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# Studies of VOCs removed from packed-bed absorber by experimental design methodology and analysis of variance

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ABSTRACT

Indoor air quality is affected by volatile organic compound (VOC) pollutants and these are often emitted by furniture and building materials. To enhance indoor air quality, removing VOCs from indoor environment is an important task. Triethylene glycol (TEG) solution was used as working solution to absorb VOCs from ambient air in this study. Plastic 5/8 in. polaring-type was packed in the packed-bed absorber, and the packed length was about 34 cm. Toluene, methanol, ethyl ether, and methyl-ethyl ketone were absorbed separately by TEG solution. Two-level factorial experimental design methodology was applied to schedule the operating variables in the experiment. The advantage of experimental design methodology is to obtain reasonable experimental results with fewer experimental runs. In addition, the analysis of variance (ANOVA) was used to analyze the effect of operating variables (factors) on mass transfer coefficient (response). The *p*-value was used to assess the mass transfer performance of VOCs absorbed by packed-bed absorber. From experimental results, effect of air flux on mass transfer coefficient was significant except for methanol because the *p*-values were smaller than 0.1 for toluene, ethyl ether, and ketone. For VOCs concentration, the effect of methanol concentration on mass transfer coefficient was extremely significant; the effect of concentration of ethyl ether was very significant; the effect of concentration of toluene was significant; the effect of methyl-ethyl ketone was insignificant. Since all the *p*-values were smaller than 0.01 for liquid flux, the effect of liquid flux on mass transfer coefficient was very significant. By analyzing the factorial interaction, the factorial couples, toluene concentration × liquid flux, TEG concentration × methanol concentration, TEG concentration × ethyl ether concentration, and ketone concentration × liquid flux can be chosen as main variables to operate the absorption system for absorption of toluene, methanol, ethyl ether, and ketone to acquire the desired mass transfer coefficient.

## 1. Introduction

Halide solutions were used as working solutions for absorption heat pump or absorption systems before 1990. For example, Shih et al. [1] used $H_2O$/LiBr and $H_2O/H_2SO_4$ as working fluid-absorbent pairs to estimate thermodynamic efficiencies of absorption heat pumps for heating, and the obtained T-S diagram could reflect the operating conditions and thermodynamic properties for different pairs. Similarly, the cascading of two stage absorption systems used two working fluids, namely $H_2O$/LiBr and $NH_3/H_2O$, as refrigerant-absorbent combination by Kaushik et al. [2] to produce much lower temperatures suitable for air-conditioning application. To predict the performance of solar driven $H_2O$/LiBr absorption units, Kouremenos et al. [3] used a model to simulate the extra absorption thermodynamic cycle. $NH_3/H_2O$ and $H_2O$/LiBr were also used as solutions to two cooperating absorption units by Kouremenos et al. [4] to obtain a high efficiency absorption-refrigeration system. Kouremenos et al. [4] found that the overall COP is considerably higher than the COP for each part of the system. However, crystallization phenomenon always occurred in the absorption system, and the liquid distributor or the finer pipe may be clogged with the crystalline particles. The glycol solutions could be used in dehumidification, antisepsis, and absorption of VOCs, and the crystallization phenomenon almost did not occur in the absorption system. Therefore, TEG solution was selected as the working solution in this study.

To obtain the correlation of column efficiency for different packings, lithium chloride and triethylene glycol solutions were used by Chung [5] to remove water vapor from air in a packed column. Since the packing type was the important factor to affect mass transfer performance, Chung et al. [6] used lithium chloride solution to absorb water vapor and to compare heat and mass transfer correlations between random and structured packings. In addition, to reduce carryover of absorbent solution, the U-shape air tunnel with

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eliminators was designed by Chung and Wu [7], and TEG solution was used to remove water vapor from moist air in a spray tower. The mass transfer performance of the spray tower with and without fin coils was compared by Chung and Wu [8], and the mass transfer correlations were also developed by some relevant operating variables. As mentioned above, the mass transfer performance of packed-bed and spray absorbers for water vapor absorbed by lithium chloride or triethylene glycol solutions have been discussed completely in the open literature. However, there has been little discussion about VOCs removed by TEG solution in an absorption system. The selected VOCs would be harmful to human beings beyond an upper limit of concentration, and these were regarded as indoor air pollutants. Therefore, the purpose of this study is to discuss the effect of operating variables on mass transfer performance of absorption of VOCs by the analysis of variance. On the basis of the principle of organic matters dissolve each other; the TEG solution was used in the packed-bed absorber to absorb VOCs. Methanol, toluene, ethyl ether, and methyl-ethyl ketone were selected as absorbates individually to be absorbed by TEG solution. The two-level factorial experimental design methodology was used to schedule the operating variables for experimental runs, and effects of operating variables on mass transfer coefficient were analyzed by ANOVA.

The major variables that affected absorber performance include air flux, liquid flux, concentration of absorbent solution, and pollutant concentration. In addition, the mass transfer performance of absorber was also affected by the design of absorber, such as the packing material and the method of packing. For example, the metallic Pall rings was packed randomly by Vu et al. [9] to study liquid distribution and local mass transfer in a packed bed. Vu et al. [9] found that mass transfer was affected by liquid distribution significantly, and liquid distribution was not affected by air flux below the loading point. Bravo et al. [10] used structured stainless packing in the packed-bed absorber, and the authors found that the mass transfer performance was not increased with the increased absorbent flux. Bravo et al. [10] thought that the channeling effect would be more significant for the structured packing than random packing, and the effective contacting area for gas and liquid phases is not increased. Therefore, the mass transfer performance almost leveled off as the absorbent flux attained a constant flow flux. Doan and Fayed [11] mounted several cuvettes under the support plate to collect and observed the distribution of liquid absorbent in the packed-bed. The heights of the packed-bed and absorbent flux were the operating variables, and absorbent solution collected by cuvettes was used to analyze the absorbent distribution. Linek et al. [12] described hydrophilic and hydrophobic packing to remove VOCs from waste water in the absorption-stripping system. From discussion above, there are many variables to affect the mass transfer performance of a packed-bed absorber, and thus variables related to fluids (gas phase and liquid absorbent) were selected in this study to determine their effect on mass transfer performance. Therefore, the fluid variables – liquid flux, air flux, TEG concentration, and VOCs concentration – were taken as operating variables.

Absorption/stripping system was often used to treat air pollutants and to replace the conventional compressor in the absorption heat pump. If there is no chemical reaction in the absorption process, then the pollutants could usually be removed from the absorbent solution by a stripping process. The regenerated solution could also be recycled to avoid waste of resource. Some inorganic gas and odoriferous gas could be treated by absorption and stripping technologies. For example, limestone suspensions were used by Lancia et al. [13] to absorb $SO_2$ in a bubbling reactor. The concentration profiles of different species were determined by integrating the model equations with $SO_2$ absorption rate and limestone dissolution rate. The knowledge of concentration profile allowed to ascertain interaction between limestone dissolution and $SO_2$ transfer. In addition, Lancia et al. [14] also focused on $SO_2$ absorption, and a diffusive model based on film theory was developed. To simulate a laboratory absorber and to develop computer models, Zidar [15] used $NaOH_{(aq)}$ to absorb $SO_2$ in a laboratory absorber, and gas–liquid equilibrium operational diagrams for concentration of $SO_2$, partial pressure of $SO_2$, and pH were set. Pradhan and Joshi [16] also used aqueous NaOH to absorb NOx in a plate column, and then a mathematical model, which assumed that interface partial pressure of water was equal to the vapor pressure over given NaOH concentration and temperature, was developed for calculating the rate of NOx reacted with $NaOH_{(aq)}$.

There are many harmful volatile organic compounds which can be found in air, such as alcohols, aromatic, ether, ketone, ester, etc., but discussions about VOCs absorbed by TEG solution in the absorption system are limited. To reduce harm to the human body and to maintain laboratory safety during experimental running, some VOCs with lower toxicity were selected to be absorbed in this present work. Therefore, four different VOCs were selected: methanol, toluene, ethyl ether, and methyl-ethyl ketone. Some studies about treating VOCs are described as follows. Moe and Qi [17] used a biofilter populated by a mixed culture of fungi to remove n-butyl acetate, methyl-ethyl ketone, methyl propyl ketone, and toluene, and results showed that the fungal biofilter could be used effectively to treat discontinuously generated solvent mixtures with weekend shutdowns. The method of biological removal was also used by Doan et al. [18] to treat propylene glycol methyl ether (PGME) in a trickle bed filter. Doan et al. let microorganism to grow and build up on the surface of the packing particles, and then various liquid flowrates, bed heights and initial concentrations of PGME were used in experiments. Doan et al. found that the dynamic liquid hold-up increased about 20% than that of a clean bed. Since the activated carbon adsorption was nondestructive technology, the photocatalyst was used to oxidize methanol [19]. $TiO_2$/activated carbon composite photocatalyst was prepared by a microwave-assisted impregnation method, and result showed that photocatalytic oxidation of methanol from humid air was successfully accomplished by the composite.

The experimental design methodology was used to schedule the operating variables for experimental runs, and the ANOVA was applied to discuss relationship between response and factors. In general, the mass transfer performance of the absorber could be affected by the liquid flux, the air flux, the absorbent concentration, and the VOC concentration. Since the more reasonable and accurate experimental results were always accompanied with more cost and experimental runs, the two-level factorial experimental design methodology was adopted to schedule operating variables for experimental runs to reduce waste of resource. Since the issues of environmental protection and saving of energy and resource were focused gradually, the two-level factorial experimental was introduced to this study. The method gave the advantage of doing less experimental runs to obtain the reasonable and correct results [20]. In addition to adopting the experimental design methodology, the method of ANOVA was used to analyze the effects of operating variables on mass transfer performance, to discuss the relationship between factorial interaction and mass transfer coefficient, and to acquire the better operating conditions for VOCs absorbed by TEG solution in this study.

## 2. Experimental

The packed-bed absorption system of this study is shown in Fig. 1. The whole absorption system includes air compressor, impinger, and packed-bed absorber. The packed-bed absorber was made of polypropylene, and the cross-section area of the packed-bed is $15 \times 15\,cm^2$. Since the ratio of absorber diameter to packing

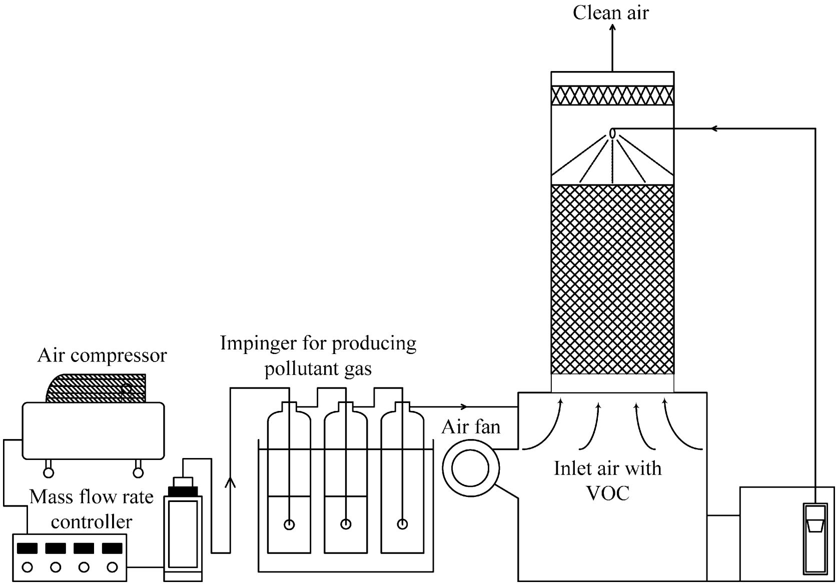


**Fig. 1.** Packed-bed absorption system of this study.

must be larger than 8 to reduce the channeling effect, 5/8 in. plastic polaring-type was chosen in this study. The packing was packed in the absorber randomly, and the total height was about 34 cm.

