A STUDY ON HEAT TRANSFER CHARACTERISTICS OF FIBONACCI SPIRAL MICROCHANNEL HEAT SINK

Cheng-Hsing Hsu[1], Jui-Chin Jiang[2], Hung-Son Dang[1], Thi-Anh-Tuyet Nguyen[2] and Ching-Chuan Chang[3]
[1] Department of Mechanical Engineering, [2] Department of Industrials & Systems Engineering,
[3] Department of Mechanical Engineering
[1, 2] Chung Yuan Christian University, 200, Zhongbei, Chungli, 32023 Taiwan, ROC
[3] Army Academy R.O.C., Taoyuan, 32023 Taiwan, ROC

ABSTRACT

A study on a Fibonacci spiral microchannel heat sink was carried out in the present work to predict thermal resistance and pressure drop of the model. The Computational Fluid Dynamics software (ANSYS Fluent 14) and Taguchi method were used to simulate and optimize the parameters of the Fibonacci spiral microchannel heat sinks. In addition, the Minitab 17 software was also used to analyze the simulated data. The result shows that the optimal design parameters can give good agreement of the overall thermal resistance and pressure drop (with the values $0.715K/Wm^2$, $15.53kPa$, respectively.) were achieved for the design of the Fibonacci spiral micro-channel heat sink.

Keywords: Spiral channel, Microchannel heat sink, Taguchi method, Fibonacci sequence and Golden ratio.

I. INTRODUCTION

To adapt to the customer requirements and electronic industrial demands of the heat transfer performance for semiconductor devices, the idea of reducing thermal resistance simplifies the selection of heat sinks. But due to the strategic development of electronic components and electric devices (e.g. tablets and smartphones) with smaller dimensions, higher power dissipation and faster processing, smaller and enhanced heat transfer devices, such as Microchannel Heat Sinks (MCHS), have become a priority which requires engineers to work diligently to meet customer demands. This also means that the heat transfer devices need to dissipate more heat in order to keep the electronic components or electric devices working properly. Different programs/methodologies were not only applied successfully but also contributed to the problem of quality enhancement for the MCHS.

Tuckerman and Pease [1] were the first to research micro-channel heat sink applications. Their work was designed to evaluate the performance of force liquid flows in MCHS and the results revealed that the minimum thermal resistance per unit area $R_T(0.1Km^2/W)$ was obtained. After the first investigation of MCHS by Tuckerman and Pease, more than a thousand papers have been reported about the investigations of various configurations of MCHS by using many different theoretical and experimental methods. Knight et al. [2] investigated the performance of the force fluid flow through a MCHS, and their results show that the thermal resistance per unit area R_T could be improved up to 35%. Hung et al. [3-5-6] optimized the design parameters of a double-layer MCHS to minimize the thermal resistance per unit area R_T, and their work achieved the best result, with regard to thermal resistance per unit area R_T and pressure drop ΔP, which improved 6.3% and 4%, respectively. Lin et al. [4] also studied the distribution of the flow rates in a double-layer MCHS. The results show that the values of thermal resistance per unit area R_T were obtained at $0.131, 0.089, 0.102$ (Km^2/W) with channel numbers $N = 69, N = 81, N = 111$, respectively. Wu et al. [7] made a parametric study on the performance of a double-layer MCHS and the results showed that the inlet velocity V_{in} affected outcomes of the thermal resistance per unit area R_T and pressure drop ΔP. Kumar et al. [8] investigated on the thermo-cycler function in various micro-chips with a MCHS. Their conclusion showed that with different materials of the MCHS, different thermo-cycler functions were established on the micro-chips. Hung et al. [9] made a numerical optimization of the thermal performance of a porous MCHS and obtained $R_T = 0.070Km^2/W$ with channel numbers $N = 108$.

Sharma et al. [10-11] investigated the effects of a channel of a trapezoidal cross section with liquid Gallium and water to a double-layer MCHS, and Xie et al. [12] made a study on a wavy MCHS. Their results showed that for removing an identical heat load, the overall thermal resistance of the single-layer wavy MCHS decrease with increasing volumetric flow rate, but the pressure drop is increased greatly. At the same flow rate, the double-layer MCHS can reduce not only pressure drop but also the overall thermal resistance compared to the single-layer wavy MCHS. Alfaryjat et al. [13] investigated the influence of geometrical shapes of the channel of the MCHS, and the results showed that different geometrical forms affected R_T of MCHS. Wong and Muezzin [14] studied heat transfer of the parallel flow in a two-layer MCHS, and the results showed that a smaller thermal resistance R_T can be achieved. Leng et al. [15] improved the design of a double-layer MCHS with truncated top channels and the results show that there exists an optimal truncation position for the top channel to achieve the best double-layer MCHS performance.

