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Study the Effect of the Flow on the Performance of a shell and Tube Type Heat Exchanger Using Experimental Design Technique

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Abstract

In the current research an experimental study was done to show the effect of pulse flow on the effectiveness of shell and tube type heat exchanger. the study was in the case of steady and pulse flows with a changing mass flow rate of hot water flowing inside the pipes of the heat exchanger for the range between (0.0273-0.0819 kg / s) at fix mass flow rate of cold water that flows through the shell and on the outer surface of the pipes when (0.0416 kg / s), to obtain pulsing a used was solenoid valve. The research aims to measure the percentage effect of independent factors which were presenting the mass flow rate of hot water, flow type and the surrounding environment conditions of the experimental side upon shell and tube type heat exchanger performance using experimental design technique at the significant level (0.05).The results derived from the experimental tests showed that pulse flow leads to increase internal heat transfer coefficient (hi) comparing with its value in the steady flow and the highest increase was by (9.75%) at a mass flow rate of hot water (0.0416 kg / s) and increases the overall heat transfer coefficient (U), where the highest percentage was by (4.68%) at a mass flow rate of hot water (0.0416kg/s). The results also showed increasing both the number of transmitted units (NTU) and the effectiveness of the shell and tube type heat exchanger (ε) in the case of pulse flow of its value in the steady flow and the highest percentage of increase occurring was (4.75%) and (1.85%), respectively, and at the mass flow rate of hot water (0.0416 kg / s). Percentage effect of mass flow rate of hot water was (97%, 97.42%, 95.5%, 99.48%) and the percentage effect of each flow type and the errors were (2.8%, 2.25%, 2.44%, 0.4%) and (0. 2, 0.33%, 2.06%, 0.12) respectively.

Keywords: Heat exchanger, Effectiveness, Design of experiments.

دراسة تأثير الجريان على أداء مبادل حراري نوع غلاف وأنبوب باستعمال تقنية تصميم التجارب

الخلاصة

تم خلال البحث الحالي إجراء دراسة عملية لبيان تأثير نبضية الجريان على فعالية مبادل حراري نوع غلاف وأنبوب (shell and tube heat exchanger) حيث تم إجراء الدراسة العملية في حالة الجريان المستقر والجريان النبضي مع تغيير معدل التدفق الكتلي للماء الساخن الذي يجري داخل أنابيب المبادل الحراري وكانت تتراوح قيمه بين (0.0273-0.0819 kg/s) مع ثبوت معدل التدفق الكتلي للماء البارد الذي يجري خلال الغلاف وعلى السطح الخارجي للأنابيب عند (0.0416 kg/s)، وللحصول على النبضي تم استخدام صمام لولبي (solenoid valve). يهدف البحث إلى قياس نسبة تأثير العوامل المستقلة والمتمثلة بالتدفق الكتلي للماء الساخن، الجريان والظروف المحيطة بالجانب العملي على أداء مبادل حراري نوع غلاف وأنبوب باستعمال تقنية تصميم التجارب عند مستوى معنوية (0.05). بينت النتائج المستحصلة من التجارب العملية إن الجريان النبضي يؤدي إلى زيادة معامل انتقال الحرارة الداخلي (hi) عن قيمته في الجريان المستقر وان أعلى زيادة كانت بنسبة

(9.75%) وعند معدل تدفق كتلي للماء الساخن (0.0416 kg/s) وزيادة معامل انتقال الحرارة الإجمالي (U) وكانت أعلى نسبة مئوية للزيادة هي (4.68%) وعند معدل تدفق كتلي للماء الساخن (0.0416 kg/s). كما أظهرت النتائج المستحصلة زيادة كلا من عدد الوحدات المنتقلة (NTU) وفعالية المبادل الحراري نوع غلاف وأنبوب (ε) في حالة الجريان النبضي عن قيمته في الجريان المستقر وكانت أعلى نسبة مئوية للزيادة الحاصلة هي (4.75%) و (1.85%) على التوالي وعند معدل تدفق الكتلي للماء الساخن (0.0416 kg/s). نسبة تأثير التدفق الكتلي للماء الساخن على الخواص قيد البحث كانت (, 95.5% 99.48%, 97.42%, 97%) ونسبة تأثير كل من الجريان والظروف المحيطة كانت (0.4%, 2.44%, 2.25%, 2.8%) ، (0.12, 2.06%, 0.33%, 0.2%) على التوالي.