The absorbent solution was sprayed homogeneously from a nozzle, and distributed over the packing. The absorbent solution and inlet air were in countercurrent flow. The fluid flux and concentration of inlet air were controlled by a mass flow controller and an air impinger. After absorbing VOC in the packed-bed, the solution was recycled to the liquid reservoir, and then to the liquid pump and controller for reuse in the absorber. Every experimental run was about 15–20 min to attain the absorption equilibrium state, and three to four experimental runs were regarded as an experimental series. Since the reduction of TEG concentration was limited in an experimental series, the batch method was adopted for every experimental series. After a series was completed, the absorbent solution was regenerated by the stripping process.

The experimental procedures can be divided into three steps. The first step includes the development of calibration curve of VOCs and the operation of VOC absorbed by the absorption system. The second step was to calculate mass transfer coefficient for every experimental run, and the derivation of mass transfer coefficient can be referred from Hines and Maddox [21]. The VOCs used in the experiment include toluene, methanol, ethyl ether, and methyl-ethyl ketone. The third step was to analyze effect of operating variables on mass transfer performance and the relationship between factorial interaction and mass transfer coefficient.

According to the MSDS, the 8-h time weighted averages (TWA) and vapor pressure are shown in Table 1. To take into consideration the experiment safety and cost, the 8-h TWA was referred to control the concentrations of VOCs and the impinger apparatus was used to produce VOC vapor. The concentrations of VOCs should not surpass far from the standard. Since the impinger apparatus was used to produce the VOC vapor, the obtained concentration depends on flow rate of carried gas, impinger number, and vapor pressure. Generally speaking, the concentration of VOC is increased with the decreased the flow rate of carried gas and the more impinger numbers. However, the vapor pressure makes the limited concentration for the system. Since the vapor pressures of toluene and methyl-ethyl ketone are 22 and 77.5 mm Hg, high levels of toluene and methyl-ethyl ketone just can be controlled at 110 and 205 ppm. Although the vapor pressure of ethyl ether came to 422 mm Hg, 500 ppm was surpassed easily by decreasing flow rate of carried gas slightly. Therefore, high level of ethyl ether was just controlled at 155 ppm. The concentrations of VOCs considered in this study are shown in Table 2.

In general, packed-bed tower were operated at air flux that corresponds to about 50–80% of flooding. In addition, reduction of carryover of liquid solution is necessary for the absorption system to maintain indoor air quality so that the higher percentage of flooding is not recommended. Both experimental safety and system loading were taken into consideration, and the air fluxes were operated from 57% to 70% of flooding. The more detail about absorber design and determinations of air and liquid fluxes can be referred from Hines and Maddox [21] (chapter 12). The settings about air and liquid fluxes can be seen in Table 2.

**Table 1**
8-h TWA and vapor pressures for VOCs selected in this work.

| Chemicals | 8-h TWA (ppm) | Vapor pressure (mmHg) |
|---|---|---|
| Methanol | 200 | 160 mm Hg (30 °C) |
| Toluene | 100 | 22 mm Hg (20 °C) |
| Ethyl ether | 400 | 422 mm Hg (20 °C) |
| Methyl-ethyl ketone | 200 | 77.5 mm Hg (20 °C) |

*Data source*: Material Safety Data Sfeet).

## 3. Two-level full factorial experimental design methodology

Generally speaking, the scientific or industrial experiments were usually set three or four values for every variable (factor).

**Table 2**
Coded level for experimental factors.

| Variable | Symbol | Coded−1 | Level +1 |
|---|---|---|---|
| Methanol concentration | Me-conc. | 210 | 369 |
| Toluene concentration | To-conc. | 62 | 110 |
| Ether concentration | Eth-conc. | 58 | 155 |
| Methyl-ethyl ketone concentration | MEK-conc. | 105 | 205 |
| TEG. concentration (wt.%) | TEG conc. | 91.5 | 96.5 |
| Air flux (kg/m$^2$ s) | G | 1.45 | 1.75 |
| Liquid flux (kg/m$^2$ s) | L | 0.85 | 1.15 |

The unit of concentration of methanol, toluene, ether, and methyl-ethyl ketone are ppm.

**Table 3**
Numbers of experimental runs for three variables and 4 variables' values in the traditional experimental method.

| No. | Variable 1 | Variable 2 | Variable 3 | No. | Variable 1 | Variable 2 | Variable 3 |
|---|---|---|---|---|---|---|---|
| 1 | A | A | A | 33 | C | A | A |
| 2 | A | A | B | 34 | C | A | B |
| 3 | A | A | C | 35 | C | A | C |
| 4 | A | A | D | 36 | C | A | D |
| 5 | A | B | A | 37 | C | B | A |
| 6 | A | B | B | 38 | C | B | B |
| 7 | A | B | C | 39 | C | B | C |
| 8 | A | B | D | 40 | C | B | D |
| 9 | A | C | A | 41 | C | C | A |
| 10 | A | C | B | 42 | C | C | B |
| 11 | A | C | C | 43 | C | C | C |
| 12 | A | C | D | 44 | C | C | D |
| 13 | A | D | A | 45 | C | D | A |
| 14 | A | D | B | 46 | C | D | B |
| 15 | A | D | C | 47 | C | D | C |
| 16 | A | D | D | 48 | C | D | D |
| 17 | B | A | A | 49 | D | A | A |
| 18 | B | A | B | 50 | D | A | B |
| 19 | B | A | C | 51 | D | A | C |
| 20 | B | A | D | 52 | D | A | D |
| 21 | B | B | A | 53 | D | B | A |
| 22 | B | B | B | 54 | D | B | B |
| 23 | B | B | C | 55 | D | B | C |
| 24 | B | B | D | 56 | D | B | D |
| 25 | B | C | A | 57 | D | C | A |
| 26 | B | C | B | 58 | D | C | B |
| 27 | B | C | C | 59 | D | C | C |
| 28 | B | C | D | 60 | D | C | D |
| 29 | B | D | A | 61 | D | D | A |
| 30 | B | D | B | 62 | D | D | B |
| 31 | B | D | C | 63 | D | D | C |
| 32 | B | D | D | 64 | D | D | D |

The symbols, A, B, C and D can be regarded as different operating conditions for every variable.

Therefore, the numbers of experimental runs are $4^3$ for the experiment involved three variables and set 4 variables' values in the traditional experimental method, as shown in Table 3. A full factorial design contains all combinations of the levels of the factors. The number of experimental runs is the product of the levels of the factors (the above example is $4 \times 4 \times 4$). For two-level designs, this is $2^k$ where $k$ is the number of factors. Since two levels and four factors are scheduled in this study, the total number of experimental runs is $2^4$ for each VOC absorbed by the TEG solution. Although the number of full factorial experimental design is still larger than the fractional factorial experimental design, the number of full factorial is much smaller than the traditional experimental method. In addition, the two-level full factorial experimental design not only reduces the number of experimental runs but also keep the more reasonable analysis for the experimental data. Therefore, the two-level full factorial experimental design was applied to this study.

## 4. Fundamental of analysis of variance, *F*-ratio testing, and *p*-value

The variance can be defined as the measure of the dispersion, or variability, of a population of measurements [22, chapter 3], and it can be calculated as the average of the squares of the distance each value is from the mean in the statistics [23, chapter 3]. Analysis of variance can be applied to various kinds of studies. The main purpose of ANOVA is to check whether the means of two or more populations are different in the statistics. In general, the means of two populations are usually compared by the *t*-test, and three or more means should be compared by the ANOVA. Since there are many factors that affect mass transfer performance, the *F*-ratio test should be adopted to analyze the relationship between operating variables and mass transfer coefficient.

ANOVA is used to check whether means of every sample are equal by comparing sum of squares within (SSW) and sum

**Table 4**
Definition of analysis of variance for one-factor ANOVA model.

| Source of variation | Sum of square (SS) | Degree of freedom (df) | Mean square (MS) |
|---|---|---|---|
| Between-group | $SSB = \sum_{i=1}^{n} (Y_i' - Y'')^2$ | $k - 1$ | $MSB = SSB/(k-1)$ |
| Within-group | $SSW = \sum_{i=1}^{n} (Y_i - Y_i')^2$ | $n - k$ | $MSW = SSW/(n - \mathrm{k})$ |
| Total | $SST = \sum_{i=1}^{n} (Y_i - Y'')^2$ | $n - 1$ | |

SSB: sum of square between-group; SSW: sum of square within-group; SST: total sum of square; MSB: mean square between-group; MSW: mean square within-group; $Yi$: variables; $Yi'$: mean value for every group; $Yi''$: mean value for all variables; $n$: number of sample; $k$: number of group (level).

**Table 5**
Definition of analysis of variance for two-factor ANOVA model.

| Source of variation | Sum of square (SS) | Degree of freedom (df) | Mean square (MS) | F-ratio |
|---|---|---|---|---|
| Component A | $SSA = \sum_{i}^{r}\sum_{j=1}^{c}(A'_j - Y'')^2$ | $r - 1$ | $MSA = SSA/(r-1)$ | $F_A = MSA/MSE$ |
| Component B | $SSB = \sum_{i}^{r}\sum_{k=1}^{n}(B'_k - Y'')^2$ | $c - 1$ | $MSB = SSB/(c-1)$ | $F_B = MSB/MSE$ |
| Component A × B | $SSAB = \sum_{i=1}^{r}\sum_{j=1}^{c}\sum_{k=1}^{n}[(A_jB_k)' - A'_j - B'_k + Y''] = SST - SSA - SSB - SSE$ | $(r-1)(c-1)$ | $MSAB = SSAB/[(r-1)(c-1)]$ | $F_{AB} = MSAB/MSE$ |
| Error | $SSE = \sum_{i=1}^{r}\sum_{j=1}^{c}\sum_{k=1}^{n}[Y'' - (A_jB_k)']^2$ | $rc(n-1)$ | $MSE = SSE/[rc(n-1)]$ | |
| Total | $SST = \sum_{i=1}^{r}\sum_{j=1}^{c}\sum_{n=1}^{k}(Y_{ijk} - Y'')^2$ | $n - 1$ | | |

of squares between (SSB), and it can be divided into the one-factor ANOVA model and two-factor ANOVA model. The one-factor ANOVA model is to study effect of a single variable on response, and the two-factor ANOVA model is to discuss the relationship between two interactive factors and response. The analyzed table of variance for the one-factor ANOVA model is shown in Table 4. The obtained *F*-ratio is mean square of factor A divided by mean square of error, and the value of *F*-ratio can be used to judge whether effect of factor (operating variable) on response (mass transfer coefficient) is significant. The analyzed table of variance for the two-factor ANOVA model is shown in Table 5. The two-factor ANOVA model is used to analyze the relationship between two interactive factors and response in statistics. By the obtained *F*-ratio or *p*-value and the interaction profile, two better operating variables can be chosen to control the absorption system to obtain the desired or better separation performance.

The *p*-value can be defined as the probability of the value of *F*-ratio larger than the obtained *F*-ratio in the *F*-distribution. The *p*-value also can be called as the observed significant level, and that is the minimum probable level to reject null hypothesis under the information of the given sample. For this study, the null hypothesis can be regarded as the effect of a certain variable on mass transfer coefficient is insignificant. As mentioned above, the larger *F*-ratio and lower *p*-value mean that the effect of factors (operating variable) on response (mass transfer coefficient) is significant in this study.

## 5. Results and discussion

One of the purposes of this study was to acquire reasonable results using fewer experimental runs. Therefore, the two-level factorial experimental design methodology was adopted to schedule the experimental operation, and the method of analysis of variance was used to analyze effects of operating variables on mass transfer coefficient. The statistical software of JMP [24] was used as auxiliary tool to complete the experimental design. In addition, the obtained *p*-value was applied to describing effects of operating variables on mass transfer coefficient and analyzing the relationship between factorial interaction and mass transfer coefficient. All operating factors must be normalized before proceeding two-level factorial experimental design. The coded levels for all factors are shown in Table 2.

