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# Experimental Study of Optimum Chilled Water Distribution Configuration in Air Conditioning Terminal Unit Using RSM Technique

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## ABSTRACT

The distribution of chilled water flow rate in terminal unit is an important factor used to evaluate the performance of central air conditioning unit. A prototype of A/C unit has been made, which contains three terminal units with a complete set of accessories (3-way valve, 2-way valve, and sensors) to study the effect of the main parameters, such as total water flow rate and chilled water supply temperature with variable valve opening. In this work, 40 tests were carried out. These tests were in two groups, 20 test for 3-way valve case and 20 test for 2-way valve case. These tests were performed at three levels of valve opening, total water flow rate and water supply temperature according to the design matrices established by Design of Experiment (DOE) software 'version 7' with Response surface methodology (RSM) technique. The model was conducted for each case of total heat rate, then checked statistically for adequacy by Analysis of variance (ANOVA), and found good with 95% confidence level. The results showed that the water supply temperature has a significant effect on the total heat rate of two cases. It was found that the optimum solution for maximum total heat rate and minimum flow deviation represented by standard deviation was obtained at 10°C water supply temperature, 5.5 l/min total water flow rate and 70% valve opening. The total heat rate and standard deviation were (890.249 Watt), (0.000513), respectively in three-way valve case and (743.155 Watt), (0.00277), respectively in two-way valve case. Finally, the predicted and experimental results of total heat rate and standard deviation were in agreement with a maximum error of 6.6 % in three-way valve case and 1.4% in two-way valve case.

**Key words:** Optimization, 3-way valve, 2-way valve, Terminal units, DOE, RSM

# دراسة عملية لأيجاد أفضل توزيع للماء المثلج في محطة تكييف للهواء بأستخدام تقنية RSM

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## الخلاصة

أن توزيع معدل تدفق المياه المثلجة في الوحدة الطرفية هوعامل مهم يستخدم لتقييم اداء وحدة التكييف المركزية. قد تم وضع نموذج لوحدة التكييف A/C التي تحتوي على ثلاث وحدات طرفية مع مجموعة كاملة من الملحقات (صمام ثلاثي الاتجاه وصمام ثنائي الاتجاه وأجهزة استشعار) لدراسة تأثير المعاملات الرئيسية مثل معدل تدفق الماء الكلي ودرجة حرارة إمدادات ماء التبريد المجهز مع فتحات

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صمام متغيرة. في هذا العمل تم اجراء 40 اختبار وكانت هذه الاختبارات على مجموعتين ، 20 اختبار لحالة الصمام ثلاثي الاتجاه و20 اختبار لحالة الصمام ثنائي الاتجاه. اجريت هذه الاختبارات على ثلاث مستويات من فتحات الصمامات وكمية الماء الكلي المتدفق ودرجة حرارة الماء المجهز وفقا لمصفوفة التصميم التي وضعها برنامج تصميم التجارب (DOE) ذو الاصدار رقم (7) مع تقنية طريقة الاستجابة السطحية (RSM) . تم اجراء نموذج رياضي للحالتين من اجمالي معدل الحرارة ، ثم تم الفحص احصائيا بواسطة تحليل (ANOVA) حيث وجدت النتائج جيدة مع مستوى ثقة 95% . اظهرت البيانات ان درجة حرارة الماء المجهز لها تأثير كبير على معدل الحرارة الكلي لكلا الحالتين . وقد وجد ان الحل الامثل لأقصى معدل حرارة كلي وادنى انحراف معياري تم الحصول عليه عند درجة حرارة ( 10 درجة سيليزية) وكمية ماء متدفق كلي ( 5.5 لتر/دقيقة ) وفتحة صمام (% 70) . حيث بلغت القيمة المثلى لمعدل الحرارة الكلي والانحراف المعياري ( 890.249 واط ) و (0.0005136) على التوالي في حالة الصمام ثلاثي الاتجاه و (743.155 واط ) ،(0.0027706) على التوالي في حالة الصمام ثنائي الاتجاه. واخيراً كان هنالك توافق كبير بين النتائج المتوقعة والعملية لمعدل الحرارة الكلي والانحراف المعياري مع نسبة خطأ قليلة جداً لا تتجاوز 6.6% في حالة الصمام الثلاثي و 1.4% في حالة الصمام الثنائي.

**الكلمات الرئيسية:** امثلية ، صمام ثلاثي الاتجاه، صمام ثنائي الاتجاه، الوحدات الطرفية، تصميم التجارب، طريقة الاستجابة السطحية.

## 1. INTRODUCTION

Cooling is essential for all types of buildings in Iraq; most of the air- central conditioning (A/C) systems used in commercial and institutional buildings are of large capacity. These systems use chillers for cooling production and a network of chilled water piping for cooling distribution to the individual Air-Handling Units (AHUs) or Fan Coil Units (FCUs). The more cooling capacity of the cooling system will be accomplished per liter of chilled water distribution if the chilled-water temperature differentials are 8.3°C or greater, **Donald, 1999**, and if the chilled water temperature difference between supply and return water at the side of the building becomes smaller than the designed value. The energy for heat distribution system and the total energy consumption in district heating and cooling system plant increase in considerable degrees, **Shimoda, 1999,** but the high chilled water temperature, low supply air temperature, and high outside air intake ratio may result in low cooling chilled water return temperature ،and the bypass bridge is not necessary and can be removed in the consumer chilled water system with the 2-way valve configuration. The removal not only reduces the first cost but also the operation cost, **Gang, 2006,** also the chilled water distribution system stability is the basic engineering knowledge for air conditioning engineer; proper sizing of control valves, layouts, and self-balancing, flow balancing and control the speed of the pump are important fundamental factors of a chilled water distribution system, **Thirakomen,** and **ASHRAE, 2007. Naxi, 2012,** studied the heat transfer performance of the cooling coils under low cooling loads and found that the laminar flow for the chilled water at low flow rate is not the main cause of the low ΔT in the chilled water system, possible causes for the piping strategy of the low ΔT existing in the chilled water system under low flow conditions are use of 2- way control valves and improper tertiary pump piping strategy. **Zhan, 2007,** focused on the blending station and found the blending station is not necessary for the building chilled water systems with 2-way modulation valves at end users, actually the end user valve configuration and control mainly impact the building chilled water temperature, as soon as the water flow control is improved, the chilled water return temperature can be controlled without the blending stations. The aim of this work is to determine the best distribution of chilled water and the best thermal performance in terminal units utilizing traditional chilled water control system (3-way valve & 2-way valve).