الكلمات الدالة: مبادل حراري، فعالية، تصميم التجارب.

Introduction

Heat exchangers are devices that facilitate heat transfer between two fluids having different temperatures with prevention of mixing with each other. Heat exchangers are used in many applications as heating and air conditioning systems in homes and in the chemical processes and energy production in large number of factories [1].

In the design of experiments, a single experiment or a sequence of experiments is performed to test and quantify the effects of one or more input variables on one or more output variables of a process or a product. The design of experiments may be used to help improve the capability of a process by identifying the process and product variables that affect the mean and the variance of quality characteristic of the product[2].

West and Taylor (1952)[3] studied Effect of pulse flow of water on the heat transfer coefficient within the Reynolds numbers (30,000 to 85,000) in a double tube heat exchanger tube and two (water - water) and (steam- Water) researchers have used pulsed air to get impulsive movement and within different frequencies, their findings explained that heat transfer coefficient of the pulse flow increasingly limited (60 - 70%) for a value in steady state at frequency (0.25 c.p.s).

Stevanovic., et al. (2001)[4] conducted a numerical study of the flow of turbulent fluid and heat transfer in the heat exchanger type shell and tube using (CFD) have been finding the distribution of speed and temperature in addition to calculating the rate of total heat transfer, researchers found that the optimal distribution of the flow is considered an essential step in the design of the heat exchanger as it leads to higher rate of heat transfer.

EL-Fawal (2011) [5] suggested a model optimized for the design heat exchanger type shell and tube by conducting an analytical study using a computer program. This researcher compared the suggested model with the used method by other researchers and found it more effective.

Legay, et al., (2012) [6] conducted a practical study to verify the performance of heat exchanger double tube without the impact of vibrations ultrasound, as researchers compared with obtained results previously of the heat exchanger shell and tube as the system composed of two straight tubes with Challenger Center and an external adapter has been linked to ultrasound greatest tube for the vibration when 35 KHz with using water as working fluid. Researchers found that the coefficient of increasing which is the ratio between the total heat transfer coefficient without ultrasound is 1.5 and 2.3 and slightly more for heat exchanger tube and shell.

Jang, et al., (2012) [7] conducted numerical analysis to predict the characteristics of difference in temperature and pressure drop, which are the performances of channel heat exchanger. In this study, the diameter of tube, the number of tubes and the number of baffles are considered as the design factors. Also, factors that affect the performances of channel heat exchanger were selected through design of experiment procedures, where the used symbols in mathematical equations can be summarized as shown in the Table (1).

Theoretical calculations

Heat transfer Coefficient for the flow inside the pipes was calculated by using the following relationship [8].

$$Nu = \frac{(h_i * D_i)}{k_w} = 0.023 * Re_d{}^{0.8} * Pr^n \quad \cdots (1)$$

At the following conditions: -

0.6< Pr < 100

2500< Re <1.25x105
Where:

N=0.4 …….(Heating)

N=0.3 …….(Cooling)

Table 1. Definitions of used symbols in mathematical equations [7]

Symbols	Definitions of used symbols	units
A	Surface area	m^2
Cp	Specific heat capacity	KJ/Kg. °C
D	Diameter	m
H	Heat transfer coefficient	W/m^2. °C
K	Thermal conductivity	W/m. °C
$\mathring{m}$	Mass flow rate	Kg/s
NTU	Number of units transmitted	—
Nu	Nusselt number	—
Pr	Brandtl number	—
Re	Reynolds number	—
U	Total heat transfer coefficient	W/m^2. °C
Greek symbols		
ε	Effectiveness of the heat exchanger	—
Lower symbols		
D	Inside pipes	—
i	Interior	—
o	Exterior	—
S	Surface	—
W	Water	—

As external heat transfer coefficient can be calculated by using the following relationship[9].

$$Nu = \frac{h_o * D_o}{k_w} = 0.683 * Re^{0.466} * Pr^{1/3} \text{ …. } (2)$$

The relationship above used at Reynolds numbers (Re) (40-4000).

