental Setup

A. Interferometer

The experimental study was carried out using Mach–Zehnder interferometry (MZI) technique. The interferometer consisted of a light source, a micro lens, a pinhole, two doublets, three mirrors and two beam splitters. Figure 2 shows the interferometer setup. Beam splitters BS1 and BS2, along with plane mirrors M1 and M2 constituted the basic MZI. The laser beam gets expanded after passing through spatial filter and the doublet1. The expanded beam is splited into two equal beams by BS1. One beam passes through the test section and the other through the undisturbed field. These two beams, again, recombine at BS2. If the four optical plates, M1, M2, BS1, and BS2 are parallel, then an infinite fringe interferograms will be formed. Further information about MZI can be found in [10–12]. The used light source is a 10 mW Helium–Neon laser with a 632.8 nm wavelength. All the interferograms were digitized with a ‘‘ARTCAM-320P’’ 1/2″ CCD camera with 3.2 M pixels. To acquire the interferograms, a camera was connected to a PC. Figure 3 shows some of the interferograms which were recorded by the CCD camera.

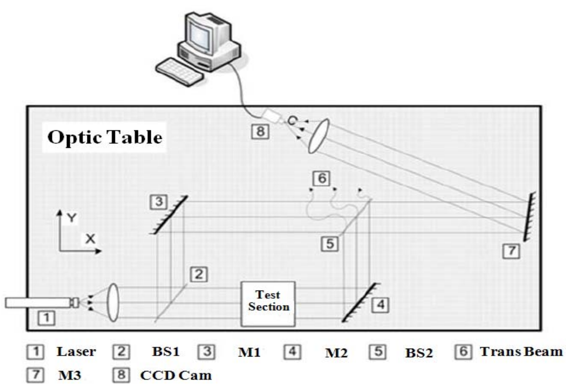
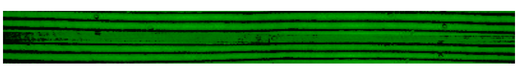
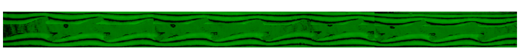


Fig. 2. Schematic representation of (MZI) setup.



(a)



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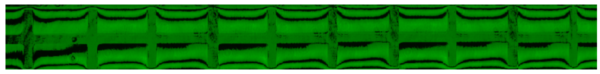
(c)



(d)

Fig. 3. Interferograms of the cavity consisting of diverters for Ra= 12000 at (a) θ=0° (b) θ=30° (c) θ=60° (d) θ=90°.

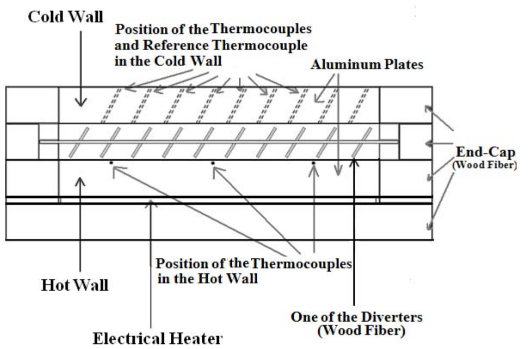


Fig. 4. Details of the horizontal cavity consisting of diverters used in the experiments.