On the basis of the factorial level listed in Table 2, the two-level factorial experimental design was used to schedule the operating conditions for all experimental variables. Table 6 is the scheduled result for absorption of methanol by the absorption system. After completing the series experiment of absorption of methanol, the calculated mass transfer coefficient $K_{GA}$ was filled with the column of $K_{GA}$ in Table 6. Besides, the method of analysis of variance was used to analyze effects of experimental factors on response and discuss the relationship between factorial interaction and mass transfer coefficient. To obtain information about the relativity between practical conditions and statistical analysis, the software of JMP also carried out the regression of factors and response by the least square method, and the determination coefficient ($R^2$) could be used to assess the degree of relativity. The definition of determination coefficient is the ratio of the explained variation to the total variation, as shown in Eq. (2). The explained variation means that the sums of square of the regressed response minus mean value.

$$\sum (Y - Y_m)^2 = \sum (Y - Y_f)^2 + \sum (Y_f - Y_m)^2 \tag{1}$$

$$R^2 = \frac{\sum (Y_f - Y_m)^2}{\sum (Y - Y_m)^2} \tag{2}$$

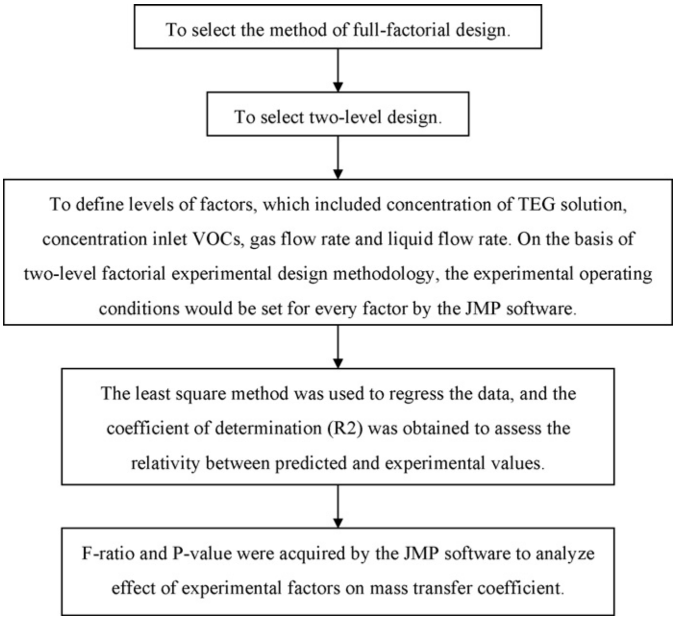
$Y$: response value; $Y_f$: response value after linear fitting; $Y_m$: mean value of the response.

In general, the more the value of $R^2$ is approached unity, the regressed results closer to the experimental data is. On the contrary, this statistical result may not be well as the value of $R^2$ is more deviated from unity. The applied procedure of the JMP software is shown in Fig. 2.

After factors and response was inputted to the related tabulation of the JMP software, effects of factors on response can be analyzed by the results of analysis of variance. Therefore, effects of single variable on mass transfer coefficient, the relationship between

**Table 6**
Variable schedule and experimental response for methanol.

| No. | Pattern | TEG conc. | Conc. | *G* | *L* | $K_{GA}$ |
|---|---|---|---|---|---|---|
| 1 | + – + + | 96.5 | 210 | 1.75 | 1.15 | 0.085149 |
| 2 | – – + – | 91.5 | 210 | 1.75 | 0.85 | 0.102681 |
| 3 | + + – + | 96.5 | 369 | 1.45 | 1.15 | 0.056022 |
| 4 | – – + + | 91.5 | 210 | 1.75 | 1.15 | 0.106711 |
| 5 | – + – – | 91.5 | 369 | 1.45 | 0.85 | 0.054461 |
| 6 | – – – – | 91.5 | 210 | 1.45 | 0.85 | 0.100996 |
| 7 | + – – + | 96.5 | 210 | 1.45 | 1.15 | 0.084373 |
| 8 | + + + – | 96.5 | 369 | 1.75 | 0.85 | 0.050154 |
| 9 | – + – + | 91.5 | 369 | 1.45 | 1.15 | 0.066873 |
| 10 | + – – – | 96.5 | 210 | 1.45 | 0.85 | 0.075470 |
| 11 | – + + + | 91.5 | 369 | 1.75 | 1.15 | 0.061835 |
| 12 | + + + + | 96.5 | 369 | 1.75 | 1.15 | 0.058976 |
| 13 | – + + – | 91.5 | 369 | 1.75 | 0.85 | 0.051690 |
| 14 | – – – + | 91.5 | 210 | 1.45 | 1.15 | 0.104947 |
| 15 | + – + – | 96.5 | 210 | 1.75 | 0.85 | 0.079255 |
| 16 | + + – – | 96.5 | 369 | 1.45 | 0.85 | 0.041292 |



To select the method of full-factorial design.

To select two-level design.

To define levels of factors, which included concentration of TEG solution, concentration inlet VOCs, gas flow rate and liquid flow rate. On the basis of two-level factorial experimental design methodology, the experimental operating conditions would be set for every factor by the JMP software.

The least square method was used to regress the data, and the coefficient of determination (R2) was obtained to assess the relativity between predicted and experimental values.

F-ratio and P-value were acquired by the JMP software to analyze effect of experimental factors on mass transfer coefficient.

**Fig. 2.** Applied processes of JMP software in this study.

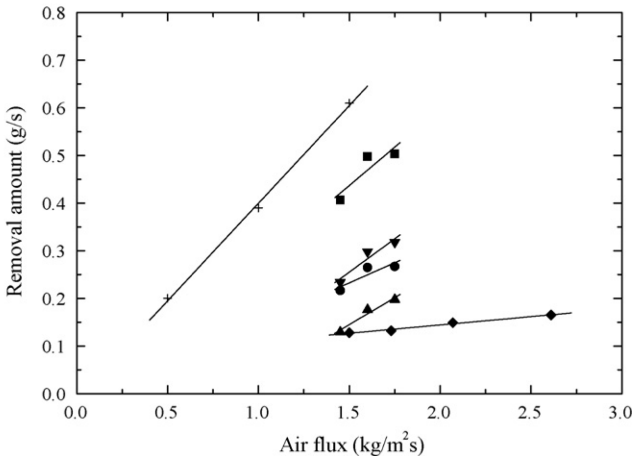


**Fig. 4.** Mass transfer data compared with literature studies for the air flux. The symbol ■ means removal amount of methanol in this present. The symbol ● means removal amount of toluene in this present. The symbol ▲ means removal amount of ethyl ether in this present. The symbol ▼ means removal amount of methyl-ethyl ketone in this present. The symbol ♦ means removal amount of water vapor in the study of Zurigat et al. [27]. The symbol + means removal amount of water vapor in the study of Oberg and Goswami [26].

factorial interaction and mass transfer coefficient, and the better operating conditions for the absorption system were discussed in this study.

### 5.1. Comparison of mass transfer data with literature studies

To compare the mass transfer data with literature studies, the total removal amount are presented and shown in Eq. (3).

$$m_r = (Y_{\text{in}} - Y_{\text{out}}) \times G \times A \tag{3}$$

where $Y_{\text{in}}$ and $Y_{\text{out}}$ are the inlet and outlet concentrations of absorbate in the gas phase (ppm), $G$ is the air flux (kg/m$^2$ s), and $A$ is the cross-sectional area (m$^2$) of the absorption column. Since the mass transfer coefficient is advantageous to designing absorber, the mass transfer coefficient is still regarded as the response value in the analysis of variance. Variables included liquid flux, air flux, and TEG concentrations were used to compare with literature data in Figs. 3–5.

Table 7 shows the effect of operating variables on performance parameter for water vapor and VOC absorbed by TEG solution. According to searching the related studies in the literature, the TEG solution was usually used to absorb water vapor in the absorber, and study about VOC absorbed by TEG solution was rare. On the basis of the fact that organic matter dissolves into an organic solution easily and the TEG solution is regenerated, the performance discussions of VOC absorbed by TEG solution were conducted in this study. In addition, there are also some information can be gotten from Table 7. For instance, the performance parameters are affected by many operating variables, but the popular variables of them are liquid flux, air flux, and concentration of absorbent solution. The performance parameters involved removal amount, absorption efficiency, and mass transfer coefficient were discussed more often for the absorption process. The effects of operating variables

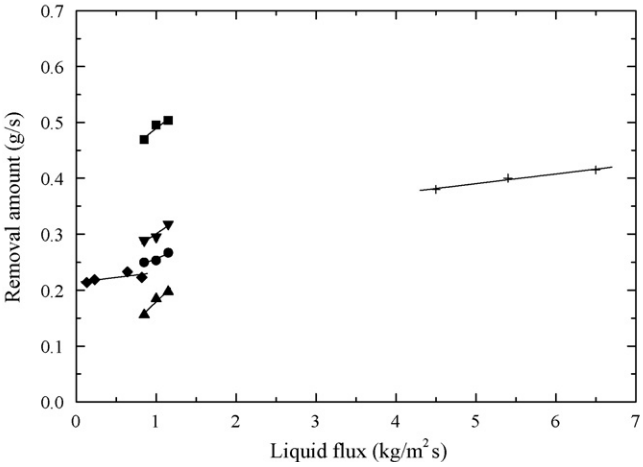


**Fig. 3.** Mass transfer data compared with literature studies for the liquid flux. The symbol ■ means removal amount of methanol in this present. The symbol ● means removal amount of toluene in this present. The symbol ▲ means removal amount of ethyl ether in this present. The symbol ▼ means removal amount of methyl-ethyl ketone in this present. The symbol ♦ means removal amount of water vapor in the study of Zurigat et al. [27]. The symbol + means removal amount of water vapor in the study of Oberg and Goswami [26].

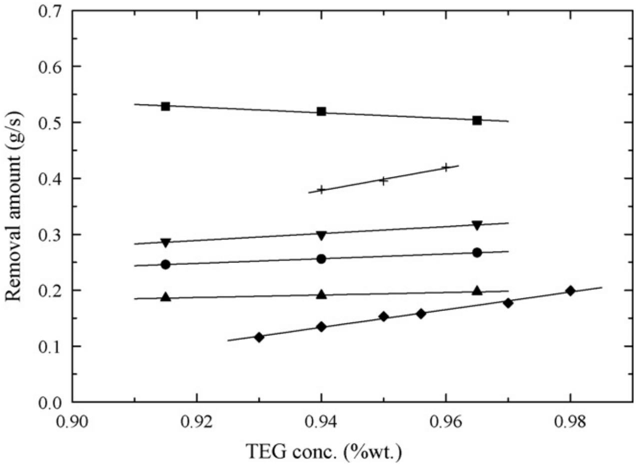


**Fig. 5.** Mass transfer data compared with literature studies for the TEG concentration. The symbol ■ means removal amount of methanol in this present. The symbol ● means removal amount of toluene in this present. The symbol ▲ means removal amount of ethyl ether in this present. The symbol ▼ means removal amount of methyl-ethyl ketone in this present. The symbol ♦ means removal amount of water vapor in the study of Zurigat et al. [27]. The symbol + means removal amount of water vapor in the study of Oberg and Goswami [26].