## 2. EXPERIMENTAL WORK

The test rig of experimental work is composed of the following main parts and measuring devices, **Fig.1** presents the photo of the experimental apparatus; the test rig consists of plastic pipes, valve (three-way & two-way), chilled water tank, return water tank, water pump, cooling coil, stabilizer and measuring devices.

### 2.1 Cooling Coil

The cooling coil used in this project is associated with an axial fan to model terminal unit in a central system like fan coil unit, the coil is made from an Aluminum material with dimensions [20 cm*15 cm*4 cm] with 17 channel.

### 2.2 Water Pump

The electric water pump is fixed to the outlet of chilled water tank, the water enters the pump from a (500 liter) tank through fixed piping system, the pump specifications are [220 V - 50 Hz - 370W], [Qmax = 30 L/min, and Hmax = 30 m], and this pump with constant speed is used to circulate the chilled waters inside the test rig.

### 2.3 Three-way Valve & Two-way Valve

The unit model is (SQS65) [LANDIS & GYR – 24V-50 Hz- Supply 0-10V- 3VA-Germany], this valve can be used manually or in automatic operating mode.

### 2.4 Chilled Water Tank

The chilled water tank is made from Galvanized plate with a capacity of 500 liters, this tank is insulated by two layers, the first layer of Polystyrene and second layer of glass wool thickness insulation. This tank is used to feed the chilled water to the test rig with approximately constant temperature (8, 10, 12, 14 and 16° C).

### 2.5 Automatic Voltage Regulator

The automatic voltage regulator (stabilizer) of 2000 VA was installed on the main wire of the test rig to maintain the supplied voltage (220V) to the test rig.

### 2.6 Data Acquisition DAQ (Arduino MEGA 2560)

The main measuring instruments that are used in this project are the National Instruments Arduino MEGA 2560. The National Instruments Arduino MEGA 2560 is a low-cost multifunction data acquisition device (DAQ) that provides the basic data acquisition functionality for many applications, such as simple data logging, portable measurements, and the laboratory experiments. This Arduino is connected with 26 temperature sensor and 4 sensors for relative humidity.

### 2.7 Experimental Procedure

For each experimental test, the following procedure was followed:-

1. Power on the stabilizer.
2. Power on the pump.
3. Power on the fans in coils.
4. Waiting about thirty to forty-five minutes to establish a steady-state condition that makes the temperature difference ($\Delta T$) of water and $\Delta T$ of air steady at the three coils.
5. Changing the valve opening manually or in automatic mode, also the total water flow rate and the supply temperature according to an experimental design matrix.

### 2.8 Test Parameters

To study the influence of inlet factors on the total heat rate and standard deviation induced by chilled water distribution process, three input factors (valve opening, total water flow rate and inlet water supply temperature) were used as separate factors with two levels as listed in **Table 1**. The levels were selected based on the practical experience.

### 2.9 Experimental Design

In the present work, a response surface methodology (RSM) technique was used to develop a mathematical model based on the experimental data. The quadratic functions of response surface should be considered, because the curvature may be insufficiently modeled by using the first-order function within the ranges of normal operating conditions. 20 runs (experiments) for each case were carried out based on the matrix of experimental design. The runs were randomly conducted according to the run order that recorded in **Table 2** for three-way valve case and two-way valve case. Different levels coded from -2 to +2 were used with each factor, whereby every utilized level adapted to an actual value corresponding to the coded value. Thus, the parameters (input factors) studied are valve opening, total water flow rate, and inlet water supply temperature. The matrix of experimental design used for input factors with the obtained values of outputs (total heat rate and standard deviation) is given in **Table 2**.

### 2.10 Calculation of Heat Rate and Standard Deviation

To calculate the heat rate of water for each coil, the following equations are used:

$$q_w = \dot{m}_w \; Cp_w \,(T_{chwo} - T_{chwi}) \qquad (1)$$

Where:

$q_w$ : Heat rejection from water (watt)

$\dot{m}_w$ : Water flow rate (kg/s)

$Cp_w$ : Specific heat of water (J/kg. °C)

$T_{chwi}$ : Chilled water inlet temperature (°C)

$T_{chwo}$ : Chilled water outlet temperature (°C)

And to calculate the standard deviation of the flow rate between three coils branches,

$$\mathrm{SD} = \sqrt{\frac{1}{N}\sum_{\mathrm{i=1}}^{\mathrm{N}}(\mathrm{flow} - \overline{\mathrm{flow}})^2} \qquad (2)$$

Where:

flow: Observed values of the sample items

$\overline{flow}$: Average value of these observations

N: Number of samples = 3 in the present work

### 2.11 Design of Experiment and Response Surface Methodology

Design of experiment (DOE) starts with defining its aims and choosing the process parameters for the study. An experimental design is the laying out of a detailed experimental plan in advance of doing the experiment. Well-chosen experimental designs increase the amount of "information" that can be got for a known amount of experimental effort. In an experiment, one or more process variables (or factors) are deliberately altered to notice the influence of the changes on one or more response variables. The (statistical) design of experiments (DOE) is an efficient procedure for planning experiments so that the data obtained can be analyzed to yield valid and objective conclusions. RSM is a group of mathematical and statistical techniques, which are useful for the modeling and analysis of problems, in which a response of interest is affected by several variables and the goal is to optimize this response. It also quantifies relationships among one or more measured responses and the vital input factors. In this work, version (7) of the Design Expert software was employed to develop the experimental plan for RSM. The same software was also used to analyze the data collected. After analyzing each response, multiple response optimizations were performed, either by inspection of the interpretation plots or with the graphical and numerical tools provided for this purpose, **Noordin, 2004**. Mathematical models were developed by using RSM based on the experimental data for two output responses (total heat rate and standard deviation). Conditions, where the curvature in the normal operating ranges is inadequately modeled by the first-order function, often occur. So, the quadratic response surface functions should be considered, **Ponnala, 2012**.