Overall Heat Transfer Coefficient was calculated by using the following relationship [10].

$$U_o = \frac{1}{\frac{1}{h_o} + \frac{r_o}{k}\ln(\frac{r_o}{r_i}) + (\frac{r_o}{r_i})\frac{1}{hi}} \text{ ………. } (3)$$

The effectiveness of the heat exchanger type (shell and tube) and used in the practical experiments has been calculated by using the following relationship [11].

$$\varepsilon = 2\left[1 + C + \sqrt{1 + C^2}\,\frac{1 + exp\left(-NTU\sqrt{1 + C^2}\right)}{1 - exp\left(-NTU\sqrt{1 + C^2}\right)}\right]^{-1} \quad (4)$$

Where:

$$NTU = \frac{UA}{\mathring{m}\,cp_{min}}$$

$$C = \frac{\mathring{m}\,cp_{min}}{\mathring{m}\,cp_{max}}$$

Two – Factor Experiments

In a two – factor experiment, the factors are usually denoted by A (mass flow rate), B (flow type) and noise of variables (Error). Let the number of levels of factor A be a, and the number of levels of factor B be b. Then, there is a total of (a × b) combinations in a full factorial design. If there are n replications, then there is a total of (n × a × b) observations .Simpler formulas for computing the sums of squares of factors are given below [12].

$$SST = \sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{n} y_{ijk}^2 - \frac{y^2}{abn} \text{ ………………..…..(5)}$$

$$SSA = \frac{\sum_{i=1}^{a} y_i^2}{bn} - \frac{y^2}{abn} \text{ …………..……..(6)}$$

$$SSB = \frac{\sum_{j}^{b} y_j^2}{an} - \frac{y^2}{abn} \text{ ………..……………..(7)}$$

$$SSE = SST - (SSA + SSB) \text{ …………………...(8)}$$

The degrees of freedom, mean squares and test statistics are summarized in Table (2).

Table 2. F Distribution: 5 percent Points [13]

v_1 \ v_2	1	2	3	4	5
1	161.45	199.50	215.71	224.58	230.16
2	18.513	19.00	9.2766	19.247	19.296
3	10.128	9.5521	6.5914	9.1172	9.0135
4	7.7086	6.9443	6.5914	6.3883	6.2560
5	6.6079	5.7861	5.4095	5.1922	5.0503

Percentage Contribution of Factors and Error

The following formulas are used for computing the approximate percentage contribution of each factor (main factor or interaction) to the variability of the response variable [13].

% contribution of A , B

$$= \frac{MSU - MSE}{SST} \times DF \times 100 \quad \cdots\cdots\cdots (9)$$

% contribution of error
= 100-(sum% A and % B factors)……….. (10)

Experimental Side Used Device

Practical experiments were done on the heat exchanger type (shell and tube) as shown in Figure (1).

solenoid valve	5	Tank of hot water	1
Heat exchanger	6	Water pump	2
Tank of cold water	7	Electric heater	3
Thermocouple	8	Flow measurement	4

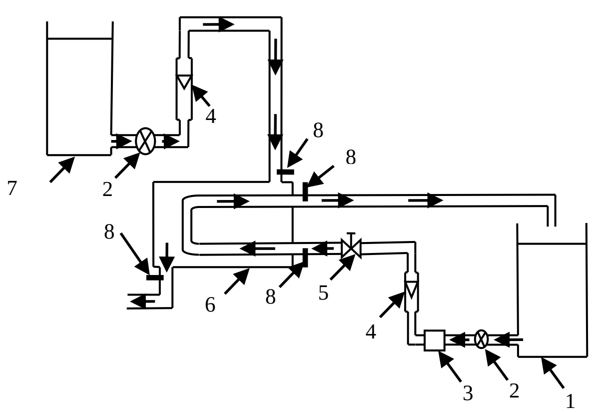

Fig. 1. Diagram of the used device in the search

Heat exchanger used contains two passages of the tubes internal diameter 12.7mm with thickness 1mm and one cylindrical shell where hot water flows inside the pipes while cold water flows through shell upon outer surface of pipes, the pulse flow of hot water obtained by using of solenoid valve, which opens and closes hot water inside to stream pipes by equal times and these times are controlled by using electronic Timer.