**Table 7**
Comparisons of performance parameter affected by operating variables with published data.

| Author (solution) | Performance parameter | Independent variables | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Present study | | $m_L$ (kg/m$^2$ s) | $m_a$ (kg/m$^2$ s) | $x$ (wt.%) | Conc. of methanol (ppm) | | | Packing size |
| | | 0.85–1.10 | 1.45–1.75 | 0.915–0.965 | 210–369 | | | 0.15 × 0.15 × 0.34 |
| (TEG) | $K_{GA}$ | ↑ | ↑ | ↓ | ↑ | | | |
| | $m_r$ | ↑ | ↑ | ↓ | ↑ | | | |
| | | $m_L$ (kg/m$^2$ s) | $m_a$ (kg/m$^2$ s) | $x$ (wt.%) | Conc. of toluene (ppm) | | | Packing size |
| | | 0.85–1.10 | 1.45–1.75 | 0.915–0.965 | 62–110 | | | 0.15 × 0.15 × 0.34 |
| (TEG) | $K_{GA}$ | ↑ | ↑ | ↑ | ↑ | | | |
| | $m_r$ | ↑ | ↑ | ↑ | ↑ | | | |
| | | $m_L$ (kg/m$^2$ s) | $m_a$ (kg/m$^2$ s) | $x$ (wt.%) | Conc. of ethyl ether (ppm) | | | Packing size |
| | | 0.85–1.10 | 1.45–1.75 | 0.915–0.965 | 58–155 | | | 0.15 × 0.15 × 0.34 |
| (TEG) | $K_{GA}$ | ↑ | ↑ | ↑ | ↑ | | | |
| | $m_r$ | ↑ | ↑ | ↑ | ↑ | | | |
| | | $m_L$ (kg/m$^2$ s) | $m_a$ (kg/m$^2$ s) | $x$ (wt.%) | Conc. of methyl-ethyl ketone (ppm) | | | Packing size |
| | | 0.85–1.10 | 1.45–1.75 | 0.915–0.965 | 105–205 | | | 0.15 × 0.15 × 0.34 |
| (TEG) | $K_{GA}$ | ↑ | ↑ | ↑ | ↑ | | | |
| | $m_r$ | ↑ | ↑ | ↑ | ↑ | | | |
| Zurigat et al. [27] | | $m_L$ (kg/m$^2$ s) | $m_a$ (kg/m$^2$ s) | $x$ (wt.%) | $T_L$ (°C) | $T_a$ (°C) | | Packing size |
| (TEG) | | 0.13–1.00 | 1.5–2.613 | 0.93–0.98 | 28–45 | 25.4–44.0 | | [$A$ (m$^2$) × $H$ (m)] |
| | $m_r$ | ↑ | ↑ | ↑ | ↓ | ↑ | | ~0.04 m$^2$ × 0.48 m |
| | $\varepsilon$ | ↑ | ↓ | ↑ | ↑ | – | | |
| Elsarrag [25] | | $m_a = 1.75$ | $m_a = 0.94$ | $m_L = 1.9$ | $Ha_{in}$ (g/kg) | $Z$ (m) | | Packing size |
| (TEG) | | $m_L$ (kg/m$^2$ s) | $m_L/m_a$ | $m_a$ (kg/m$^2$ s) | | | | [$L$ (m) × $W$ (m) × $H$ (m)] |
| | | 1.75–2.2 | 1.9–2.4 | 0.9–2.2 | 17–26 | 0.4–0.5 | | 0.4 × 0.4 × (0.4–0.5) |
| | $m_r$ | ↑ | – | ↑ | ↑ | ↑ | | |
| Chung et al. [6] | | $m_L$ (kg/m$^2$ s) | $m_a$ (kg/m$^2$ s) | $x$ (wt.%) | | | | Packing size |
| (LiCl) | | 4.6–6.5 | 0.5–2.0 | 0.94–0.96 | | | | [$A$ (m$^2$) × $H$ (m)] |
| | $\varepsilon$ | ↑ | ↓ | ↑ | | | | 0.0182 × 0.42 |
| | $K_{GA}$ | ↑ | ↑ | ↑ | | | | |
| Oberg and Goswami [26] | | $m_L$ (kg/m$^2$ s) | $m_a$ (kg/m$^2$ s) | $x$ (wt.%) | $T_L$ (°C) | $Ha_{in}$ (g/kg) | $Z$ (m) | Packing size |
| | | 4.5–6.5 | 0.5–2.0 | 0.94–0.96 | 25–35 | 11–22 | 0.4–0.8 | [$A$ (m$^2$) × $H$ (m)] |
| (TEG) | $m_r$ | – | ↑ | ↑ | ↓ | ↑ | ↑ | 0.0452 × (0.4–0.8) |
| | $\varepsilon$ | – | ↓ | – | – | – | ↑ | |
| Pontis and Lenz [28] | | $m_L$ (kg/m$^2$ s) | | | | | | Packing size |
| | | 0.2–1.2 | | | | | | [$A$ (m$^2$) × $H$ (m)] |
| (TEG) | $m_r$ | ↑ | | | | | | 0.5153 × 2 |

on performance parameters of this present were almost consistent with literature data. Since the wetting degree of packing should be depend on the liquid flux, the effect of the ratio of liquid flux to air flux on performance parameter was discussed by Elsarrag [25]. Elsarrag [25] found that the removal amount and absorption efficiency were increased with the increased ratio of liquid flux to air flux in the range between 0.97 and 1.3, which was attributed to wetting degree of packing was increased under the operating conditions. The performance parameter was not affected by the ratio of liquid flux to air flux in the range between 1.9 and 2.4. The author deduced that the best wetting degree had been attained, leading the performance not to be affected by the increased liquid flux. In addition to liquid and air fluxes, the absorption performance was also affected by wetting area of packing and the size of packed-bed. The size of packed-bed was always presented to describe absorption system, and the total number or total area of packing was barely presented in the report. Therefore, the size of packed-bed was also shown in Table 7 to compare the difference from literature studies. Since the size of the packed-bed of Elsarrag [25] was larger than Oberg and Goswami [26], Zurigat et al. [27], and this study, and the size of packed-bed of this present was similar to that of Zurigat et al. [27] and Oberg and Goswami [26]. Therefore, the mass transfer data of Oberg and Goswami [26], Zurigat et al. [27], and this present were compared in Figs. 3–5. In addition, one of the purposes of showing Figs. 3–5 was to analyze the relationship between operating variables and removal amount qualitatively.

The ratios of liquid flux to air flux are in the range between 0.58 and 0.8, and the removal amount was increased with the increased liquid flux. To reduce the carryover with the larger air flux, the air flux was operated from 57% to 70% of flooding in this study, and the controlled range of air flux is smaller as comparing the air flux with literature data. Nevertheless, the removal amount of this present was increased with the increased air flux, and the trend was similar to the present of Oberg and Goswami [26]; however, the increase of the removal amount presented by Zurigat et al. [27] was less significant than others in Fig. 4. The major difference between literature studies and this study was that water vapor absorbed by TEG solution were conducted by literature studies, and VOCs was removed by TEG solution in this study. Figs. 3–5 showed that the removal amounts of VOCs and water vapor absorbed by TEG solutions were in the same order of magnitude. Fig. 3 showed that the removal amount was increased with the increased liquid flux for both of water vapor and VOCs. The liquid flux operated by Oberg and Goswami [26] was larger than that of Zruigat et al. [27] and this study, leading the removal amount of Oberg and Goswami [26] to be higher than most data in Fig. 3; however, it was still lower than that of methanol in this study. Mentioned above, the result of TEG solution suitable for absorption of VOCs was demonstrated in Figs. 3–5.

Similarly, the removal amounts were increased with the increased air flux in Fig. 4. Since the size of packed-bed designed by Oberg and Goswami [26] was larger than that of Zurigat et al. [27] and this study, the removal amounts obtained by Oberg and Goswami [26] were higher than others in Fig. 4. Except methanol, the removal amounts were increased with the increased TEG concentration, as shown in Fig. 5. Since methanol almost dissolve into water liquid fully, and the attraction between methanol and water could be stronger than that between methanol and TEG. Therefore, the mass transfer performance was decreased with the increased TEG concentration. Fig. 5 also shows that the concentrations of TEG solutions were always controlled between 91 and 98 wt.% to work as absorbent solution.

### 5.2. *Effect of single factor on mass transfer coefficient*

The obtained *p*-value and *F*-ratio can be used to judge is the effect of experimental factor on response significant? The effect of experimental factor on response is more significant with the larger *F*-ratio or smaller *p*-value. On the contrary, the response is not affected by factors significantly with the smaller *F*-ratio or larger *p*-value. The degree of response affected by factors was defined by Montgomery [29] to assess the test results of *p*-value, which were listed as follows.

(1) $p$ value > 0.10, insignificant
(2) $0.05 < p$ value $\leqq 0.10$, significant slightly
(3) $0.01 < p$ value $\leqq 0.05$, significant
(4) $0.001 < p$ value $\leqq 0.01$, very significant
(5) $p$ value $\leqq 0.001$, extremely significant

The operating variables of individual VOC absorbed by TEG solution were scheduled by the two-level factorial experimental design methodology. For example, the designed tabulation for absorption of methanol was shown in Table 6. The obtained mass transfer coefficients were filled in Tables 6 and 8. Finally, the analysis of variables was performed to analyze experimental results. After regressed by the JMP software, the obtained values of determination coefficient ($R^2$) were 0.97, 0.96, 0.94, 0.99 for ethyl ether, methyl-ethyl ketone, toluene, and methanol, respectively. Since the entire determination coefficients are larger than 0.94, the regressed results should consist with experimental data. The results also mean that the experimental data should be correct and reasonable.

Since the action of H-bonding existed between methanol and water molecule, the attraction was stronger than the van der Waals' force between other VOCs and water molecule. The intermolecular attraction between methanol and water almost made methanol dissolve into water liquid fully, and the attraction between methanol and water was stronger than that between methanol and TEG. Therefore, the mass transfer coefficient was decreased with the increased TEG concentration. In view of statistics, the *p*-value was smaller than 0.0001 as TEG concentration was taken as variable for absorption of methanol. The result meant that effect of TEG concentration on mass transfer coefficient was extremely significant for absorption of methanol, as shown in Table 9. The mass transfer coefficient was not affected by air flux significantly as comparing with TEG concentration. Table 9 also shows the *p*-values for other VOCs were smaller than 0.1 except for methanol, so that effect of air flux on mass transfer coefficient was significant for other VOCs.

Since the VOCs concentrations were different for every VOC in the gas phase, the effect of VOCs concentration on mass transfer coefficient were different for every VOC. These results were described as follows. The concentration of methanol was ranged from 210 to 369 ppm, and the effect was extremely significant; the concentration of ethyl ether was ranged from 58 to 155 ppm, and the effect was very significant; the concentration of toluene was ranged from 62 to 110 ppm, and the effect was significant; the concentration of methyl-ethyl ketone was ranged from 105 to 205 ppm,

**Table 8**
Two-level factorial experimental design methodology and mass transfer coefficient.

| No. | Pattern | $K_{GA}$ for methanol | $K_{GA}$ for toluene | $K_{GA}$ for ethyl ether | $K_{GA}$ for ketone |
|---|---|---|---|---|---|
| 1 | + − + + | 0.0851 | 0.1477 | 0.0777 | 0.0670 |
| 2 | − − + − | 0.1027 | 0.1030 | 0.0484 | 0.0553 |
| 3 | + + − + | 0.0560 | 0.1139 | 0.0463 | 0.0561 |
| 4 | − − + + | 0.1067 | 0.1457 | 0.0617 | 0.0614 |
| 5 | − + − − | 0.0545 | 0.0817 | 0.0358 | 0.0397 |
| 6 | − − − − | 0.1010 | 0.0971 | 0.0388 | 0.0408 |
| 7 | + − − + | 0.0844 | 0.1415 | 0.0564 | 0.0574 |
| 8 | + + + − | 0.0502 | 0.1084 | 0.0447 | 0.0590 |
| 9 | − + − + | 0.0669 | 0.1177 | 0.0451 | 0.0486 |
| 10 | + − − − | 0.0754 | 0.1081 | 0.0402 | 0.0414 |
| 11 | − + + + | 0.0618 | 0.1221 | 0.0553 | 0.0590 |
| 12 | + + + + | 0.0590 | 0.1211 | 0.0582 | 0.0658 |
| 13 | − + + − | 0.0517 | 0.1008 | 0.0430 | 0.0550 |
| 14 | − − − + | 0.1049 | 0.1256 | 0.0486 | 0.0573 |
| 15 | + − + − | 0.0793 | 0.0984 | 0.0682 | 0.0593 |
| 16 | + + − − | 0.0413 | 0.0844 | 0.0378 | 0.0511 |

According to the sentence of the pattern: high level (+) of TEG conc. = 96.5 wt.%, low level (−) = 91.5 wt.%; high level (+) of VOCs conc. = 369 ppm for methanol, 110 ppm for toluene, 155 ppm for ethyl ether, 205 ppm for ketone, low level (−) = 210 ppm for methanol, 62 ppm for toluene, 58 ppm for ethyl ether, 105 ppm for ketone; high level (+) of air flux = 1.75 kg/m$^2$ s, low level (−) = 1.45 kg/m$^2$ s; high level (+) of liquid flux = 1.15 kg/m$^2$ s, low level (−) = 0.85 kg/m$^2$ s.