## 3 RESULTS AND DISCUSSION

### 3.1 Modeling of Total Heat Rate

The quadratic response surface model for total heat rate was developed by using the experimental data given in **Table 2**. From **Table 3** and **Table 4**, model F-value of 158.98 and 297.45 respectively of 3- way and 2-way valve case implies the model is significant. Values of " Prob > F " less than 0.05 indicate model terms are significant. In this case, A, B, C, $A^2$, $B^2$, and $C^2$ are significant model terms. Therefore, this model indicates that these parameters had a great impact on the total heat rate. The empirical quadratic predicted model built for the total heat rate developed is given as follows:

**Total heat rate of 3-way valve =** $5424.56818 - 41.61477 * A - 516.93182 * B - 256.60227 * C + 0.28455 * A^2 + 55.81818 * B^2 + 7.05114 * C^2$ (3)

**Total heat rate of 2-way valve =** $1609.72727 - 5.14091 * A - 229.27273 * B - 9.59091 * C + 0.031818 * A^2 + 26.72727 * B^2 - 1.14205 * C^2$ (4)

Where:

A: Valve opening

B: Total water flow rate

C: Water supply temperature

For 3-way valve and 2-way valve case, **Fig. 2** and **Fig. 3** respectively manifest that the predicted values of total heat rate are near to actual ones measured in the tests, indicating that both the experimental and predicted results have a good agreement. For 3-way valve case, **Fig. 4** reveals the perturbation of total heat rate in this model. It also shows that the valve opening (A) increased significantly the total heat rate over the whole selected input levels (70% – 90%). Also, it can be observed that the total water flow rate (B) increased slightly the total heat rate over the whole selected input levels (4.5 l/min – 5.5 l/min), While water supply temperature (C) has an adverse effect, and the total heat rate value decreased largely at high level (16°C). The result is also confirmed by the 2D contour plot and 3D surface plot depicted in **Fig. 5** and **Fig. 6** respectively as a function of valve opening and total water flow rate at medium value (center level) of water supply temperature (10°C), where a similar behavior was observed when varying the valve opening and the total heat rate over the ranges (70 - 90 %) and (4.5 – 5.5 l/min), respectively. For 2-way valve case, **Fig. 7** reveals the perturbation of total heat rate. It shows that the valve opening (A) does not affect significantly on the total heat rate over the whole selected input levels (70% – 90%). Also, it can be observed that the total water flow rate (B) increased slightly the total heat rate over the whole selected input levels (4.5 l/min – 5.5 l/min), while water supply temperature (C) has an adverse effect, and the total heat rate value decreased largely at high level (16°C). The result is also confirmed by the 2D contour plot and 3D surface plot depicted in **Fig. 8** and **Fig. 9**, respectively as a function of valve opening and total water flow rate at medium value (center level) of water supply temperature (10°C), where a similar behavior was observed when varying the valve opening and the total heat rate over the ranges (70 - 90 %) and (4.5 – 5.5 l/min), respectively.

### 3.2 Optimization of Total Heat Rate

The design of experiment software was used to perform the numerical optimization and to determine the optimum combinations of factors to accomplish the requirements as desired. Therefore, this software was used for optimization purpose depending on the results of a prediction model of one response, total heat rate, as a function of three input factors: valve opening, total water flow rate and water supply temperature. To establish a new predicted model, an objective function called desirability that permits for suitable combining the aims was estimated. Desirability should be maximized by numerical optimization, and it ranges from 0 to 1 for the aim. Characteristics of the aim may be changed by adjusting the weight or importance of the desirability, and the goal of optimization is to determine the proper set of conditions to satisfy all the aims. Normally, the weights are utilized to develop the estimation of the aim's 3D importance during maximizing the desirability of this work, weights were not changed since the total heat rate (response) has the main importance. The major purpose of the optimization was to determine maximum total heat rate and minimum standard deviation response satisfying the variable features with a maximum desirability. The constraints of each factor for optimizing water distribution are listed in **Table 5** and **Table 6** for 3- way and 2-way valve case, respectively. According to these tables, one possible run fulfilled these specified constraints to obtain the maximum total heat rate value and minimum standard deviation, as given in **Table (7)** of 3-way valve case. It can be seen that for this run, the maximum selected desirability is (0.802). **Fig. 10** illustrates the optimum value of the maximum total heat rate in the 3D surface plot (890.249 Watt). Also for 2-way valve case, it can be seen from **Table (8)** that the maximum selected desirability is (0.816). **Fig. 11** illustrates the optimum value of the maximum total heat rate in the 3D surface plot (743.155 Watt).

### 3.3 Confirmation Tests

To check the validity of this model, proofing tests were carried out at the optimum predicted values of the input parameters obtained in this model to measure the total heat rate. The experimental results of these measurements are given together with the predicted results in **Table 9** for comparison purposes. This table indicates that both the experimental and predicted results have a good agreement with a maximum error of 6.6%, 1.4 % of 3- way and 2-way valve case, respectively.

## 4. CONCLUSIONS

**1-** Valve opening, total water flow rate and water supply temperature have a significant effect on the total heat rate at three-way valve case. Where, the valve opening and total water flow rate greatly increased the total heat rate over the whole selected input levels (70% - 90%) and (4.5 l/min – 5.5l/min), respectively. While, the water supply temperature has an adverse effect, and the total heat rate value decreased largely at high level (16°C) and for two-way valve case, the total water flow rate greatly increased the total heat rate over the whole selected input levels (4.5 l/min – 5.5l/min) . While the valve opening does not affect greatly on the total heat rate. Also, the water supply temperature has an adverse effect, and the total heat rate value decreased largely at a high level (16°C).

**2-** According to DOE with RMS, the optimum solution for maximum total heat rate and the minimum standard deviation was found at 70% valve opening, 10°C water supply temperature and 5.5 l/min total water flow rate. Where, the optimum values of total heat rate and standard deviation were (890.249 Watt), (0.00051), respectively for three-way valve case and (743.155 Watt), (0.00277), respectively for two-way valve case.
**3-** It was found a good agreement between the experimental and predicted results of total heat rate with a maximum error of 6.6% for three-way valve case and 1.4% for two-way valve case.
**4-** It was proved that DOE with RSM can be a good tool to predict the total heat rate and standard deviation for all given input parameters values used in the chilled water distribution process.