Flow Measurement

To measure the temperature of points that shown in Figure (1) was used thermocouples type (T) and connecting all thermocouples connected with digital thermometer.

Temperature Measurement

To measure the flow of water was used rotor rotameter, which is a listed glass tube containing a float with range (0-300 L \ hr) and controlled of the flow rate through the valve (Valve).

Testing Procedure Steps

Practical experiments were conducted on type heat exchanger (shell and tube) as follows:

1. Water supplied to the heat exchanger and flowed within and across exchanger tubes, using two centrifugal pumps by two water reservoirs.
2. Water Heater supplied with Electricity to raise the temperature of water that flowed inside heat exchanger tubes 60 ºC.
3. After a period of time until the arrival of the flow to the steady state, Practical readings was taking and different flow rates for hot water (100 -300 L/hr)**.**
4. Solenoid valve was linked to obtain pulse flow of hot water, which opened and closed during a certain time 2 sec. And solenoid valve linking electronic timer.
5. After a period of time and after reaching steady state was recording practical readings to pulse flow.

Results and Discussion

In this research an experimental work was done to show the effect of pulse flow on the effectiveness of a shell and tube type heat exchanger. Figure (2) show the effect of pulse flow on internal heat transfer coefficient at different rates of total flow of hot water where the figure showed increasing the internal heat transfer coefficient with increasing total flow rate of hot water, to the rate of heat transfer was increased due to the fluid momentum, as shown in the figure heat transfer coefficient of internal state pulse flow pulse was higher than its value in the steady flow state due to increase the turbulence in the flow, where the highest percentage of increasing was 9.75% and at the mass flow rate of hot water 0.041kg/s.

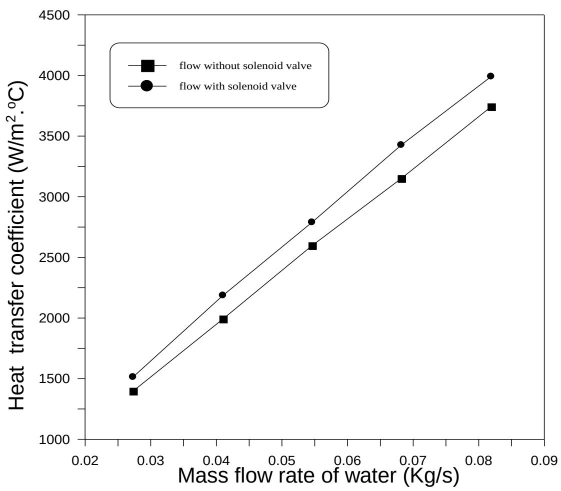

Fig. 2. The effect of pulse flow on the internal heat transfer coefficient at different rates for the mass flow of water inside the tube

As Figure (3) had shown the effect of pulse flow on total heat transfer coefficient at different rates of mass flow rate of hot water the figure showed increasing total heat transfer coefficient with increasing the rate of mass flow rate of water, increasing the total heat transfer coefficient in pulse flow from its value in the steady flow because of increasing the level of turbulence in the water flow and the highest percentage was 4.68% at the mass flow rate of hot water 0.041kg/s.

Figure (4) had shown the effect of pulse flow on the number of transmitted units where the figure showed increasing the number of transmitted units in pulse flow from its value in the steady state due to increase turbulence in the flow of hot water inside pipes of heat exchanger and the highest percentage of increase was 4.75 at the mass flow rate of hot water 0.041kg/s.