**Table 9**
*F* ratio and *p* value obtained from analysis of variance.

| Source | *F* ratio for methanol | *p* value for methanol | *F* ratio for toluene | *p* value for toluene | *F* ratio for ethyl ether | *p* value for ethyl ether | *F* ratio for ketone | *p* value for ketone |
|---|---|---|---|---|---|---|---|---|
| TEG conc. | 158.7796 | 0.000056 | 0.7556 | 0.424450 | 14.1916 | 0.013061 | 12.6471 | 0.016279 |
| VOC conc. | 989.1960 | 0.000001 | 11.6182 | 0.019073 | 27.7942 | 0.003366 | 0.2411 | 0.644200 |
| $G$ | 1.6056 | 0.260927 | 5.0752 | 0.074016 | 59.4684 | 0.000585 | 62.3377 | 0.000524 |
| $L$ | 52.7608 | 0.000773 | 54.6370 | 0.000713 | 43.7945 | 0.001186 | 39.5403 | 0.001495 |
| TEG conc. × VOC conc. | 43.6715 | 0.001193 | 0.2924 | 0.611868 | 7.0965 | 0.044673 | 2.9455 | 0.146771 |
| TEG conc. × $G$ | 4.7811 | 0.080443 | 0.4072 | 0.551451 | 3.9860 | 0.102397 | 0.0055 | 0.943562 |
| VOC conc. × $G$ | 0.1782 | 0.690494 | 0.8781 | 0.391734 | 6.5976 | 0.050122 | 0.0655 | 0.808151 |
| TEG conc. × $L$ | 0.6783 | 0.447647 | 0.0106 | 0.922167 | 0.0413 | 0.846988 | 0.0000 | 0.997246 |
| VOC conc. × $L$ | 6.0521 | 0.057222 | 2.4928 | 0.175202 | 0.1385 | 0.725021 | 3.6320 | 0.115006 |
| $G \times L$ | 1.3711 | 0.294383 | 0.0016 | 0.969776 | 0.1221 | 0.740996 | 3.6313 | 0.115033 |

**Table 10**
Mass transfer coefficient compared between high and low levels of VOCs concentration.

| Liquid flux (kg/m$^2$ s) | $K_{GA}$ for high level of VOCs (kmol/m$^3$ s) | $K_{GA}$ for low level of VOCs (kmol/m$^3$ s) | Difference between high and low levels |
|---|---|---|---|
| Methanol | | | |
| 0.85 | 0.0800 | 0.0502 | 0.0298 |
| 1 | 0.0830 | 0.0580 | 0.0250 |
| 1.15 | 0.0851 | 0.0618 | 0.0233 |
| Toluene | | | |
| 0.85 | 0.1150 | 0.1084 | 0.0066 |
| 1 | 0.1256 | 0.1100 | 0.0156 |
| 1.15 | 0.1477 | 0.1212 | 0.0265 |
| Ethyl ether | | | |
| 0.85 | 0.0680 | 0.0447 | 0.0233 |
| 1 | 0.0700 | 0.0540 | 0.0160 |
| 1.15 | 0.0777 | 0.0582 | 0.0195 |
| Methyl-ethyl ketine | | | |
| 0.85 | 0.0600 | 0.0580 | 0.0020 |
| 1 | 0.0630 | 0.0600 | 0.0030 |
| 1.15 | 0.0670 | 0.0650 | 0.0020 |

and the effect was insignificant. Table 10 shows that effect of high and low level of VOCs concentration on mass transfer coefficient. By observing the gap between high and low level of VOCs concentrations, the extent of the impact should be in the sequence of methanol, ethyl ether, toluene, and methyl-ethyl ketone. These results demonstrated that the *p*-value testing agreed with experimental results well as the statistical results were compared with Table 10. In addition, all the *p*-values were smaller than 0.01 as liquid flux was taken as variable and effect of liquid flux on mass transfer coefficient was very significant in this study. In addition to this study, some studies also show that the liquid flow was an important factor for the absorption system. For example, Wen et al. [30] and Yuan et al. [31] showed that the mass transfer performance of packed column was affected by liquid flow distribution and superficial liquid flow velocity, respectively. Besides, Yin et al. [32] and Zanfir et al. [33] also thought that the liquid distribution and liquid volume were the important factor to affect mass transfer conditions, and then the factor about liquid flow was considered in their modeling.

### 5.3. *The meaning of factorial interaction in the statistics and the application to engineering study*

To explain the relationship between factorial interaction and response, temperature and pressure are regarded as two selected variables. Figs. 6 and 7 show the factorial interaction is insignificant; Figs. 8 and 9 show the factorial interaction is extremely significant.

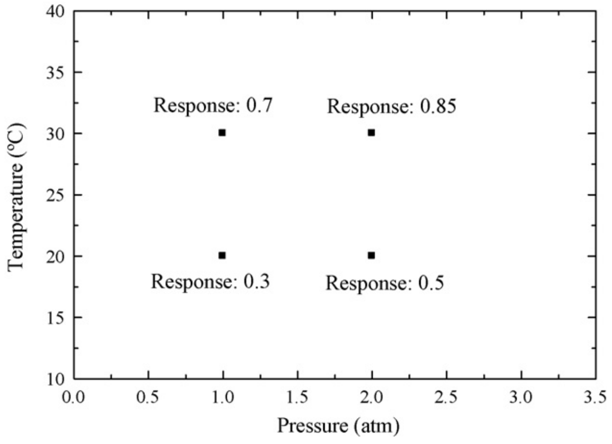


**Fig. 6.** Factorial interaction between temperature and pressure (insignificant).

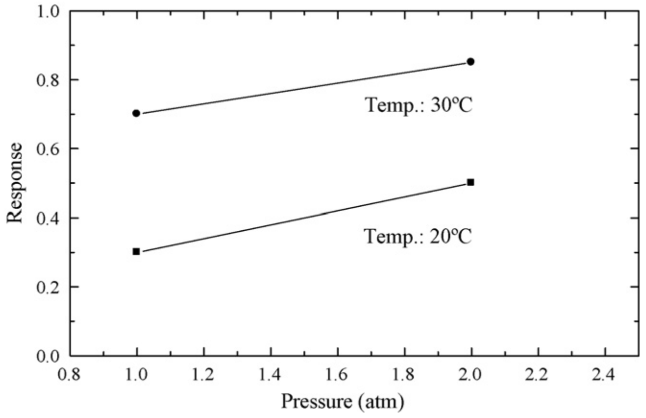


**Fig. 7.** Response affected by the second variable (temperature) with the increased pressure (insignificant).

The factorial interaction is insignificant, and the responses display similar tendency with the increased variable 1 (that is pressure, or the variable in the transverse axis) for the temperature at 20 and 30 °C, respectively, as shown in Figs. 6 and 7. The factorial interaction is extremely significant, and the responses display opposite tendency with the increased variable 1 for the different variable 2, as shown in Figs. 8 and 9. That is the slope

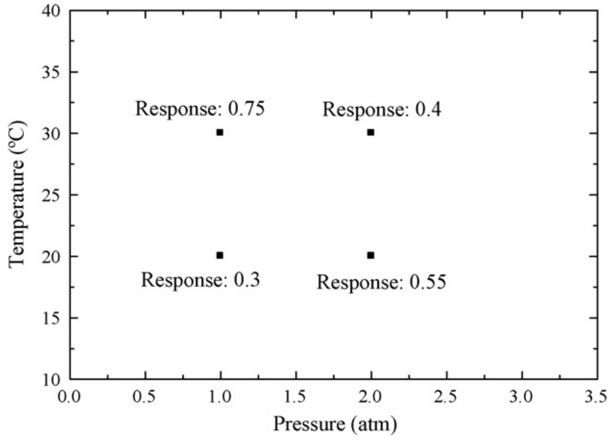


**Fig. 8.** Factorial interaction between temperature and pressure (extremely significant).

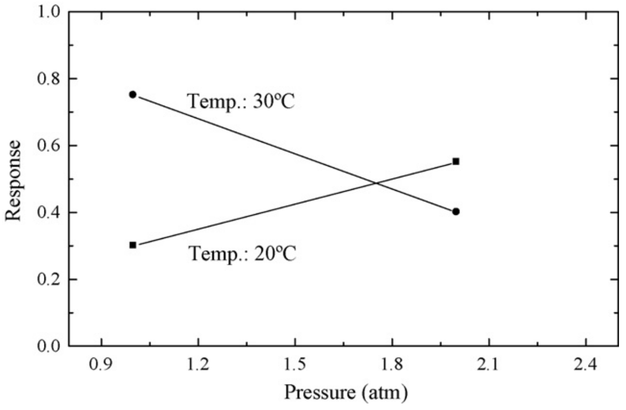


**Fig. 9.** Response affected by the second variable (temperature) with the increased pressure (extremely significant).

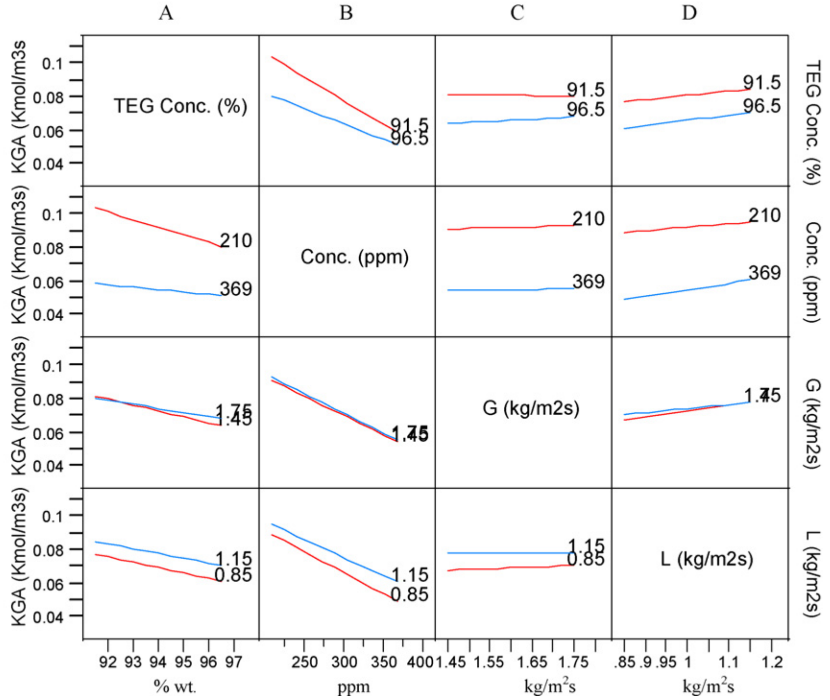


**Fig. 10.** Relationship between factorial interaction and mass transfer coefficient for methanol.

is positive for one line, and the other is negative. These results will be reacted to the Fig. 10. Although the slopes of two lines in any diagrams of Fig. 10 do not display opposite tendency, the different slope between two lines can be observed in some diagrams of Fig. 10. For example, the slopes of two lines are different in A2 and B1 diagrams. The *p*-value obtained from ANOVA is 0.001193 and the factorial interaction between TEG conc. and VOC conc. is very significant. Of course, the larger factorial interaction occurs under the responses display opposite tendency for different variable 2; however, the factorial interaction may also be very significant or significant for two lines with just different slopes. Generally speaking, the smaller is the *p*-value, the larger difference of slope between two lines is. That means the factorial interaction is more significant for the smaller *p*-value.

On the other point of view, the industrial or engineering studies are focused on the control of response, and many operating variables exist in the industrial or engineering processes. Therefore, how to select some main variables to operate the system and to acquire the desired response seem to be the more important task for the industrial and engineering field. In addition, one purpose of this study is to find the main operating variables. Therefore, comparison of size of *p*-value should be more important than the message of the factorial interaction is significant or insignificant. Mentioned above, the factorial interaction is higher for the smaller *p*-value. According to the obtained *p*-value and the figure of relationship between factorial interaction and mass transfer coefficient, we found that the significant interaction between two factors reveals some information, (1) both factors affect the response significantly, (2) the overlap of two lines is not significant in the diagram of response vs. variables, (3) and the distribution of mass transfer coefficient is wider. Therefore, the smaller *p*-value for the factorial couple was also deduced that the distribution of the response should be wider under the factorial couple, and the desired response should also be obtained or controlled easily by the factorial couple. Therefore, the concept can be used to obtain the desired response by the main variables in any industrial or scientific study.