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**NOMENCLATURE**

DOE = design of experiment
RSM = response surface methodology
ANOVA=analysis of variance
DAQ = data acquisition
ΔT = temperature difference, °C.
A/C = air- central conditioning
SD = standard deviation
Prop >F = proportion of time or probability you would expect to get the stated F value
Cor total = totals of all information corrected for the mean
CV = coefficient of variation
d.f. = degrees of freedom
Adeq. Precision = adequate precision
Adj. *R*-squared = adjusted *R*-squared
Pred. R-squared= predicted R-squared
Press= predicted residual error sum of squares
R-squared = coefficient of determination

**Table 1.** Used levels of input factors**.**

| **Input factor** | **Levels** | | | |
|---|---|---|---|---|
| | **-2** | **-1** | **+ 1** | **+ 2** |
| **Valve opening (%)** | 60 | 70 | 90 | 100 |
| **Total water flow rate (l/min)** | 4 | 4.5 | 5.5 | 6 |
| **Inlet water supply temperature (°C)** | 8 | 10 | 14 | 16 |

**Table 2.** Design matrix for input factors and outputs**.**

| **No.** | **Valve opening (%)** | **Total water flow rate (l/min)** | **Water Supply Temp. (°C)** | **Three-way valve** | | **Two-way valve** | |
|---|---|---|---|---|---|---|---|
| | | | | **Total heat rate (watt)** | **Standard deviation** | **Total heat rate (watt)** | **Standard deviation** |
| 1 | 70 | 4.5 | 10 | 860 | 0.001493 | 724 | 0.002136 |
| 2 | 90 | 4.5 | 10 | 930 | 0.000904 | 702 | 0.003682 |
| 3 | 70 | 5.5 | 10 | 913 | 0.00055 | 740 | 0.002732 |
| 4 | 90 | 5.5 | 10 | 991 | 0.000864 | 747 | 0.004089 |
| 5 | 70 | 4.5 | 14 | 481 | 0.00082 | 553 | 0.003062 |
| 6 | 90 | 4.5 | 14 | 560 | 0.00055 | 577 | 0.004357 |
| 7 | 70 | 5.5 | 14 | 554 | 0.000831 | 589 | 0.004804 |
| 8 | 90 | 5.5 | 14 | 575 | 0.001179 | 588 | 0.006104 |
| 9 | 60 | 5 | 12 | 675 | 0.000393 | 659 | 0.001589 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 10 | 100 | 5 | 12 | 868 | 0.001427 | 655 | 0.004095 |
| 11 | 80 | 4 | 12 | 681 | 0.000943 | 602 | 0.002533 |
| 12 | 80 | 6 | 12 | 759 | 0.000629 | 715 | 0.003879 |
| 13 | 80 | 5 | 8 | 1092 | 0.002361 | 770 | 0.004101 |
| 14 | 80 | 5 | 16 | 451 | 0.001493 | 480 | 0.004781 |
| 15 | 80 | 5 | 12 | 684 | 0.00055 | 632 | 0.003539 |
| 16 | 80 | 5 | 12 | 696 | 0.00055 | 638 | 0.003539 |
| 17 | 80 | 5 | 12 | 671 | 0.00055 | 650 | 0.003539 |
| 18 | 80 | 5 | 12 | 668 | 0.00055 | 652 | 0.003539 |
| 19 | 80 | 5 | 12 | 660 | 0.00055 | 637 | 0.003539 |
| 20 | 80 | 5 | 12 | 641 | 0.00055 | 642 | 0.003539 |

**Table 3.** ANOVA for response surface reduced quadratic model for total heat rate (3-way valve case).

| **Source** | **Sum of Squares** | **df** | **Mean Square** | **F Value** | **p-value Prob > F** |
|---|---|---|---|---|---|
| Model | 5.54E+05 | 6 | 92260.28 | 158.98 | < 0.0001 significant |
| A-Valve opening | 24492.25 | 1 | 24492.25 | 42.21 | < 0.0001 |
| B-Water flow rate | 6806.25 | 1 | 6806.25 | 11.73 | 0.0045 |
| C-Supply temperature | 4.89E+05 | 1 | 4.89E+05 | 841.96 | < 0.0001 |
| $A^2$ | 20357.19 | 1 | 20357.19 | 35.08 | < 0.0001 |
| $B^2$ | 4896.05 | 1 | 4896.05 | 8.44 | 0.0123 |
| $C^2$ | 20001.05 | 1 | 20001.05 | 34.47 | < 0.0001 |
| Residual | 7544.09 | 13 | 580.31 | | |
| Lack of Fit | 5279.26 | 8 | 662.16 | 1.47 | 0.3478 not significant |
| Pure Error | 2246.83 | 5 | 449.37 | | |
| Cor. Total | 5.61E+05 | 19 | | | |
| Std. Dev. | 24.09 | | R-Squared | | 0.9866 |
| Mean | 719.90 | | Adj R-Squared | | 0.9803 |
| C.V. % | 3.35 | | Pred R-Squared | | 0.9447 |
| PRESS | 31036.45 | | Adeq Precision | | 49.047 |

**Table 4.** ANOVA for response surface reduced quadratic model for total heat rate (2-way valve case).

| Source | Sum of Squares | df | Mean Square | F Value | p-value Prob > F |
|---|---|---|---|---|---|
| Model | 95681.85 | 6 | 15946.97 | 297.45 | < 0.0001 significant |
| A-Valve opening | 4 | 1 | 4 | 0.075 | 0.789 |
| B-Total water flow rate | 5776 | 1 | 5776 | 107.74 | < 0.0001 |
| C-Supply temperature | 87616 | 1 | 87616 | 1634.26 | < 0.0001 |
| $A^2$ | 254.55 | 1 | 254.55 | 4.75 | 0.0483 |
| $B^2$ | 1122.55 | 1 | 1122.55 | 20.94 | 0.0005 |
| $C^2$ | 524.69 | 1 | 524.69 | 9.79 | 0.008 |
| Residual | 696.95 | 13 | 53.61 | | |
| Lack of Fit | 522.95 | 8 | 65.37 | 1.88 | 0.2526 not significant |
| Pure Error | 174 | 5 | 34.8 | | |
| Cor Total | 96378.8 | 19 | | | |
| Std. Dev. | 7.32 | | R-Squared | 0.9928 | |
| Mean | 648.60 | | Adj R-Squared | 0.9894 | |
| C.V. % | 1.13 | | Pred R-Squared | 0.9769 | |
| PRESS | 2227.27 | | Adeq Precision | 68.332 | |