B. Experiment Test Section

The details of the horizontal cavity used in the experiments are shown schematically in figure 4. The length of each isothermal wall was chosen as 140 mm which causes the induced flow to be two-dimensional. Also, the wooden end caps with thermal conductivity of 0.05 W/m K [13] were installed on each aluminum plate bases to minimize the end effects. By passing electricity through the heater placed at the back of the aluminum plate and considering relatively thick-walled (16mm) aluminum plate, we achieved constant surface temperature. The uniformity of each plate surface temperature was experimentally validated by measuring it at 3 different locations. The differences in temperature readings for each aluminum plate surface were about 0.1˚C. The local surface temperatures of the heated aluminum plate were recorded via three type-K thermocouples, embedded vertically in the aluminum plate wall, as it is shown in figure 4. Two other thermocouples of the same type were used to measure the ambient and the reference temperatures for data reduction. All the temperatures were monitored continuously in a PC by a selector switch and a ‘‘TESTO 177 T4’’ four channel data logger. The laboratory pressure was recorded during all the experiments. The maximum uncertainties of temperature and pressure measurement for the present test condition were ±0.1˚C and ±100 Pa, respectively. In all of the experiments the heater voltage and current were recorded. In order to ascertain the accuracy of the measurements, the energy balance calculation for many cases was done by calculating free convection heat transfer from the fringe patterns of the Mach–Zehnder interferometer and measuring electrical power input to the heaters. A compression between the heat transfer coefficients obtained by two methods shows a complete agreement. Four ten-diverter sets of dimensions 167 m × 14 m × 1.5 m, with thermal conductivity of 0.05 W/m K with angle of 0°, 30°, 60° and 90° with respect to horizon were built to use in the cavity for each experiment with its associated angle. In each set, the diverters were glued to a thin rod. Two windows were used on both sides of the cavity for the prevention of external air to enter to the cavity. In order to eliminate the effect of any air disturbances on the experimental test section, the entire interferometer table was located within a top open transparent plastic enclosure of dimensions 3 m × 1.5 m × 1.5 m.

III. DATA REDUCTION

The aim of the data reduction procedure was to determine the local and average Nusselt numbers. Three interferograms with ten seconds interval were captured in each case for the assurance of experiment repeatability. In order to determine the local and average Nusselt number on the hot wall, a code with MATLAB software has been developed. The temperature of the interference fringes as well as their distance from the surface of the aluminum plate in vertical direction was calculated by the method explained by Eckert and Goldstein [11] and Hauf and Grigull [10]. The local air temperature gradient at the aluminum plate surface is obtained from the following equation:

$$\left.\frac{dT}{dx}\right|_{x=0} = \left.\frac{dT}{d\varepsilon}\right|_{x=0} . \left.\frac{d\varepsilon}{dx}\right|_{x=0} \tag{1}$$

where ε is the fringe shift value. Using the ideal gas and Lorenz–Lorenz equations [10] $\left.\frac{dT}{d\varepsilon}\right|_{x=0}$ is calculated as follow:

$$\left.\frac{dT}{d\varepsilon}\right|_{x=0} = \frac{3C(\frac{L}{\lambda})\frac{P}{R}}{(\frac{3}{2}C(\frac{L}{\lambda})\frac{P}{RT_{ref}} - 2\varepsilon)^2_{x=0}} \tag{2}$$

where, $R = 287 \quad J/kgK$ is the gas constant, P_∞ is the ambient pressure, C is the Gladstone–Dale constant, and T_{ref} is the temperature of reference fringe. The local heat transfer coefficient and the Nusselt number are determined as follows:

$$h_x = -k_{Sh}\left.\frac{dT}{dr}\right|_{x=0} \frac{1}{T_{Sh} - T_\infty} \tag{3}$$

Then the local Nusselt number is obtained from:

$$Nu_x = \frac{h_x x}{k_f} \tag{4}$$

where T_f is the film temperature and $T_f = \frac{T_{Sh} + T_\infty}{2}$, k_{Sh} and k_f are the thermal conductivity of air evaluated at the surface temperature T_{Sh} and the film temperature. The average Nusselt number is calculated from the following formula:

$$\overline{Nu} = \frac{\bar{h}L}{k_f} \qquad \bar{h} = \frac{1}{L}\int_0^L h_x dx \tag{5}$$

where, x is the distance perpendicular to the aluminum plate surface. Also, convective heat flux of the heated wall in the cavity is calculated from:

$$q'' = \bar{h}\ (T_{Sh} - T_\infty) \tag{6}$$

IV. ADAPTIVE NEURO-FUZZY INFERENCE SYSTEM

ANFIS [14], [15] is a fuzzy inference system implemented in the framework of neural networks. This combination merges the advantages of fuzzy systems and neural networks. The main target of ANFIS is to find a model which can model the inputs with the outputs accurately. An ANFIS is used to map input characteristics to input membership functions, input membership function to a set of TSK-type fuzzy *if- then* rules, rules to a set of output characteristics, output characteristics to output membership functions, and the output membership function to a single-valued output or a decision associated with the output [16]. At the computational level, ANFIS can be regarded as a flexible mathematical structure that can approximate a large class of complex nonlinear systems to a desired degree of accuracy.