### 5.4. Effect of factorial interaction on mass transfer coefficient

There are many operating variables in the manufacturing processes of the industry, and how to select one or two major variables among all variables to control the response of the manufacturing processes is an important task. Mentioned above, the method of ANOVA not only can be used to analyze effect of single factor on response, but also can be used to describe the relationship between factorial interaction and mass transfer coefficient. Therefore, the method of ANOVA was performed to discuss the relationships between operating variables and mass transfer performance of the absorption system.

Since the descriptions of relationships between factorial interaction and mass transfer coefficient are similar for every VOC absorbed by TEG solution, the relationship for absorption of methanol is chosen to describe in this section. Both of *p*-value and *F*-ratio are shown in Table 9 to present effects of single factor and factorial interaction on mass transfer coefficient. In addition, Fig. 10, obtained from the statistical software, shows the mass transfer coefficient changed with variables for methanol, and all diagrams included two variables. Therefore, the relationships between factorial interaction and mass transfer coefficient can be analyzed in Table 9 and Fig. 10, and the results are described as follows. The smaller is the *p*-value, the more the response (mass transfer coefficient) is affected by two chosen factors. The phenomena of the more divided curves in Fig. 10 and the wider distributions of mass transfer coefficient are accompanied with the smaller *p*-value. On the contrary, the less the response is affected by two selected factors, the larger the *p*-value is. The phenomena of the closer curves in Fig. 10 and the narrower distributions of mass transfer coefficient are accompanied with the larger *p*-value. Briefly, the overlap of response is insignificant for the lower *p*-value, that is, the mass transfer coefficient can be controlled easier by two chosen variables with the lower *p*-value, and the concept can be used to adjust the desired response in the industry.

The *p*-value for factorial interaction between TEG concentration and methanol concentration is 0.001193. The value means that the mass transfer coefficient is affected by these two variables, and the distribution of mass transfer coefficient would be wider than other couples of variables. Since the *p*-value (0.057222) for factorial interaction between methanol concentration and liquid flux is larger than that between TEG concentration and methanol concentration, the relationship between factors and mass transfer coefficient is less significant than effect of TEG and methanol concentrations on mass transfer coefficient. That is the mass transfer coefficient might be only affected by one of these two variables or might be changed insignificantly by these two variables. Besides, the distribution of mass transfer coefficient is narrower than effect of TEG and methanol concentrations. The *p*-value for factorial interaction between TEG concentration and air flux is 0.080443, and effect of TEG concentration and air flux on mass transfer coefficient is similar to that of methanol concentration and liquid flux. The *p*-values for methanol concentration × air flux, TEG concentration × liquid flux, air flux × liquid flux are 0.690494, 0.447647, and 0.294383, respectively, and the relationships between factorial interaction and mass transfer coefficient are insignificant. The results seem to reveal some information for *p*-value larger than 0.1: (1) the mass transfer coefficient might be affected by two selected variables insignificantly, (2) although the mass transfer coefficient is affected by these two variables, the overlap of curves in Fig. 10 could be significant for these two variables. In addition, the relationship between factorial interaction and mass transfer coefficient can be described in detail by Fig. 10 as follows.

Fig. 10 shows the relationship between factorial interaction and mass transfer coefficient. The ordinate is the overall mass transfer coefficient for the gas phase, and the abscissa is the operating variables. High and low levels of the second variable are also involved in every diagram. The mass transfer coefficient affected by factorial interaction of TEG concentration and methanol concentration can be discussed from A2 and B1 diagrams, and the mass transfer coefficient affected by factorial interaction of methanol concentration and liquid flux can be discussed from B4 and D2 diagrams. The remaining relationships between factorial interaction and mass transfer coefficient can also be found out the diagrams from Fig. 10 for other couples of variables. Followed above, the *p*-value for TEG concentration and methanol concentration is 0.001193, and effect of variables on mass transfer coefficient is very significant. The relationship between two variables and mass transfer coefficient can be analyzed from A2 and B1 diagrams. As shown in A2 diagram, the mass transfer coefficients for high and low level of methanol concentration are decreased and not overlapped with the increased TEG concentration. In addition, the B1 diagram shows that the curves for 91.5 and 96.5 wt.% TEG concentrations do not overlap and the distribution of mass transfer coefficients is wider with the increased methanol concentration. Briefly, the interactive effects of TEG concentration and methanol concentration on mass transfer coefficient are significant.

The *p*-value for methanol concentration and air flux is 0.690494, and effect of variables on mass transfer coefficient would be insignificant. The relationships between methanol concentration × air flux and mass transfer coefficient can analyzed by B3 and C2 diagrams. The B3 diagram shows that the curves for 1.45 and 1.75 kg/m$^2$ s air fluxes are almost approached each other. Although the distribution of mass transfer coefficient is wide (0.05–0.09), the changes of mass transfer coefficient depend on methanol concentration mainly. As shown in C2 diagram, the curves for 210 and 369 ppm methanol concentrations do not overlap; however, the mass transfer coefficients are not changed with the increased air flux significantly. Since the effect of air flux on mass transfer coefficient is insignificant (the *p*-value is 0.260927), the curves in the C2 diagram almost tend toward two horizontal line. Though the mass transfer coefficients are decreased with methanol concentration significantly, the mass transfer coefficients are not affected by the air flux significantly. Briefly, the relationships between methanol concentration × air flux and mass transfer coefficient are insignificant. The effect of air flux on mass transfer coefficient can also be observed from C1, C2, and C4 diagrams and these curves almost tend toward a horizontal line. The results lead the interactive effects of air flux and the other variable on mass transfer coefficient to be insignificant. Mentioned above, not only the effect of single factor on response can be discussed by the *p*-value, but also the distribution of mass transfer coefficient can be analyzed by two chosen variables from the related diagrams in the statistics. The interaction profiles for toluene, ethyl ether, and methyl-ethyl ketone were shown in Appendix A, and discussions about relationship between factors and mass transfer coefficient can be referred as described above.

### 5.5. Analysis of the better operating conditions for the absorption system

Although the development of statistics has a history of over two hundred years, engineering studies which employ the experimental design methodology and analysis of variance have been limited [33–36], especially in absorption processes. In addition, some definitions or descriptions in statistical terminology are not applicable in the engineering field, and should be redefined to enlarge the application in the engineering area. For example, the factorial interaction in statistics might be reinterpreted to describe the relationship between variables and response in engineering, such as the effect of variables on response, the distribution of response, and the properties of curves in the diagram of interaction profile. How much extent of effect of variable on response is changed by another variable is the focus of factorial interaction in statistics; however, most of the engineering processes are focused on how to attain the desired response by the less cost and time, and the inner variables could be chosen from experimental results. Therefore, the interaction profiles of the ANOVA could be used to observe the effect of variables on mass transfer coefficient, the distribution of mass transfer coefficient, and whether the curves are overlapped in the diagram. Mentioned in Section 5.3, the significant interaction for the engineering application reveals that: (1) the response will be affected by the two factors, (2) the overlap of the curves is not significant in the diagram of response vs. variables, (3) and the distribution of mass transfer coefficient is wider. Mentioned above, the response can be controlled or adjusted easier or faster in the engineering by the more significant interaction between factors in the statistics.

Observed from the experimental results, high level of liquid and air fluxes always gave larger mass transfer coefficients. The mass transfer coefficient is increased with the higher TEG concentration except for methanol. Besides, the mass transfer coefficient is larger with the lower concentration of VOCs under the controlled concentration in this study. To obtain the larger mass transfer coefficient for absorbing methanol by TEG solution, the operating conditions should be controlled under the lower TEG concentration, the lower VOC concentration, and the higher gas and liquid fluxes. However, the larger mass transfer coefficient should be obtained under the higher TEG concentration, the lower VOC concentration, and the higher liquid and air fluxes for toluene, ethyl ether, and methyl-ethyl ketone.

On the basis of reinterpretation of the factorial interaction, the factorial couple with more significant interaction can be chosen as main operating factors to acquire the desired mass transfer coefficient for the absorption system. Observed from Table 9, the lowest *p*-values are concentration of toluene × liquid flux, TEG concentration × concentration of methanol, TEG concentration × concentration of ethyl ether, and concentration of ketone × liquid flux for absorption of toluene, methanol, ethyl ether, and ketone, respectively. These factorial couples can be

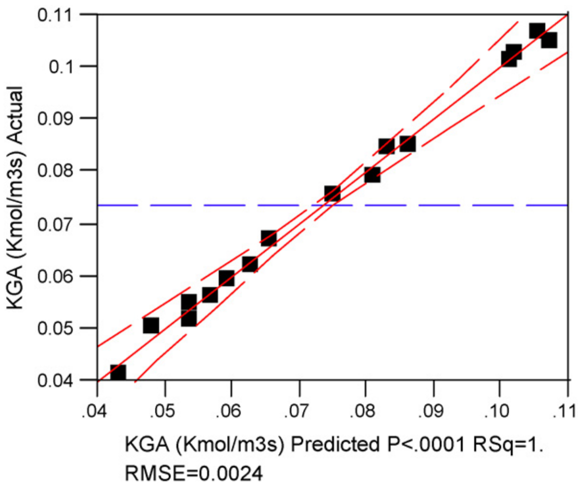


**Fig. 11.** Relationship between experimental and predicted mass transfer coefficient for methanol.

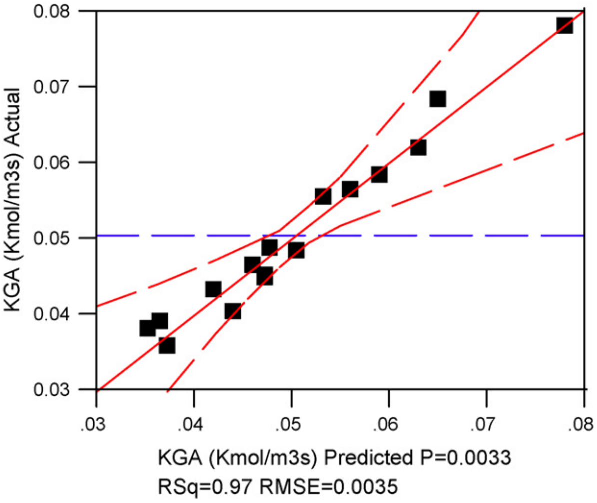


**Fig. 13.** Relationship between experimental and predicted mass transfer coefficient for ethyl ether.

regarded as the main variables to operate the absorption systems at first. Oppositely, if the couples with higher $p$-values are selected unwarily, the researchers or engineers could find that the distribution of the response value could be narrow, or the response could be affected by only one factor, that is, the effect of the other factor on response was almost insignificant.