**Table 5.** Constraints of the optimization of total heat rate (3-way valve case).

| Name | Lower Goal | Upper Limit | Lower Limit | Lower Weight | Upper Weight | importance |
|---|---|---|---|---|---|---|
| A: Valve opening | is inrange | 70 | 90 | 1 | 1 | 3 |
| B: Total water flow rate | is in range | 4.5 | 5.5 | 1 | 1 | 3 |
| C: Supply temperature | is in range | 10 | 14 | 1 | 1 | 3 |
| Total heat rate | maximize | 451 | 1092 | 1 | 1 | 3 |
| Standard deviation | minimize | 0.00039284 | 0.002361 | 1 | 1 | 3 |

**Table 6.** Constraints of the optimization of total heat rate (2-way valve case).

| **Name** | **Lower Goal** | **Upper Limit** | **Lower Limit** | **Lower Weight** | **Upper Weight** | **importance** |
|---|---|---|---|---|---|---|
| A: Valve opening | is inrange | 70 | 90 | 1 | 1 | 3 |
| B: Total water flow rate | is in range | 4.5 | 5.5 | 1 | 1 | 3 |
| C: Supply temperature | is in range | 10 | 14 | 1 | 1 | 3 |
| Total heat rate | maximize | 480 | 770 | 1 | 1 | 3 |
| Standard deviation | minimize | 0.00158893 | 0.0060139 | 1 | 1 | 3 |

**Table 7.** Optimum solution for maximum total heat rate and minimum standard deviation (Three-way valve case).

| **Number** | **Valve opening** | **Total water flow rate** | **Supply temperature** | **Total heat rate** | **SD** | **Desirability** |
|---|---|---|---|---|---|---|
| | **%** | **l/min** | **°C** | **(Watt)** | | |
| 1 | 70 | 5.5 | 10 | 890.249 | 0.000514 | 0.802 Selected |

**Table 8.** Optimum solution for maximum total heat rate and minimum standard deviation (Two-way valve case).

| **Number** | **Valve opening** | **Total water flow rate** | **Supply temperature** | **Total heat rate** | **SD** | **Desirability** |
|---|---|---|---|---|---|---|
| | **%** | **l/min** | **°C** | **(Watt)** | | |
| 1 | 70 | 5.5 | 10 | 743.155 | 0.0027706 | 0.816 Selected |

**Table 9.** Comparison between the experimental and predicted total heat rate.

| Case | Valve opening (%) | Total water flow rate (l/min) | Water supply temp. (°C) | Total heat rate (watt) | | | Standard deviation | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Predict. | Exp. | Max. Error (%) | Predict. | Exp. | Max. Error (%) |
| 3- way valve | 70 | 5.5 | 10 | 890.249 | 913 | 2.4 | 0.00051 | 0.00055 | 6.6 |
| 2- way valve | 70 | 5.5 | 10 | 743.155 | 740 | 0.42 | 0.00277 | 0.00273 | 1.4 |