Nowadays, with the development of technologies, MCHS not only used in the industry of electronic and electrical engineering but also used in other fields, such as Chemical and Biological applications. In biological industry, many micro-channel devices have been studied extensively for different applications, and the spiral microchannel device is the most interested one. Martel and Toner [16] conducted research on the spiral microchannel device. They focused on the dynamics and the characteristics of the particle motions in the low aspect ratio channel. The results showed that the primary and secondary streak was observed in the lowest aspect ratio channels at high average downstream velocities. Jimenez et al. [17] investigated the efficient separation of microparticles in a spiral channel by using a high flow-rate inlet. Bhagat et al. [18] studied spiral microchannels by using dean flows and differential migration. The results showed the strong effect of dean flows on the microfluidic devices. Santana et al. [19] studied numerically mixing reactions of Jatropha curcas oil and ethanol for producing biodiesel by using a spiral-micro-mixer. The results showed that the highest conversion of vegetable oil to biodiesel was obtained with the T-micro-mixer and the spiral-micro-mixer. Wang et al. [20] used a microchip with double spiral microchannels to study a new micro-flow injection chemiluminescence system. The results proved that the new system had the advantages of high sensitivity and precision. MacInnes et al. [21] demonstrated experimentally by using a rotating spiral microchannel to produce multistage distillations. The prototype design of this device obtained the results can demonstrate the practical feasibility of a rotating spiral contacting and providing initial quantitative data used to evaluate the performance achieved by the device. Hasabnis [22] initially focus on applying a spiral channel in bio-cells, and the results obtained showed the relationships among critical geometrical parameters, i.e. width, cross-section, curvature, etc. Amin [23] investigated a differential format spiral microchannel with variable channel width. Chung et al. [24] carried out an investigation of a continuous-flow polymerase chain in a spiral microchannel with varying width. Peng and Li [25] designed a spiral microchannel in order to create a multi-sample-multi-probe DNA microarray on a circular disk, and a constant flow velocity was employed to analyze the fluid advance in the channel. Guan et al. [26] studied three-dimensional spiral channels and focused on the particle streams along the depth and the width of the cross-section of the channel. Their results showed that the particles concentrated near the top and bottom of the channel. Based on the results, we can understand more about the balance of the force in spiral channels.

After the review of the papers mentioned above, it reveals two aspects. First, an optimal micro-channel can be found by the changing of the geometric dimensions, and the second is the analysis and design algorithms. With the changing of dimensions of the MCHS, the geometry of the channel was changed from a macro-channel to a mini-channel and now toward a microchannel. Some researchers introduced a way to achieve higher heat dissipation by increasing the thermal conductivity of the fluid used in the channel with the suspension of nanoparticles Sharma et al. [10-11], which has higher thermal conductivity than the fluid. Others chose different microchannel geometries as well as materials and higher thermal conductivity working fluid coolants, which led to a significant effect on the heat dissipation performance Knight et al. [2], Hung et al. [3-5-6]. Besides that, with the changing of the algorithm, scientists used a lot of mathematic algorithms to investigate many physical characteristics of the microchannel in order to obtain the optimal heat transfer result. The flow and heat transfer in micro-channels have become a subject of growing research attention since the early 1990s. It is clear that a successful design of the microchannel based heat sink requires a fundamental understanding of the transport processes occurring on the micro scale.

One disadvantage of the MCHS is the relatively high and non-uniform temperature distribution along the channel as compared to that of other heat sinks. This high and non-uniform temperature distribution produces thermal stresses in IC chips or packages and then reduces the electrical performance via electrical-thermal instability and thermal breakdown, etc. One way to reduce variations in non-uniform temperature distribution is to allow more coolant to flow through the channels, but this means pressure drop will increase. By redesigning the double layer channels for a specific geometry dimension, we can achieve more coolant flow through the channel with a reasonable pressure drop. But there are still many drawbacks for the double-layer microchannel, such as more expensive for manufacturing, and higher power supply requirement. Beside the straight channel, multi-layer MCHS, and double-layer MCHS, curved channels have received less attention as research subjects. However, the spiral microchannel phenomena have been studied in a variation of designs in the fields of biology, biochemistry, separation bacteria, blood, and bio-energy, but still fewer studies on the applications of curved channels and spiral channels have been conducted in the field of heat transfer.