For simplicity, assume that the fuzzy inference system has two inputs (*x, y*) and one output (*f*). for the first order Sugeno fuzzy model, A single fuzzy if-then rule assumes the form
Rule1: *if* x *is* A_1 *and* y *is* B_1, *then* $f_1 = p_1x+q_1y+r_1$
Rule2: *if* x *is* A_2 *and* y *is* B_2, *then* $f_2 = p_2x+q_2y+r_2$

where p_i, q_i and r_i are linear output parameters (consequent parameters) and i=1, 2.

The reasoning mechanism for this Sugeno model is illustrated in figure5. Also, the corresponding equivalent ANFIS architecture is shown in figure6.

The layers shown in figure6 are defined as follows [17]:

- Layer 1: Every node in this layer contains membership functions described by triangular[18] function:

$$\mu_A(x) = \left\{ \begin{array}{ll} 0, & x \le a_i \\ \frac{x-a_i}{b_i-a_i}, & a_i \le x \le b_i \\ \frac{c_i-x}{c_i-b_i}, & b_i \le x \le c_i \\ 0, & c_i \le x \end{array} \right\}$$

where $\{a_i, b_i, c_i\}$ are referred to premise parameters.

- Layer 2: Every node in this layer is a fixed node and calculates the firing strength of a rule multiplication.
- Layer 3: Every node in this layer calculates the weight, which is normalized. The outputs of this layer are called normalized firing strengths.
- Layer 4: The output of this layer is compressed of a linear combination of the inputs multiplied by the normalized firing strength w.

- Layer 5: This layer is the simple summation of the outputs of layer 4.

The adjustment of the modifiable parameters (consequent parameters) is a two-step process [16,17]. First, the consequent parameters are identified by the least square estimation, then the premised parameters are updated by the gradient descend.

ANFIS is a strong instrument for the modeling and simulation in many engineering applications. In this study, the variation of average convective heat flux of the heated wall in the horizontal cavity with Rayleigh number and diverter angle has been modeled via ANFIS. The input parameters are Rayleigh number (Ra) ranging from 0.6×10^4 to 1.2×10^4, and diverter angle (θ) from 0° to 90° and the output parameter is average heat flux (q'') calculated by equation (6). A simplified of the proposed ANFIS model is shown in figure7.

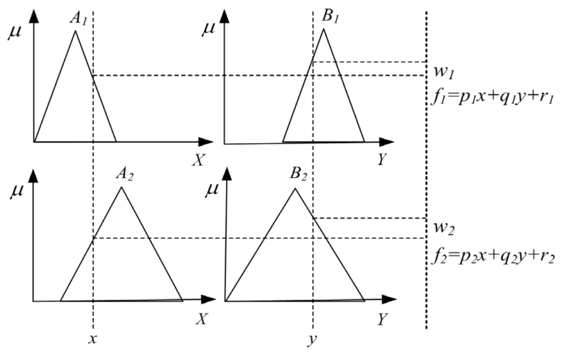


Fig. 5. The inference method of Sugeno model.

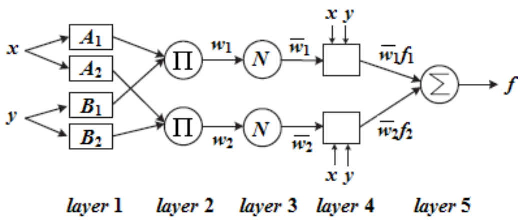


Fig. 6. ANFIS architecture based on takagi-sugeno.

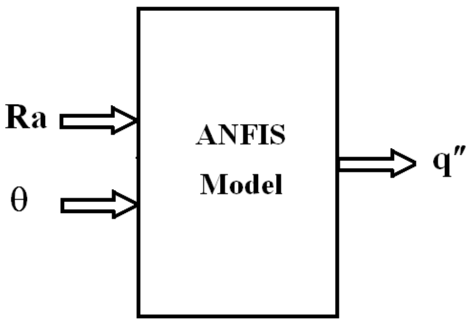


Fig. 7. A simple schematic of ANFIS model。

V. ANFIS Simulation Results and Discussion

To build the ANFIS model, 12 data (about 75% of whole data) have been used for training and 4 data (about 25% of whole data) were used for testing the ANFIS model. The final ANFIS architecture used in this study is described in table1. The training and testing results of the proposed ANFIS model are shown in figures 8 and 9 and Table 2, wherein the mean relative error difference is given by:

$$MRE = \frac{1}{N}\times\sum_{i=1}^{N}\left|\frac{q''_{\exp}-q''_{pred}}{q''_{\exp}}\right|$$

where $q''_{\exp}$ and q''_{pred} are experimental and predicted values of the average heat flux, respectively and N is the number of data.