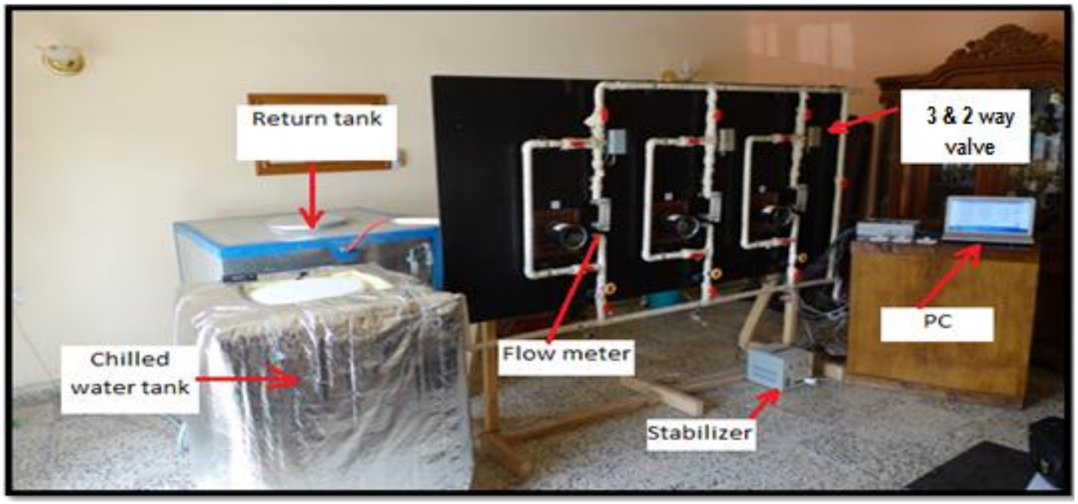


**Figure1.** Photograph of the test rig including the main parts.

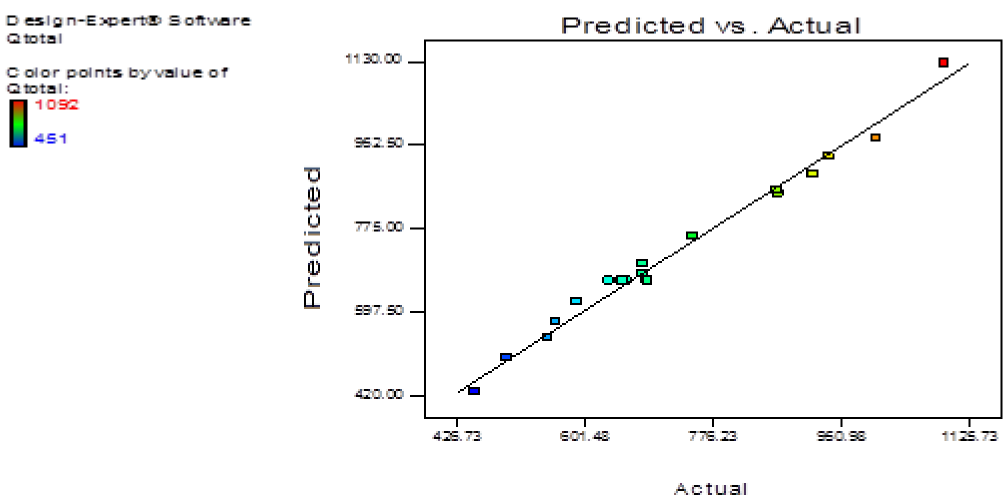


**Figure 2.** Predicted versus actual total heat rate data for comparison (Three-way valve case).

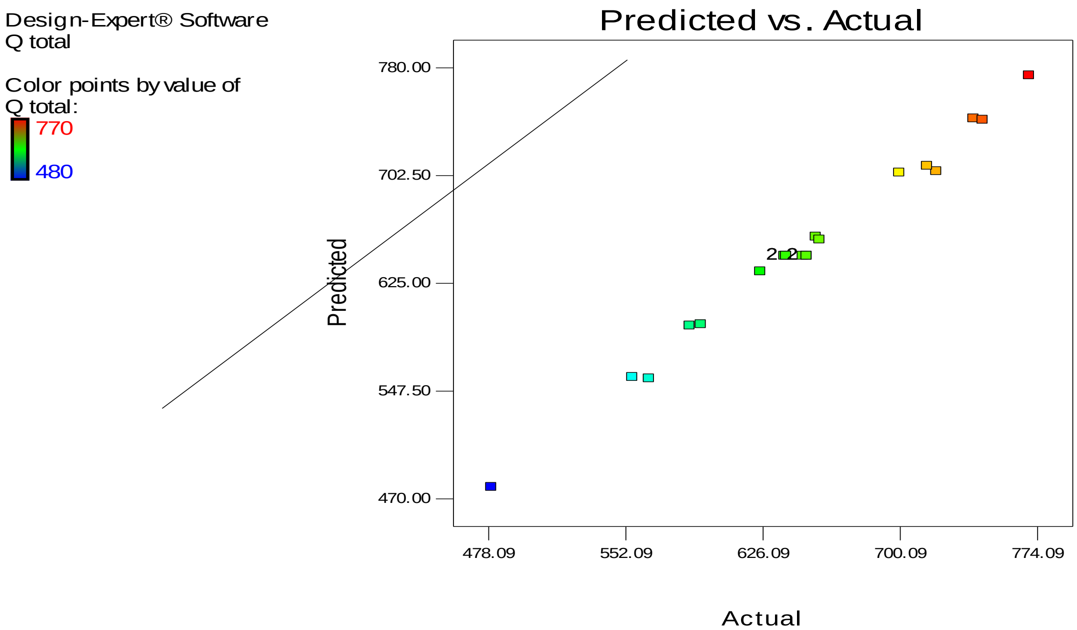


**Figure 3.** Predicted versus actual total heat rate data for comparison (Two-way valve case).

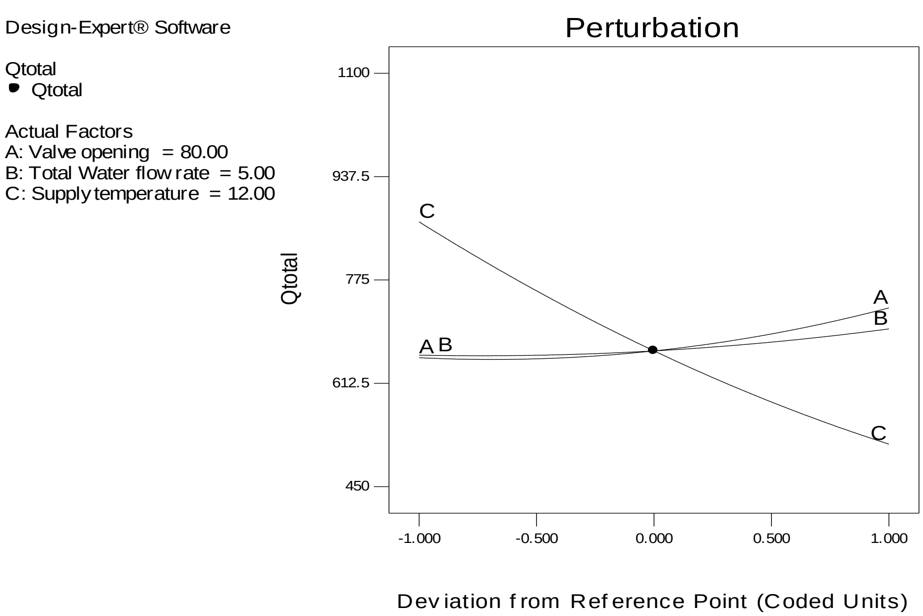


**Figure 4.** Perturbation of total heat rate showing the effect of each input parameter over the selected level, (Three-way valve case).

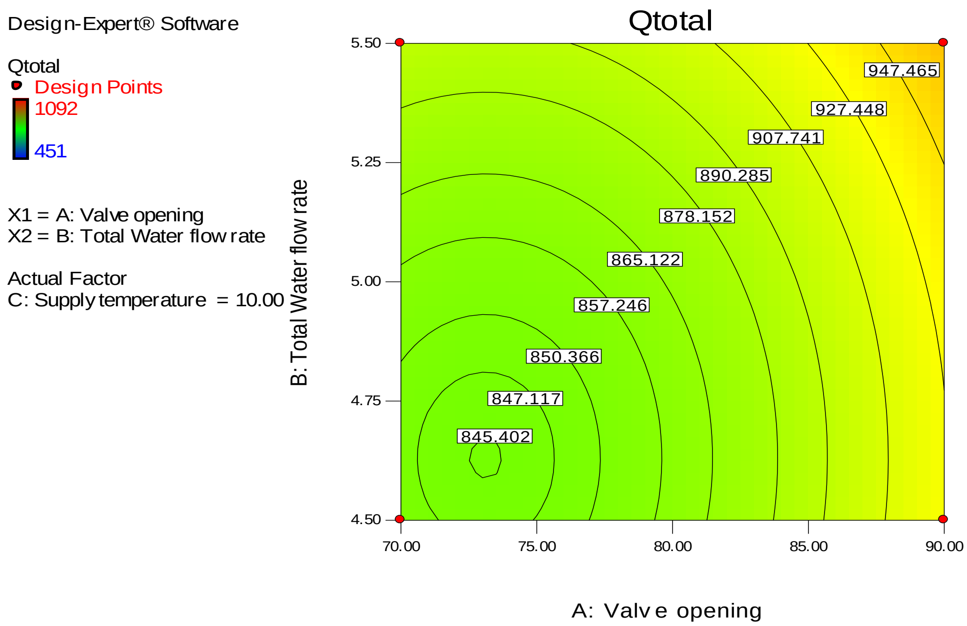


**Figure 5.** 2D Plot of total heat rate as a function at the center level of water supply temperature (10°C), (Three-way valve case).