The purpose of the present study is to employ the Fibonacci sequence in the design of microchannel heat sink parameters and to investigate thermal characteristics on a spiral microchannel heat sink in light of the recent advances in the micro-fabrication techniques. This investigation will find the optimal factors and new dimensions of new geometry for the designed models and ensures a success of heat transfer performance under a high-pressure operation condition and a stronger heat source. Therefore, the optimal dimensions of the spiral microchannel heat sink are utilized to obtain the smallest thermal resistance as the effects on the working conditions of the channel.

NOMENCLATURE

q_w	W/cm2	*Uniform heat flux*
N		*Number of channels*
U_{in}	m/s	*Inlet velocity*
d_1	mm	*Outer substrate thickness*
d_2	mm	*Inner substrate thickness*
H_{C1}	mm	*Outer channel height*
H_{C2}	mm	*Inner channel height*
W_{C1}	mm	*Inner channel width*
T	[K]	*Temperature*
L_X	[m]	*Cartesian axis direction*
L_Y	[m]	*Cartesian axis direction*
L_Z	[m]	*Cartesian axis direction*

Special characters

σ^2	*[]*	*Variance*
β_x	*[]*	*Predict variable for model I*
β'_x	*[]*	*Predict variable for model II*
α		*Level of significant*

Subscripts

t^*	*T value*
R^2	*Coefficient of multiple correlations*

II. FIBONACCI SEQUENCE AND FIBONACCI SPIRAL

2.1 The Fibonacci sequence

The Fibonacci numbers are the numbers in the following integer sequence, which is called the Fibonacci sequence. Every number in the sequence is formed by the sum of two preceding ones and is named after the Italian mathematician Leonardo of Pisa, known as Fibonacci. The sequence F_n of Fibonacci number was defined by the recurrence in relation to mathematical terms:

$$F_n = F_{n-1} + F_{n-2} \tag{1}$$

With the seed values:

$$F_1 = 1, F_2 = 1 \; or \; F_0 = 0, F_1 = 1$$

2.2 The Fibonacci spiral

By drawing circular arcs and connect the opposite corners of the squares in the Fibonacci sequence use, referred to Eq. 1, we can create the Fibonacci spiral which approximates with the golden ratio and is shown in figure 1 with values $1,1,2,3,5,8,13,21,\ldots(mm)$.

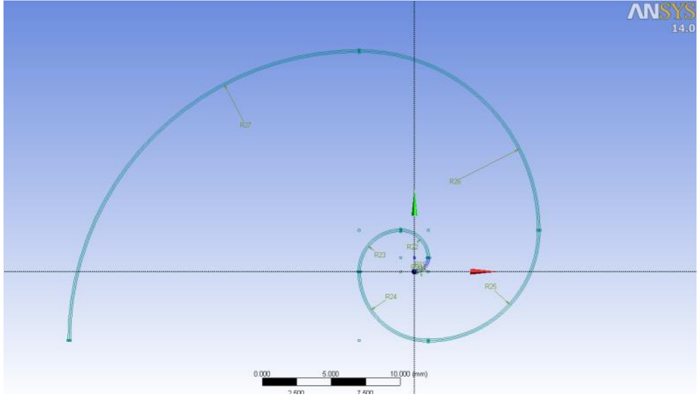

Fig. 1 The spiral microchannel heat sink

III. QUALITY FUNCTION DEPLOYMENT AND THE CONCEPTUAL FRAMEWORK

In the measured phase, the main requirements were performed in the Quality Function Deployment process (QFD) to translate the Voice of Customers (VOCs) into engineering requirements. The key design factors and critical parameters were identified to ensure that the designed product satisfies the requirements of customers. QFD helps design engineers reduce development time. Functional requirements involved in the procedures that must be performed in a design ensure that the product or process satisfies the customer requirements. Each functional requirement has a specific design metric that must be met. The design metrics were tested in each prototype design to ensure that the product met or exceeded customer. All features were an assigned level of the relationship against the design characteristics.

Based on the reviewed literature, the descriptive research model was investigated in this study and the conceptual framework of the study was proposed as below.