### 5.6. *Comparison of experimental mass transfer coefficients with predicted results*

The relationship between experimental and predicted mass transfer coefficient is acquired easily by the JMP software, and the results of methanol, toluene, ethyl ether and methyl-ethyl ketone are shown in Figs. 11–14, respectively. The values of determination coefficient ($R^2$) were 1.00, 0.94, 0.97, and 0.96 for methanol, toluene, ethyl ether, and methyl-ethyl ketone, respectively. Since all the determination coefficients are larger than 0.94, the experimental mass transfer coefficients would be agreed well with predicted mass transfer coefficient. The results of analysis of variance would also be confident. The calculated formula for predicting mass transfer coefficient of methanol can be shown as follows.

$$
\begin{aligned}
&\text{Predicted mass transfer coefficient of methanol} = 0.422523974528309\\
&+\{(-0.002987575000000)\times[\text{TEG conc.}(\%)]\}\\
&+(-0.000234496069182)\times[\text{conc.}(\text{ppm})]\\
&+0.000751062500000\times\left\{\frac{G(\text{kg/m}^2\,\text{s})-1.6}{0.15}\right\}\\
&+0.004305437500000\times\left\{\frac{L(\text{kg/m}^2\,\text{s})-1}{0.15}\right\}\\
&+\{[\text{TEG conc.}(\%)-94]\times[\text{conc.}(\text{ppm})-289.5]\times 0.000019708490566\}\\
&+\left\{[\text{TEG conc.}(\%)-94]\times\left\{\frac{G(\text{kg/m}^2\,\text{s})-1.6}{0.15}\right\}\times 0.000518425000000\right\}\\
&+\left\{[\text{TEG conc.}(\%)-94]\times\left\{\frac{L(\text{kg/m}^2\,\text{s})-1}{0.15}\right\}\times 0.000195275000000\right\}\\
&+\left\{[\text{Conc.}(\text{ppm})-289.5]\times\left\{\frac{G(\text{kg/m}^2\,\text{s})-1.6}{0.15}\right\}\times(-0.000003147012579)\right\}\\
&+\left\{[\text{Conc.}(\text{ppm})-289.5]\times\left\{\frac{L(\text{kg/m}^2\,\text{s})-1}{0.15}\right\}\times 0.000018341981132\right\}\\
&+\left\{\left\{\frac{G(\text{kg/m}^2\,\text{s})-1.6}{0.15}\right\}\times\left\{\frac{L(\text{kg/m}^2\,\text{s})-1}{0.15}\right\}\times(-0.000694062499999)\right\}
\end{aligned}
$$

The calculated formula can be obtained from statistical result speedily, and the format is similar to other VOCs. Therefore,

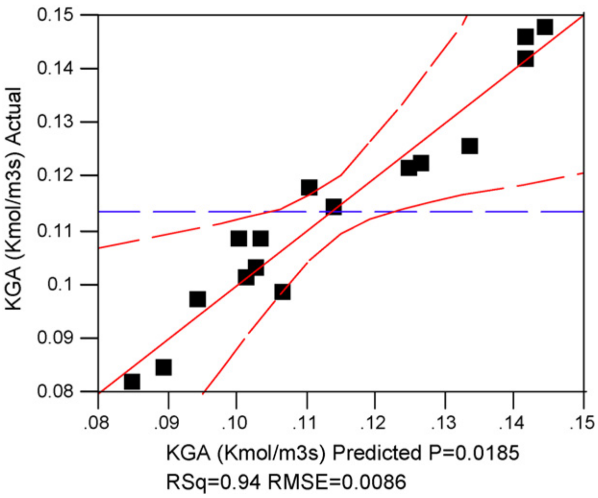


**Fig. 12.** Relationship between experimental and predicted mass transfer coefficient for toluene.

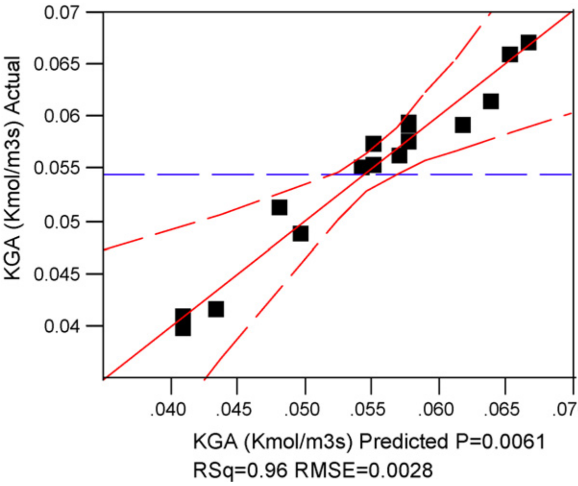


**Fig. 14.** Relationship between experimental and predicted mass transfer coefficient for methyl-ethyl ketone.

formulas for predicting mass transfer coefficients of toluene, ethyl ether, and methyl-ethyl ketone are only shown in Appendix to be referred.

## 6. Conclusion

A two-level factorial experimental design methodology was used to schedule the operating variables for a packed-bed absorber. The experimental design methodology and ANOVA were introduced into engineering study successfully. The effects of factors on response were analyzed by the method of ANOVA, and the statistical results were consistent with experimental results. The major operating variables were found from analysis of factorial interaction, and most mass transfer coefficient can be acquired by them for the absorption system. Some important results are itemized as follows.

1. From ANOVA, the relationships between mass transfer coefficient and operating variables are shown as follows. The mass transfer coefficients of methanol absorbed by TEG solution were affected by TEG concentration, methanol concentration, and liquid flux significantly. The mass transfer coefficients of toluene absorbed by TEG solution were affected by TEG concentration, air flux, and liquid flux significantly. The mass transfer coefficients of ethyl ether absorbed by TEG solution were affected by TEG concentration, air flux, and liquid flux significantly. The mass transfer coefficients of ketone absorbed by TEG solution were affected by air flux and liquid flux significantly.
2. The experimental results show that the operating conditions should be controlled under the lower TEG concentration, the lower VOC concentration, and the higher air and liquid fluxes to obtain the larger mass transfer coefficient for methanol absorbed by TEG solution; However, the operating conditions should be controlled under the higher TEG concentration, the lower VOC concentration, and the higher liquid and air fluxes to obtain the larger mass transfer coefficient for toluene, ethyl ether, and methyl-ethyl ketone absorbed by TEG solution.
3. The significant factorial interaction means that mass transfer coefficient was affected by two chosen factors significantly, the curves in the diagram of mass transfer coefficient vs. factor did not overlap and the distribution of mass transfer coefficient is wider than other factorial couples. As shown in Table 9, the lowest *p*-values and factorial couples for each VOC are summarized as follows. The lowest *p*-value and factorial couple are 0.175202 and toluene concentration × liquid flux for toluene. The lowest *p*-value and factorial couple are 0.001193 and TEG concentration × methanol concentration for methanol. The lowest *p*-value and factorial couple are 0.044673 and TEG concentration × ethyl ether concentration for ethyl ether. The lowest *p*-value and factorial couple are 0.115006 and ketone concentration × liquid flux for ketone. The results show that the desired mass transfer coefficient could be acquired easily by these major variables for the absorption system.

Mentioned above, the method of ANOVA not only can analyze to what extent the mass transfer coefficient is affected by a single variable, but also can help to choose the main factors to improve the mass transfer coefficient. In addition, the experimental design methodology with ANOVA can help researchers to obtain correct and reasonable results from fewer experimental runs. The mass transfer data can also be referred by designers and researchers to set up related absorbers.

## Acknowledgments

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## Appendix A.

Experimental schedule, interaction profile, and predicted formula of mass transfer coefficient for ethyl ether, toluene, and methyl-ethyl ketone.

The experimental schedule and interaction profile for ethyl ether is shown in Table A1 and Fig. A1.

$$
\begin{aligned}
&\text{Predicted formula for ethyl ether} = 0.050362169007732\\
&\quad + 0.003294252126289 \times \left\{ \frac{[\text{TEG conc.}(\%) - 94]}{2.5} \right\}\\
&\quad + (-0.004567288724227) \times \left\{ \frac{[\text{ethyl ether}(\text{ppm}) - 106.85]}{48.05} \right\}\\
&\quad + 0.006743478801546 \times \left\{ \frac{G(\text{kg/m}^2\,\text{s}) - 1.6}{0.15} \right\}\\
&\quad + 0.005786963981959 \times \left\{ \frac{L(\text{kg/m}^2\,\text{s}) - 1}{0.15} \right\}\\
&\quad + \left\{ \frac{[\text{TEG conc.}(\%) - 94]}{2.5} \right\} \times \left\{ \frac{[\text{ethyl ether}(\text{ppm}) - 106.85]}{48.05} \right\} (-0.002307824162371)\\
&\quad + \left\{ \frac{[\text{TEG conc.}(\%) - 94]}{2.5} \right\} \times \left\{ \frac{G(\text{kg/m}^2\,\text{s}) - 1.6}{0.15} \right\} \times 0.001745812499999\\
&\quad + \left\{ \frac{[\text{ethyl ether}(\text{ppm}) - 106.85]}{48.05} \right\} \times \left\{ \frac{G(\text{kg/m}^2\,\text{s}) - 1.6}{0.15} \right\} \times (-0.00222522274485)\\
&\quad + \left\{ \frac{[\text{TEG conc.}(\%) - 94]}{2.5} \right\} \times \left\{ \frac{L(\text{kg/m}^2\,\text{s}) - 1}{0.15} \right\} \times 0.000177687499999\\
&\quad + \left\{ \frac{[\text{ethyl ether}(\text{ppm}) - 106.85]}{48.05} \right\} \times \left\{ \frac{L(\text{kg/m}^2\,\text{s}) - 1}{0.15} \right\} \times (-0.000322417976804)\\
&\quad + \left\{ \frac{[G(\text{kg/m}^2\,\text{s}) - 1.6]}{0.15} \right\} \times \left\{ \frac{[L(\text{kg/m}^2\,\text{s}) - 1]}{0.15} \right\} \times 0.000305562500000
\end{aligned}
$$

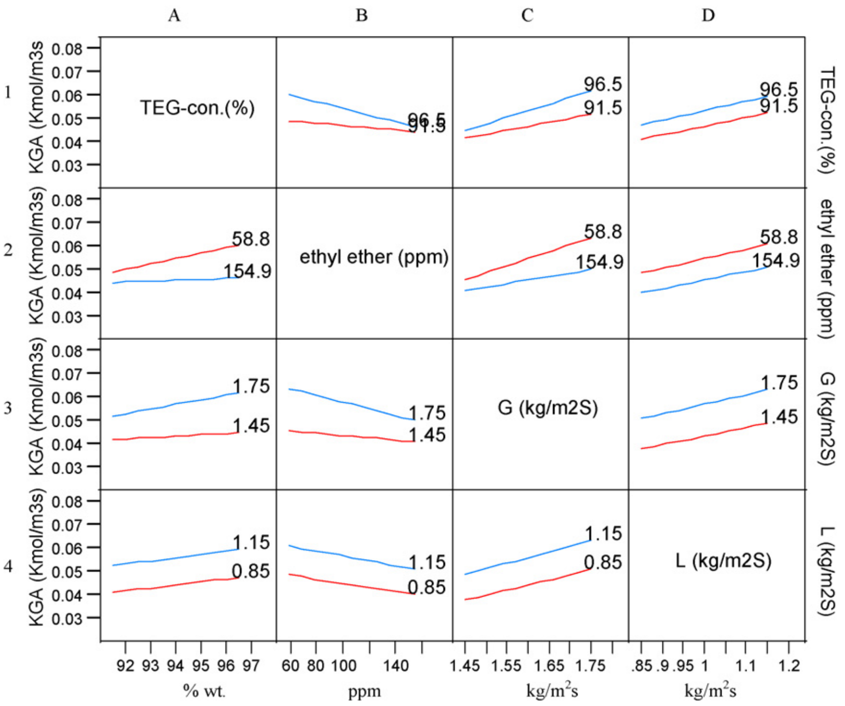

**Fig. A1.** Relationship between factorial interaction and mass transfer coefficient for ethyl ether.

**Table A1**
Variable schedule and experimental response for ethyl ether.

| No. | Pattern | TEG conc. | Conc. | $G$ | $L$ | $K_{GA}$ |
|---|---|---|---|---|---|---|
| 1 | + – + + | 96.5 | 58 | 3.0 | 1.43 | 0.077748 |
| 2 | – – + – | 91.5 | 58 | 3.0 | 1.24 | 0.048357 |
| 3 | + + – + | 96.5 | 155 | 2.75 | 1.43 | 0.046339 |
| 4 | – – + + | 91.5 | 58 | 3.0 | 1.43 | 0.061734 |
| 5 | – + – – | 91.5 | 155 | 2.75 | 1.24 | 0.035773 |
| 6 | – – – – | 91.5 | 58 | 2.75 | 1.24 | 0.038756 |
| 7 | + – – + | 96.5 | 58 | 2.75 | 1.43 | 0.056386 |
| 8 | + + + – | 96.5 | 155 | 3.0 | 1.24 | 0.044673 |
| 9 | – + – + | 91.5 | 155 | 2.75 | 1.43 | 0.045140 |
| 10 | + – – – | 96.5 | 58 | 2.75 | 1.24 | 0.040244 |
| 11 | – + + + | 91.5 | 155 | 3.0 | 1.43 | 0.055297 |
| 12 | + + + + | 96.5 | 155 | 3.0 | 1.43 | 0.058221 |
| 13 | – + + – | 91.5 | 155 | 3.0 | 1.24 | 0.043005 |
| 14 | – – – + | 91.5 | 58 | 2.75 | 1.43 | 0.048613 |
| 15 | + – + – | 96.5 | 58 | 3.0 | 1.24 | 0.068206 |
| 16 | + + – – | 96.5 | 155 | 2.75 | 1.24 | 0.037835 |