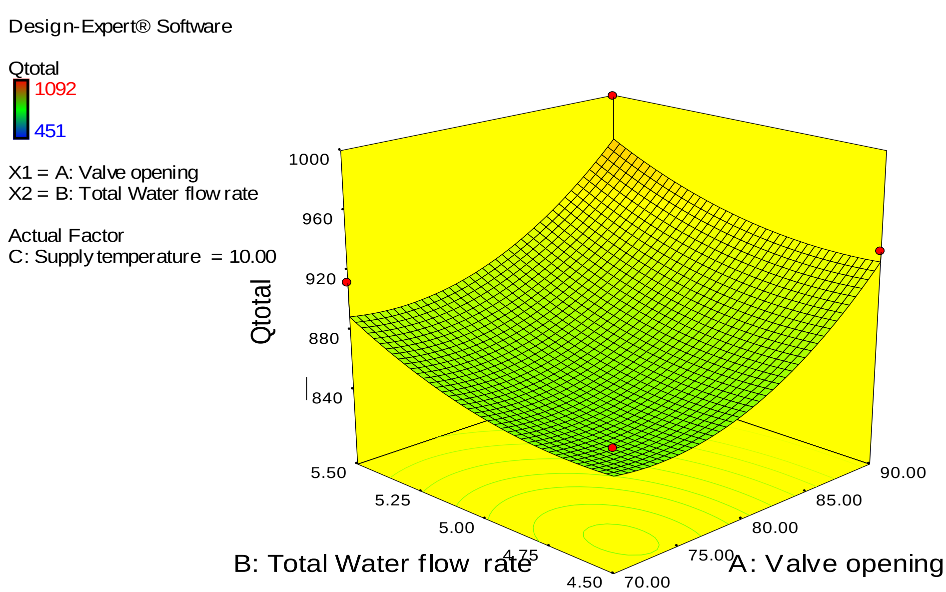


**Figure 6.** 3D Plot of total heat rate as a function at the center level of water supply temperature (10°C), (Three-way valve case).

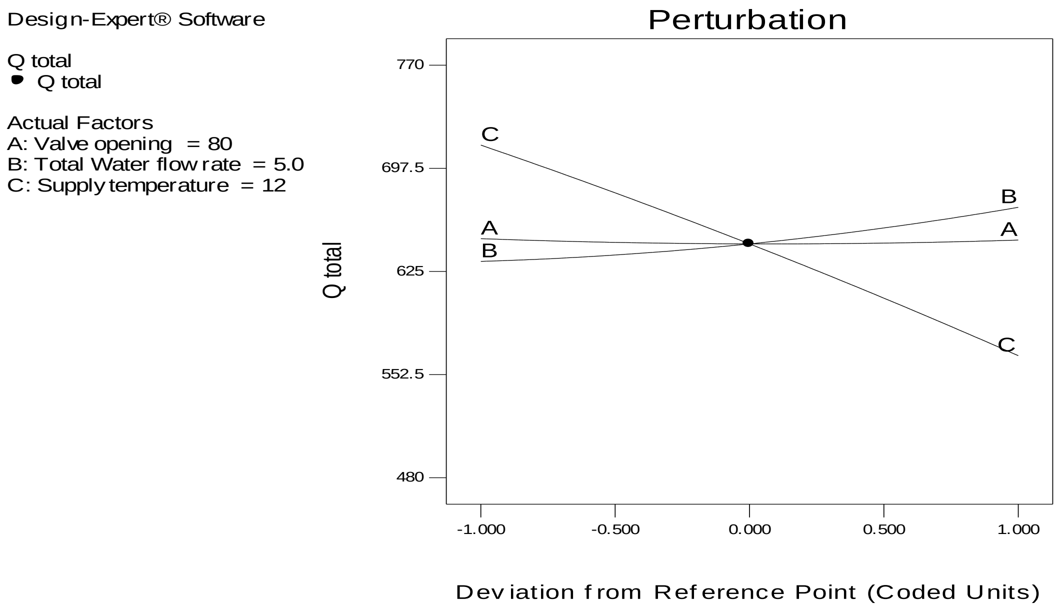


**Figure 7.** Perturbation of total heat rate showing the effect of each input parameter over the selected level, (Two-way valve case).

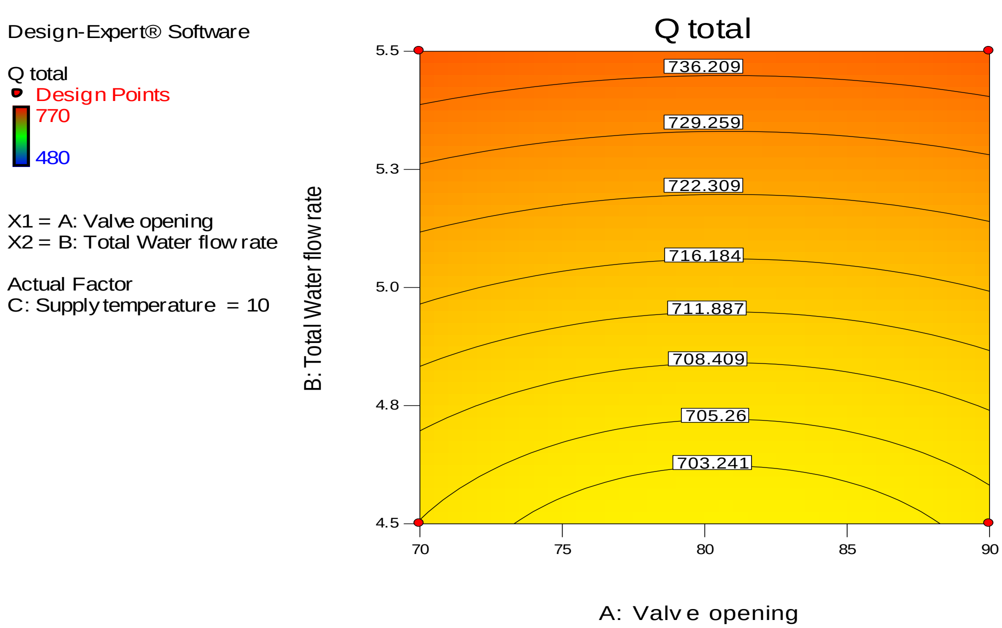


**Figure 8.** 2D Plot of total heat rate as a function at the center level of water supply temperature (10°C), (Two-way valve case).