Hypothesis Model I: H_x (the variables: x) is significant and positively related to thermal resistance (R_T).Where $E\{YR_i\}$ are the values of the response variables in the i^{th} trial for the Model, $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7$, are parameters for Model. The variables $x = (A_i, B_i, C_i, D_i, E_i, F_i, G_i, H_i)$ are known to be constants, namely, the value of the predictor variables in the i^{th} trial for Model. The random error terms e_i are with the means of $E\{Ye_i\} = 0$ and variances $\sigma^2\{e_i\} = \sigma^2, i = 1,2,3,\ldots,27$.

IV. THE FIBONACCI SPIRAL MICRO-CHANNEL HEAT SINK DESIGN

In the present study, the design structure of the new model, named the Fibonacci spiral microchannel heat sink, was selected, as shown in figure 2. The dimensions and geometry configuration of the Fibonacci spiral microchannel heat sink with a rectangular cross-section are designed.

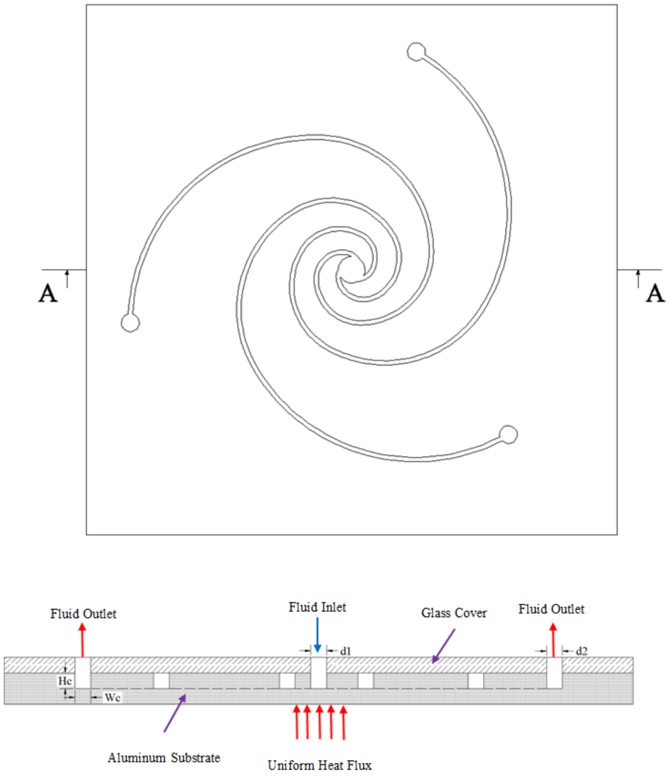

Fig. 2 The cut view sketch of Fibonacci spiral channel design (A-A section)

All the channels in a given layer are assumed to have the same boundary conditions. The bottom wall which contacts with the chipset is heated with a completely uniform heat flux (q_w).

The Taguchi method is employed to identify the effects of different parameters of the present Fibonacci spiral microchannel heat sink on thermal resistance to establish the initial factors. The levels and dimensions of each factor are selected and listed in table 1. The noise factors, the uniform heat flux, and inlet temperature are created by the random distribution sequence (Matlab). For this reason, L_{27} is suitable for the study. L_{27} is chosen for investigation and five repetitions are run for response variables (thermal resistance) There are 134 degrees of freedom and eight design parameter factors. In the present study, the optimal level of the process parameters is the level with the smaller mean values is better. In addition to the factor analysis, the correlation and the regression analysis relative to the model framework tests are performed to analyze data. The three dimensional of heat transfer were obtained from the simulation results (ANSYS FLUENT 14.0 software package).

Minitab 17 software is used for factor analysis, correlation analysis, and regression analysis.

V. RESULTS AND DISCUSSION

The computational Fluid Dynamics (CFD) software (ANSYS 14) was used to predict the heat transfer, and related phenomena of the Fibonacci spiral microchannel heat sink by solving the governing equations. Numerical data were analyzed based on the Taguchi method to figure out the most significant factor and the optimal combination value of the model. The simulation results for thermal resistance were then analyzed by Minitab 17 Software and the factor analysis, correlation analysis and hierarchical regression analysis related to framework tests were also conducted and analyzed.

5.1. Correlation Matrix Analysis

Based on the results from Minitab output, the correlations between predictor variables and response variables for each model have been obtained. The correlation between predictor variables and response variables for the model and factor D has a strongest negative correlation with a thermal resistance ($r = -0.936$), which indicating an increase in factor D will lead to a decrease in thermal resistance.

5.2 The interaction effect of predictor variables

Following the analysis mentioned before, a multiple regression analysis was performed to find the factors that affect response variables, as well as the interaction between predictor variables. The t^* (T-Value) the test is performed to present the interaction effects at a level significant ($\alpha = 0.5$):

$H_0: \beta_i = 0$, there is no interaction between predictor variables.