TABLE I: Optimal Architecture and Specifiations Anfis Model

Type of fuzzy inference system (FIS)	Sugeno
Inputs / Output	2/1
Input membership function Types	Triangular
Output membership function Types	Linear
Number of input membership functions	3/3
Number of output membership function	9
Rules Weight	1
Number of fuzzy rules	9
Number of epochs	175

TABLE II. The Error Information of the Proposed ANFIS Model

MRE%	Train	Test
Min	0	0.02520
Max	0.14840	6.65100
Mean	0.04914	2.5400

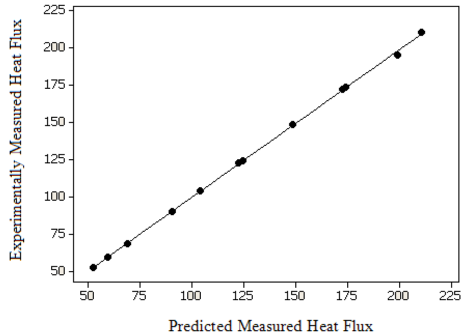


Fig. 8. The comparison between experimental and predicted values of average heat flux using ANFIS for training data.

The comparison between average heat fluxes obtained from experiments and predicted one by the ANFIS model, as a function of diverter angle for some arbitrary Rayleigh numbers are shown in figure10. According to this figure and also the results shown in figures 8 and 9, the maximum errors of the proposed ANFIS model in predicting the heat flux for the train and test data are 0.148% and 6.651%, respectively. Also the mean relative errors for the train and test data are 0.049% and 2.54%, respectively. Therefore, the error values are low and it can be concluded that there is a good agreement between the experimental and predicted results for the train and test data sets. Therefore, the ANFIS results can be applied to model the experiments precisely. As it can be observed from these figures, at each Rayleigh number, the maximum heat transfer occurs at the diverter angle of 30˚ and the minimum heat transfer at the angle of 90˚. These behaviors can be described as follows:

For diverter angle of 0°, because of the insulated wall, circulating force between cold and hot walls weakens and the diverters prevent hot air to reach to the cold wall. With increasing the diverter angle to 30°, because of the creation of chimney effect between cold and hot wall, heat transfer increases enormously. Again, with increasing the angle from 30^o to 90^o, the distance between the tips of the diverters and the heated wall will be decreased. The ability of the air circulating flow to pass though this gap will be decreased due to decrease in its velocity and, consequently, the heat transfer decreases.

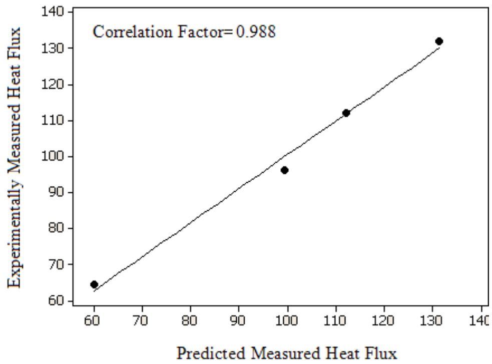
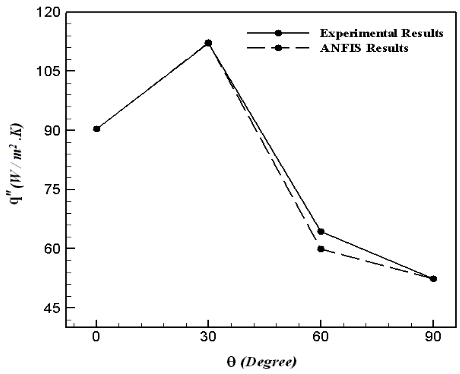
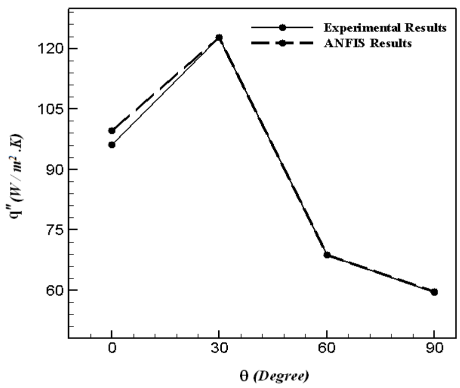