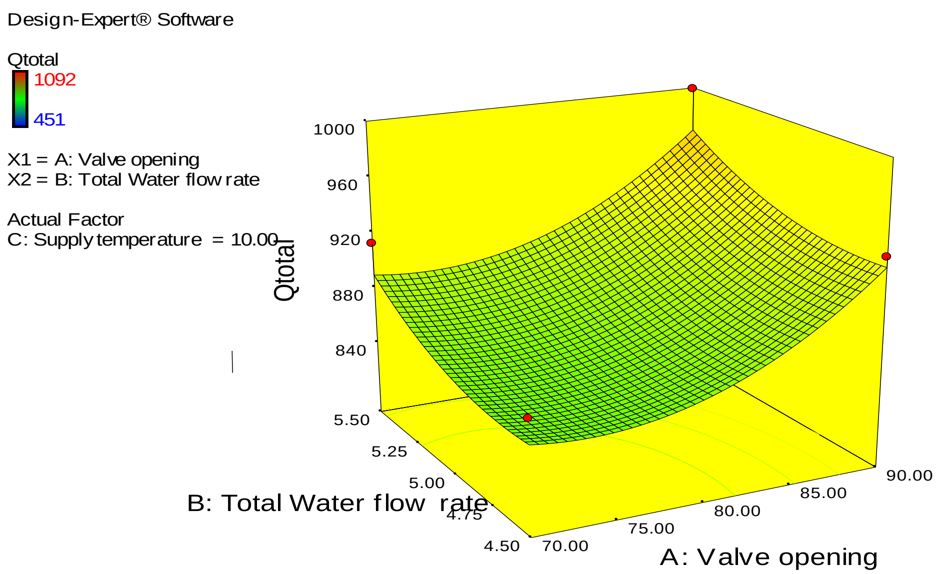


**Figure 9.** 3D Plot of total heat rate as a function at the center level of water supply temperature (10°C), (Two-way valve case).

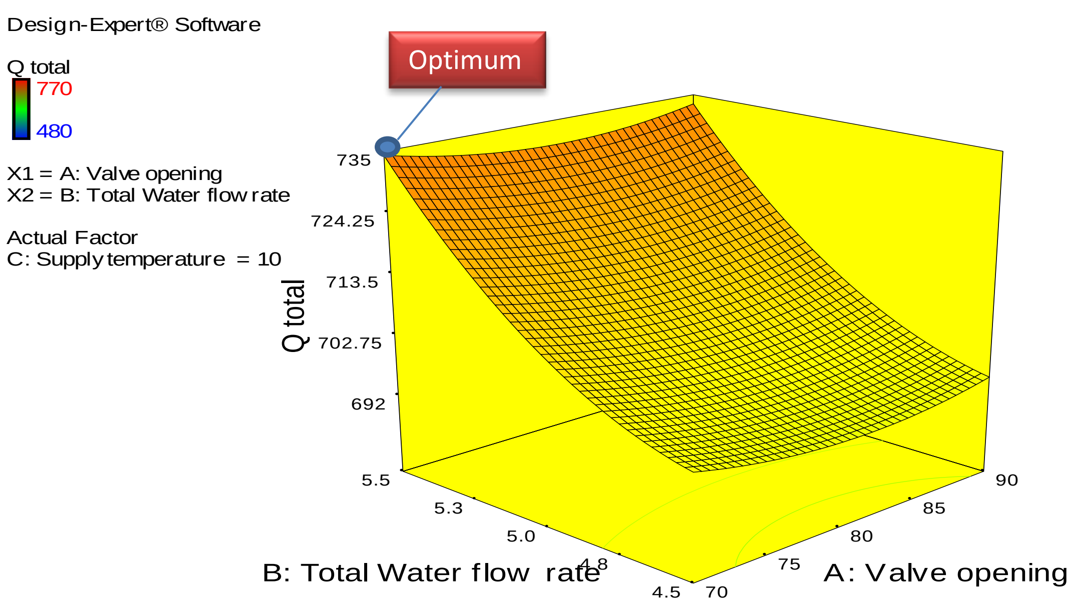


**Figure10.** The maximum total heat rate at the optimum parameters (valve opening = 70%, total water flow rate= 5.5 l/min and supply temperature = 10°C), (3-way valve case).

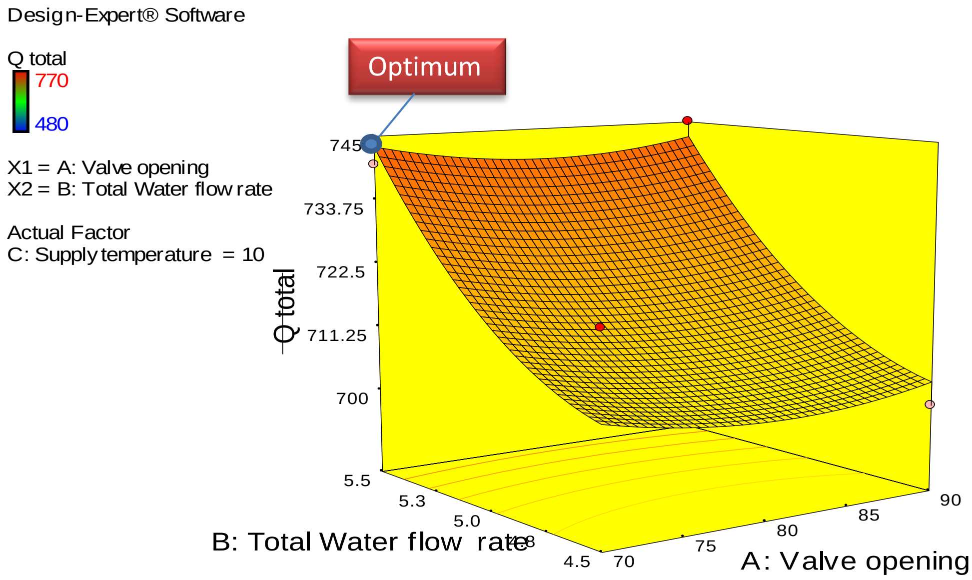


**Figure11.** The maximum total heat rate at the optimum parameters (valve opening = 70%, total water flow rate= 5.5 l/min and supply temperature = 10°C), (2-way valve case).