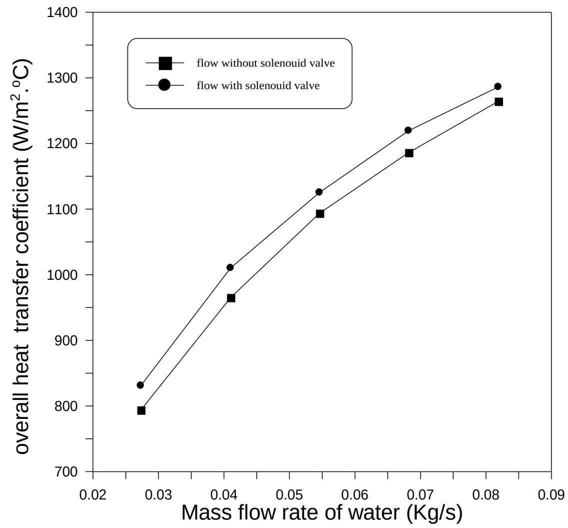

Fig. 3. The effect of pulse flow on total heat transfer coefficient at different rates for the mass flow of water inside the tube

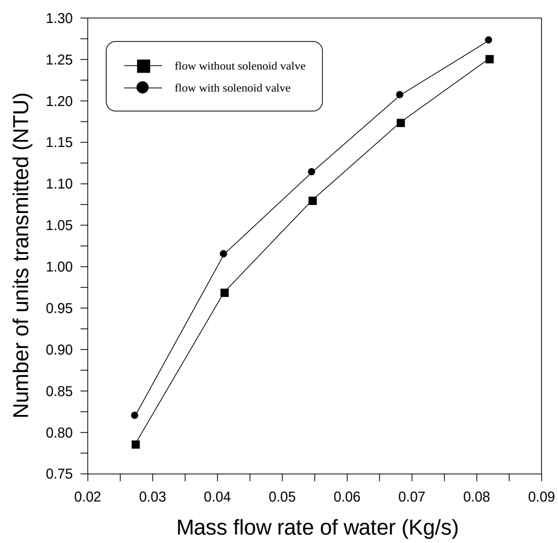

Fig. 4. The effect of pulse flow on the number of transmitted units at different rates for the mass flow of water inside the tube

Figure (5) showed increasing the effectiveness of the used heat exchanger in the experiments (shell and tube heat exchanger) for the case of pulse flow from its value in the steady flow due to increase turbulence in the flow of hot water inside exchanger pipes and the highest percentage of increasing was 1.85% at the mass flow rate of hot water 0.041kg/s.

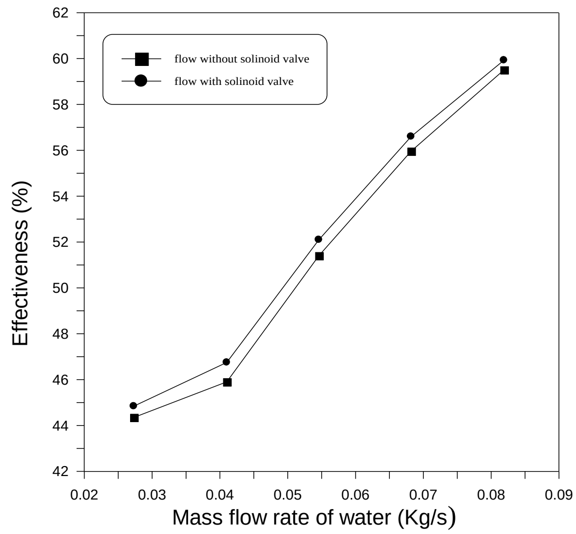

Fig. 5. The effect of Pulse flow on the effectiveness of heat exchanger at different rates for the mass flow of water inside the tube

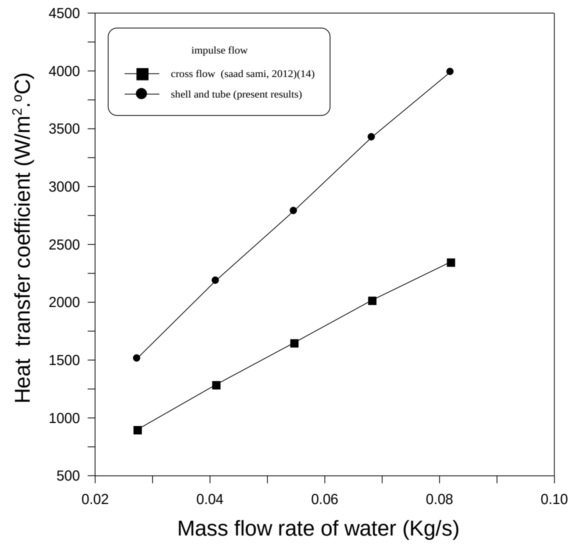

Fig. 6. Comprision between shell and Tube heat exchanger with cross flow heat exchanger experimental data [14]