$H_a: \beta_i \neq 0$, there are interactions between predictor variables.

From the Minitab outputs, the results show the absolute of t^* values for the combination of two factors A^*B for thermal resistance. In the same way, with all factors, the results of the absolute of t^* values for each combination of any two factors for thermal resistance. For the level of significance,($\alpha = 0.5$) we require:

$$t\left(\frac{1-\alpha}{2}; d_f \text{ of error}\right) = 2.776$$

Since:

$|t^*| \leq 2.776$, we may conclude $H_0, \beta_i = 0$.

$|t^*| \geq 2.776$, we may conclude $H_a, \beta_i \neq 0$.

For model: There are four interactions between each factor A^*B, A^*C, B^*C and F^*G. The relationship of interactions factors for Model I are described in figure 3. We can identify the interaction values of each factor from the interaction plot. The values can provide engineers with more details for each factor, which can then be used for the design of the model to adapt to the requirement of the thermal resistance.

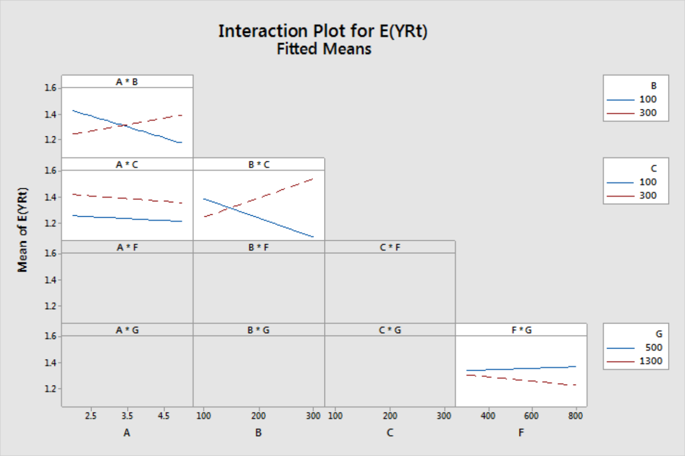

Fig. 3 Interaction plots for Model I ($E(YRt)$)

5.3 Regression Analysis

Table 2 show the F-Value and P-Value, which can be used to analyze the affection between predictor variables and response variables, and a value of 0.05 is chosen to indicate a significant affection for each model. Based on F-Value and P-Value of each predictor variable (factor), we can conclude.

For model: Factors A and D have a significant effect on thermal resistance ($P - \text{Value} = 0.037$ and $0.000 \leq 0.05$, respectively). Factors B, C, E, F, G, and H have no significant effect on thermal resistance ($P - \text{Value} = 0.994, 0.359, 0.657, 0.765, 0.240$ and $0.951 \geq 0.05$, respectively). In other words, we conclude H_A, H_D, and reject $H_B, H_C, H_E, H_F, H_G, H_H$.

In addition, the average performance effects of each factor of thermal resistance plot are also obtained for a visual inspection as given in figure 4. The results show that:

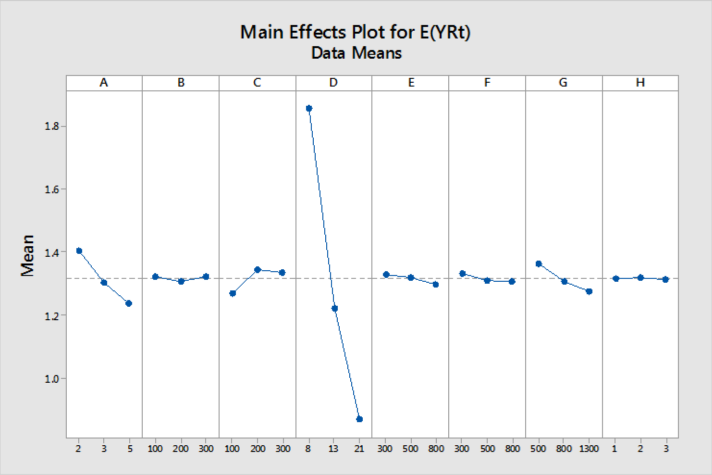

Fig. 4 Main effects plot for Model I ($E(YRt)$)

For model: The optimal combination factor of thermal resistance is A3B2C1D3E3F3G3H3 ($N = 5$ (A3), $H_C = 0.2$ (mm) (B2), $W_C = 0.1$ (mm) (C1), $U = 21$ (ml/min) (D3), $d_1 = 0.8$ (mm) (E3), $d_2 = 0.8$ (mm) (F3), $\delta_s = 1.3$ (mm) (G3), and H3 (Circle)).