Fig. 9. The comparison between experimental and predicted values of average heat flux using ANFIS for testing data.



(a)



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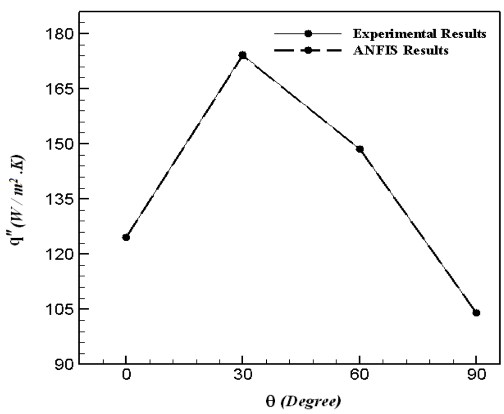

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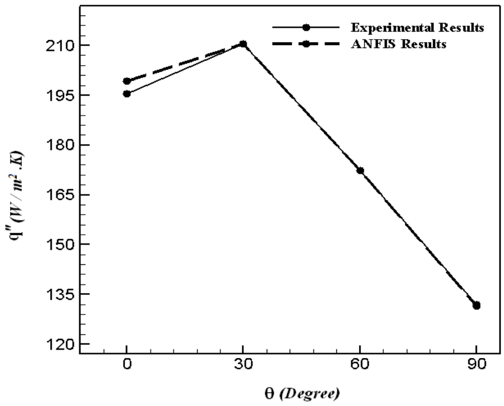

(d)

Fig. 10. Comparison between experimental and predicted values of convective heat flux using ANFIS for a) Ra=6000 b) Ra=8000 c) Ra=10000 d) Ra=12000.

VI. Conclusion

The prediction of experimental results of free convection heat transfer in a horizontal cavity with adiabatic vertical and isothermally horizontal walls and adiabatic diverters was studied, via the use of adaptive neuro-fuzzy inference system (ANFIS). This method was used to gain the relationship between two input parameters namely Rayleigh number, the diverter angle and an output variable, average heat flux. Experiments have been carried out using a Mach-Zehnder interferometer. The effects of Rayleigh number and the diverter angle on free convection heat transfer in a horizontal cavity were studied. It was observed that, at each Rayleigh number, maximum and minimum heat transfer occurs at the diverter angle of 30^o and 90^o, respectively. Another main result of this study is that ANFIS is a reliable method for the prediction of results due to its high accuracy and can be used to model the experiments precisely.

Nomenclature

e	Thickness of each diverter(mm)
g	gravitational acceleration (m/s^2)
$\overline{h}$	Average heat transfer coefficient (W / m^2 .K)
h_x	Local heat transfer coefficient (W / m^2 .K)
H	Length of the cavity (mm)
L	Length of each diverter (mm)
$\overline{Nu}$	Average Nusselt number
Nu_x	Local Nusselt number
p	Pitch of diverters(mm)
q''	Average heat flux (W/m^2)
Ra	Rayleigh number based on the cavity side length
T	Temperature (K)
W	Cavity side length (mm)
x	Direction normal to the hot surface
y	Direction along the hot surface
Greek symbols	
θ	Diverter angle

Subscripts

Sc	Cold condition
Sh	Warm condition
∞	Ambient condition

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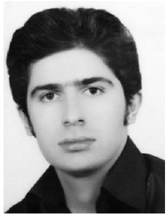

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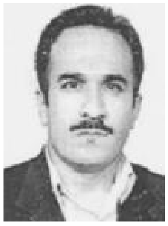

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