The present experimental results were compared the internal heat transfer coefficient for the used heat exchanger type shell and tube with the researcher [14], who used fin tube cross flow heat exchanger as shown in Figure (6), for the same operating conditions which were water temperature entering the exchanger 60 °C and time of opening and closing the valve pulse 2 sec. It was noted that the highest percentage increasing in the values of internal heat transfer coefficient in the present work was 70.1% at (m^o=0.0819 kg/s) compared with the researcher, due to the difference in the quality of the fluid used to cool the heat exchanger, where we used the water was used in the present research and the researcher used air to cool the heat exchanger.

Analysis of Variance (ANOVA)

● The results of ANOVA for the four characteristics were presented in Tables (4, 5, 6 and 7).

Table 4. Results of ANOVA of factors vs. heat transfer coefficient

Source of variation	Sum of squares	D.O.F	Mean square	Computed F	F From table
A	3515204.1	3	1171734.7	1366	6.5914
B	103803.9	1	103803.9	121	10.128
Error	2573.6	3	857.9	-----	------
Total	3621581.6	7	-------	-----	------

Table 5. Results of ANOVA of factors vs. overall heat transfer coefficient

Source of variation	Sum of squares	D.O.F	Mean square	Computed F	F From table
A	92616.3	3	30872.1	684.3	6.5914
B	2179.98	1	2179.98	48.3	10.128
Error	135.4	3	45.1	-----	------
Total	94931.6	7	-------	-----	------

Table 6. Results of ANOVA of factors vs. number of transmitted units

Source of variation	Sum of squares	D.O.F	Mean square	Computed F	F From table
A	0.082	3	0.0273	118.7	6.591
B	0.0023	1	0.0023	10	10.128
Error	0.0007	3	0.00023	-----	------
Total	0.085	7	-------	-----	------

Table 7. Results of ANOVA of factors vs. effectiveness

Source of variation	Sum of squares	D.O.F	Mean square	Computed F	F From table
A	201.92	3	67.306	3959.2	6.5914
B	0.85	1	0.85	50	10.128
Error	0.05	3	0.017	-----	------
Total	202.92	7	-------	-----	------

It was noted that F from table at (α=0.05) for both main effects are smaller than F calculated, indicating that the mass flow rate of hot water and flow type significantly affect surface temperature excepted flow type in table 5 was not significant.

● Statistically, F-test provides a confidence decision as to whether these estimates are significantly different. Larger F-value indicates that the variation of the process parameter makes a big change on the performance.

● According to this analysis, the most effective parameters with respect to four characteristics were mass flow rate of hot water, flow type and error. According to Figures (7,8,9,and 10), the percentage contribution of mass flow rat of hot water was found to be the major factor affecting the four characteristics were (97% , 97.42%, 95.5% 99.48%) and the percentage contribution of flow type and error were much lower being (2.8%, 2.25%, 2.44%, 0.4%) and (0.2%, 0.33%, 2.06%, 0.12%) respectively.