**Table A2**
Variable schedule and experimental response for toluene.

| No. | Pattern | TEG conc. | Conc. | $G$ | $L$ | $K_{GA}$ |
|---|---|---|---|---|---|---|
| 1 | + – + + | 96.5 | 62 | 3.0 | 1.43 | 0.147682 |
| 2 | – – + – | 91.5 | 62 | 3.0 | 1.24 | 0.103016 |
| 3 | + + – + | 96.5 | 110 | 2.75 | 1.43 | 0.113964 |
| 4 | – – + + | 91.5 | 62 | 3.0 | 1.43 | 0.145744 |
| 5 | – + – – | 91.5 | 110 | 2.75 | 1.24 | 0.081661 |
| 6 | – – – – | 91.5 | 62 | 2.75 | 1.24 | 0.097115 |
| 7 | + – – + | 96.5 | 62 | 2.75 | 1.43 | 0.141468 |
| 8 | + + + – | 96.5 | 110 | 3.0 | 1.24 | 0.108355 |
| 9 | – + – + | 91.5 | 110 | 2.75 | 1.43 | 0.117715 |
| 10 | + – – – | 96.5 | 62 | 2.75 | 1.24 | 0.108101 |
| 11 | – + + + | 91.5 | 110 | 3.0 | 1.43 | 0.122092 |
| 12 | + + + + | 96.5 | 110 | 3.0 | 1.43 | 0.121193 |
| 13 | – + + – | 91.5 | 110 | 3.0 | 1.24 | 0.100831 |
| 14 | – – – + | 91.5 | 62 | 2.75 | 1.43 | 0.125609 |
| 15 | + – + – | 96.5 | 62 | 3.0 | 1.24 | 0.098417 |
| 16 | + + – – | 96.5 | 110 | 2.75 | 1.24 | 0.084421 |

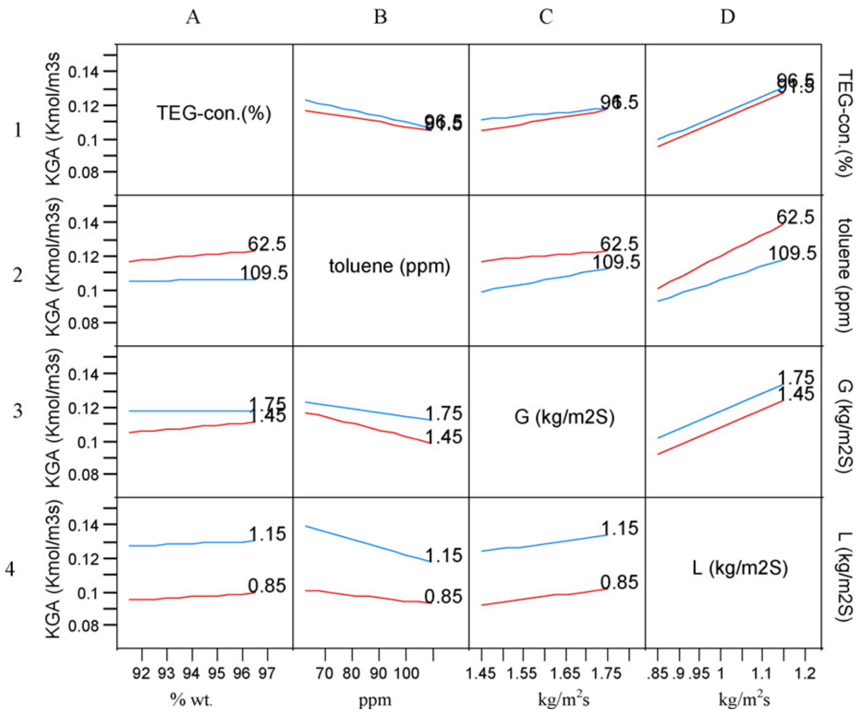

**Fig. A2.** Relationship between factorial interaction and mass transfer coefficient for toluene.

The experimental schedule and interaction profile for toluene is shown in Table A2 and Fig. A2.

$$
\begin{aligned}
&\text{Predicted formula for toluene} = 0.1135865\\
&+ 0.001863624999999 \times \left\{\frac{[\text{TEG conc.}(\%) - 94]}{2.5}\right\}\\
&+ (-0.007155260416667) \times \left\{\frac{[\text{toluene}(\text{ppm}) - 86]}{23.5}\right\}\\
&+ 0.00482974999999 \times \left\{\frac{G(\text{kg/m}^2\,\text{s}) - 1.6}{0.15}\right\}\\
&+ 0.015846875 \times \left\{\frac{L(\text{kg/m}^2\,\text{s}) - 1}{0.15}\right\}\\
&+ \left\{\frac{[\text{TEG conc.}(\%) - 94]}{2.5}\right\} \times \left\{\frac{[\text{toluene}(\text{ppm}) - 86]}{23.5}\right\} \times (-0.001135221354167)\\
&+ \left\{\frac{[\text{TEG conc.}(\%) - 94]}{2.5}\right\} \times \left\{\frac{G(\text{kg/m}^2\,\text{s}) - 1.6}{0.15}\right\} \times (-0.00136812499999)\\
&+ \left\{\frac{[\text{toluene}(\text{ppm}) - 86]}{23.5}\right\} \times \left\{\frac{G(\text{kg/m}^2\,\text{s}) - 1.6}{0.15}\right\} \times 0.001967145833333\\
&+ \left\{\frac{[\text{TEG conc.}(\%) - 94]}{2.5}\right\} \times \left\{\frac{L(\text{kg/m}^2\,\text{s}) - 1}{0.15}\right\} \times (-0.000220250000000)\\
&+ \left\{\frac{[\text{toluene}(\text{ppm}) - 86]}{23.5}\right\} \times \left\{\frac{L(\text{kg/m}^2\,\text{s}) - 1}{0.15}\right\} \times (-0.003314356770833)\\
&+ \left\{\frac{[G(\text{kg/m}^2\,\text{s}) - 1.6]}{0.15}\right\} \times \left\{\frac{[L(\text{kg/m}^2\,\text{s}) - 1]}{0.15}\right\} \times (-0.000085374999999)
\end{aligned}
$$

**Table A3**
Variable schedule and experimental response for ketone.

| No. | Pattern | TEG conc. | Conc. | $G$ | $L$ | $K_{GA}$ |
|---|---|---|---|---|---|---|
| 1 | + − + + | 96.5 | 105 | 3.0 | 1.43 | 0.067018 |
| 2 | − − + − | 91.5 | 105 | 3.0 | 1.24 | 0.055251 |
| 3 | + + − + | 96.5 | 205 | 2.75 | 1.43 | 0.056142 |
| 4 | − − + + | 91.5 | 105 | 3.0 | 1.43 | 0.061391 |
| 5 | − + − − | 91.5 | 205 | 2.75 | 1.24 | 0.039737 |
| 6 | − − − − | 91.5 | 105 | 2.75 | 1.24 | 0.040803 |
| 7 | + − − + | 96.5 | 105 | 2.75 | 1.43 | 0.057384 |
| 8 | + + + − | 96.5 | 205 | 3.0 | 1.24 | 0.058961 |
| 9 | − + − + | 91.5 | 205 | 2.75 | 1.43 | 0.048573 |
| 10 | + − − − | 96.5 | 105 | 2.75 | 1.24 | 0.041427 |
| 11 | − + + + | 91.5 | 205 | 3.0 | 1.43 | 0.059000 |
| 12 | + + + + | 96.5 | 205 | 3.0 | 1.43 | 0.065828 |
| 13 | − + + − | 91.5 | 205 | 3.0 | 1.24 | 0.054956 |
| 14 | − − − + | 91.5 | 105 | 2.75 | 1.43 | 0.057293 |
| 15 | + − + − | 96.5 | 105 | 3.0 | 1.24 | 0.059306 |
| 16 | + + − − | 96.5 | 205 | 2.75 | 1.24 | 0.051127 |

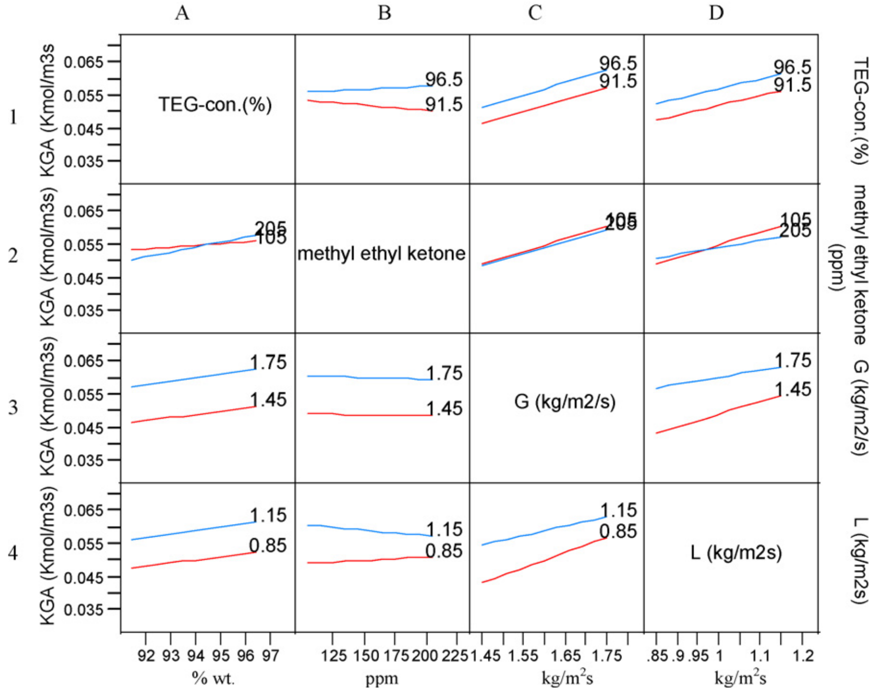

**Fig. A3.** Relationship between factorial interaction and mass transfer coefficient for methyl-ethyl ketone.

The experimental schedule and interaction profile for methyl-ethyl ketone is shown in Table A3 and Fig. A3.

$$
\begin{aligned}
&\text{Predicted formula for methyl-ethyl ketone} = 0.0546373125\\
&\quad + 0.0025118125 \times \left\{\frac{[\text{TEG conc.}(\%) - 94]}{2.5}\right\}\\
&\quad + (-0.0003468125000000) \times \left\{\frac{[\text{methyl-ethyl ketone}(\text{ppm}) - 155]}{50}\right\}\\
&\quad + 0.005576562500000 \times \left\{\frac{G(\text{kg/m}^2\,\text{s}) - 1.6}{0.15}\right\}\\
&\quad + 0.0044413125 \times \left\{\frac{L(\text{kg/m}^2\,\text{s}) - 1}{0.15}\right\}\\
&\quad + \left\{\frac{[\text{TEG conc.}(\%) - 94]}{2.5}\right\} \times \left\{\frac{[\text{methyl-ethyl ketone}(\text{ppm}) - 155]}{50}\right\} \times 0.001212187500\\
&\quad + \left\{\frac{[\text{TEG conc.}(\%) - 94]}{2.5}\right\} \times \left\{\frac{G(\text{kg/m}^2\,\text{s}) - 1.6}{0.15}\right\} \times 0.000052562500000\\
&\quad + \left\{\frac{[\text{methyl-ethyl ketone}(\text{ppm}) - 155}{50}\right\} \times \left\{\frac{G(\text{kg/m}^2\,\text{s}) - 1.6}{0.15}\right\} \times (-0.000180812499)\\
&\quad + \left\{\frac{[\text{TEG conc.}(\%) - 94]}{2.5}\right\} \times \left\{\frac{L(\text{kg/m}^2\,\text{s}) - 1}{0.15}\right\} \times 0.000002562499999\\
&\quad + \left\{\frac{[\text{methyl-ethyl ketone}(\text{ppm}) - 155]}{50}\right\} \times \left\{\frac{L(\text{kg/m}^2\,\text{s}) - 1}{0.15}\right\} \times (-0.00134606249999)\\
&\quad + \left\{\frac{[G(\text{kg/m}^2\,\text{s}) - 1.6]}{0.15}\right\} \times \left\{\frac{[L(\text{kg/m}^2\,\text{s}) - 1]}{0.15}\right\} \times (-0.001345937500000)
\end{aligned}
$$

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