5.4 Validation

The Computational Fluid Dynamics software (CFD) (ANSYS 14) was separately conducted again to predict the thermal resistance optimal combinations had been achieved above (A3B2C1D3E3F3G3H3). The results indicate that thermal resistance is $0.715(\mathrm{K}/\mathrm{W}m^2)$ which is shown in figure 5.

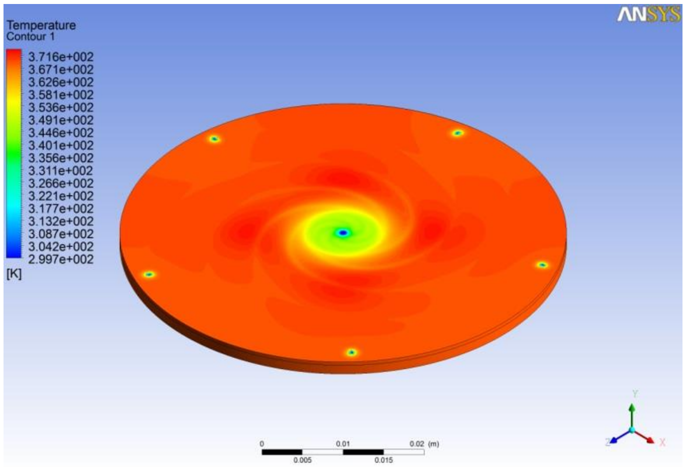

Fig. 5 Contour plot for Model ($E(YRt)$)

VI. CONCLUSIONS

The computational Fluid Dynamics software (CFD) (ANSYS 14) and Taguchi method were conducted to predict thermal resistance of the design of a Fibonacci spiral microchannel heat sink, and the results indicated the most valuable combination factors. The optimal combination of overall thermal resistance is A3B2C1D3E3F3G3H3 with the value equal to $0.715(\mathrm{K}/\mathrm{W}m^2)$. There are four interactions $\mathrm{A}^*\mathrm{B}, \mathrm{A}^*\mathrm{C}, \mathrm{B}^*\mathrm{C}$ and $\mathrm{F}^*\mathrm{G}$, and factors A and D have the most significant effect on thermal resistance.

FUTURE RESEARCH

In the present study, there are still limitations in simulation due to the ideal model used in computations. Experimentally collected data, which are better to use in performing the optimization algorithm, are highly recommended in the future works. Future research, by carefully utilizing and expanding new techniques or ideas, can enhance the design processes even more efficient and effective, which a greater improvement in design quality, less time consumption as well as the additional innovations will be enlightened by performing experiments. Consequently, it will lead to better stability and reliability of the product and manufacturing processes.

Besides that, some interesting phenomena of the temperature distribution of spiral microchannel heat sink under higher inlet velocity and higher heat flux has been reported by some other researchers. So, in Fibonacci spiral microchannel heat sinks, there may also promise to generate more interesting results in the future studies.

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Table 1 Parameters and values levels

Parameters Factors	**Levels**		
	1	2	3
A: Number of channels N	2	3	5
B: The channel height H_C	0.1	0.2	0.3
C: The channel width W_C	0.1	0.2	0.3
D: Inlet flow rate U	8	13	21
E: The inlet dimension d_1	0.3	0.5	0.8
F: The outlet dimension d_2	0.3	0.5	0.8
G: The substrate thickness δ_s	0.5	0.8	1.3
H: The geometry of model	1(Rec)	2(Hex)	3(Circle)

Table 2 Analysis of variance for Model I ($E(YRt)$)

Source	**DF**	**SS**	**MS**	**F-Value**	**P-Value**
Regression	8	4.26400	0.53300	23.63	0.000
A	1	0.11437	0.11437	5.07	0.037
B	1	0.00000	0.00000	0.00	0.994
C	1	0.02002	0.02002	0.89	0.359
D	1	4.08946	4.08946	181.28	0.000
E	1	0.00461	0.00461	0.20	0.657
F	1	0.00209	0.00209	0.09	0.765
G	1	0.03336	0.03336	1.48	0.240
H	1	0.00009	0.00009	0.00	0.951
Error	18	0.40593	0.02256		
Total	26	4.67005			