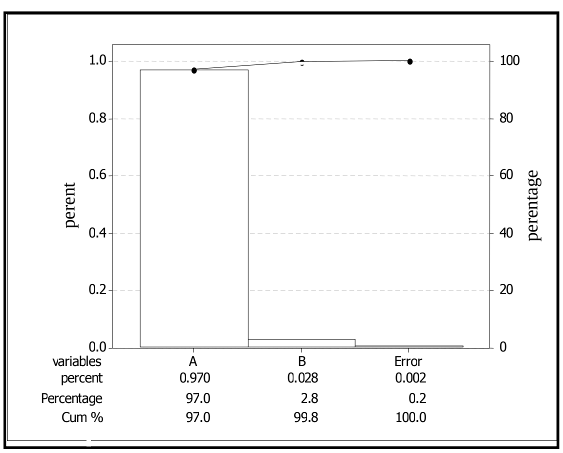

Fig. 7. Pareto chart of contribution Factors vs. heat transfer coefficient

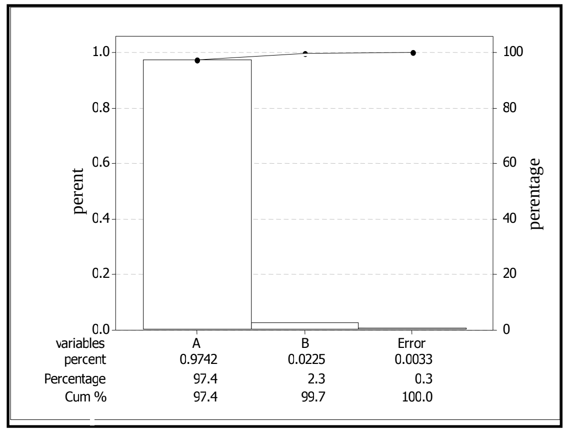

Fig. 8. Pareto chart of contribution factors vs. overall heat transfer coefficient

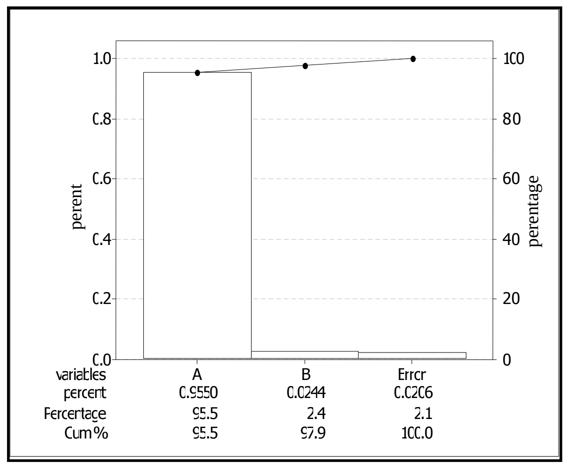

Fig. 9. Pareto chart of contribution factors vs. number of transmitted units

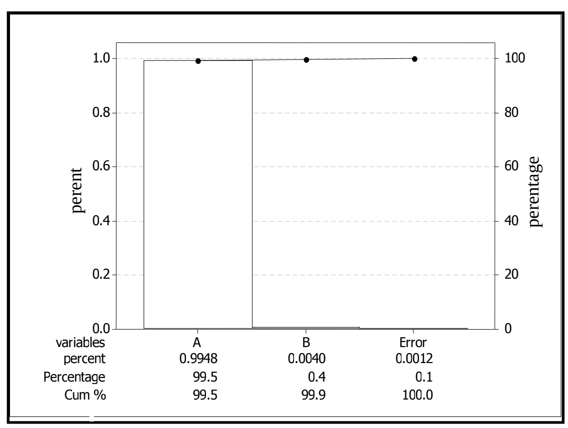

Fig. 10. Pareto chart of contribution factors vs. effectiveness

Conclusions and Recommendations

1- the pulse flow leads to increase internal heat transfer coefficient (hi) higher than its value in the steady flow and the highest increase was by 9.75% at a mass flow rate of hot water 0.0416kg/s and increases the overall heat transfer coefficient (U) where the highest percentage was by 4.68% at a mass flow rate of hot water 0.0416kg/s.

2- The results showed increasing both the number of transmitted units (NTU) and the effectiveness of the heat exchanger type shell and tube (ε) in the case of pulse flow of its value in the steady flow and the highest percentage of increase occurring was 4.75% and 1.85%, respectively, and at the mass flow rate of hot water 0.0416 kg/s.

3- A large percentage of contribution by mass flow rate of hot water was observed 99.48 % for effectiveness where a small percentage of contribution by flow type for characteristic effectiveness and error were (0.4 %, 0.12 %).

4- The parameter of mass flow rate of hot water had a great effect on the performance of shell and tube type heat exchanger while the parameter flow type had a small effect on the performance of heat exchanger.

5- The effect of an interaction between main effects is not found.

6- Reduction of an inherent variation in the process due to noise variables and improvement of heat exchanger performance.

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