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Comparison of Fixed and Fluidized Beds Adsorber with Economic, Engineering, and Environmental approach

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ABSTRACT

Release Volatile organic compounds (VOCs) as environmental and occupational pollutant cause macro perspective affect such as climate change, humans and economic consequences. Although fixed bed absorber is widely used as a controlling method because of its economically and availability, but these absorbers are facing some issue like high pressure drop, non-uniform distribution of fluid, channeling and blocking. Fixed and fluidized beds adsorbent was compared from three economic, environmental and engineering perspectives using Multi Criteria Decision Making analysis (MCDA) technique. An annular fluidized bed adsorber was designed and charged with 50-100 µm (100-140 ASTM mesh) activated carbon (AC) particles. Effects of factors like flow rate, particle size, inlet concentration and adsorption capacity of VOCs was investigated under steady state. In the flow rate less than 0.25(Lit.min^{-1}), inlet gas slowly passes through the void spaces of the bed's particles. By increasing the inlet flow from 0.3(Lit/min^{-1}), bubbles start to form in the bed and the bed pressure drop decrease. The pressure drop of 6 (g) of AC in minimum fluidization velocity was 20(KN.m^{-2}). However, the pressure drop of 10 and 20(g) of AC were 150 and 420(KN.m^{-2}) respectively. "maximin" technique used for comparison of two beds indicated that minimum score of pack bed absorber are 0.37 while the minimum score of fluidized bed adsorber are 0.5. It indicated when the adsorbent particles are smaller, fluidized bed adsorber are more suitable to use. In addition, using MCDA technique indicated that annular fluidized bed adsorber could considered as an alternative of fixed beds adsorber.

KEYWORDS: *Air pollutants, Volatile organic compounds, Adsorption, Annular fluidized bed reactor, Activated Carbon*

INTRODUCTION

Volatile organic compounds (VOCs) are the most abundant compounds in the atmosphere [1]. According to European environmental agency, there is more than 300 process causing VOCs emission [2]. VOCs are known as common pollutants in oil refinery and petrochemical industries [3]. In terms of the environment, it is necessary to prevent the emission of VOCs.

These compounds cause macro perspective affect such as climate change, humans and economic consequences.

Many of these compounds such as benzene, dichloromethane and chloroform, are known as carcinogens [1]. A survey conducted on a petrochemical's surrounding residents indicated that, living for more than five years increases the risk respiratory symptoms [4]. Another study on gasoline station's workers in Thailand shows that, due to exposure to VOCs the risk of cancer increases [5-6]. The relationship between the amount of VOCs released in each county and cancer frequency

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were studied in an epidemiological investigation in 92 Indiana countries. Results indicated that there were significant relationship between emissions of VOCs and the incidence of some types of cancer [7].

There are several studies regarding the economic consequences of emissions of volatile organic compounds into the atmosphere and its control method like Cofala et al. study [2]. Recent estimates of the global emission of VOCs into the atmosphere range from about 1200-1600 (TgC year^{-1})[8]. The estimates damage cost attributable to organic compounds are almost: 1100 ($ per Mega gr of VOCs) [9]. (E.g. Global estimation of hydrocarbons from different source is: Transportation=22, Stationary sources=4, Industrial processing including natural gas production=17, Biomass burning, forest fires=45, Organic solvents=15 Tg/yr)[10].

VOCs control techniques divided into process equipment modification for lower emissions, and use of control equipment which can divided to recovering techniques (e.g. adsorption) and destructive techniques (e.g. incineration, biodegradation and photocatalytic oxidation) [3, 11].

different VOCs controlling methods cost comparison shows that annual operating cost of thermal oxidation, catalytic oxidation, bio filtration and adsorption activated carbon are 15–90 , 15–90, 15–75 and 10–35 ($/CFM) respectively. However the performances of them are 95–99, 90–98, 60–95 and 80–90 percent respectively [3]. Among these methods, adsorptions are widely used due to availability, ease of use and economical aspects [3,12,13]. Selecting a suitable adsorbent is primary step in the process of adsorption [3]. The most important factors in determination of suitable adsorbent are adsorption type, capacity, mass transfer rate, startup cost, run cost, abundance and recyclables [12]. Activated carbon adsorptions are considered common methods in controlling VOCs and odor. Start-up cost of this system is lower than other similar controlling systems [3], [11]. Adsorption process of VOCs is usually carried out in the fixed or fluidized beds [14]. In fluidized bed adsorber solids particle behave like liquids. Gas fluidized bed is the best way for contacting different materials and resembles a boiling liquid and shows liquid-like behavior [15].

Factors should be considered prior to selecting a particular piece of air pollution control system is engineering, economic and environmental aspects [16]. There are some research have investigated the optimal selection of air pollution control equipment like Fesharaki et al. study which attempted to choose optimally, a pollution control system for emission of steel furnaces with the green and environmental friendly approach [17]. Sometimes it seems difficult for decision makers (DM) to select an air pollution control system. In single criteria decision making, is usually tried to choose the best solution, but in most real cases, which several criteria are in conflict with each other, finding a solution which all criteria have been at their best are impossible.

In cases that several criteria affect an issue, Multi Criteria Decision Making analysis (MCDA) technique are very useful. MCDA techniques are very useful in complex enterprise decision-making, including the field of economic and energy systems and environmental management [18]. MCDA includes a variety of techniques that help for the better and easier decision making in complex problems [18]. Several techniques based on weighted average, fuzzy rules and their combination has been used in the field of energy management [19, 20] like Tzeng et al. study [21]. Although some studies have been conducted about the application MCDA methods in occupational health and safety (OSH) issues [22], but there are limited number studies published in the field of air pollution controlling system. There is multiple criteria Influence selection of air pollution control system. In some decisions, some of these criteria are weighted more or less than their actual value or some of them do not get enough attention.

In this study, fixed and fluidized beds adsorbents were compared from three economic, environmental and engineering perspectives. For this purpose, the adsorption of VOCs vapors and the effects of factors such as flow rate, particle size and concentration and adsorption capacity in fluidized bed have been investigated. Then fixed and fluidized bed adsorbed were compared using multiple criteria decision making techniques from different aspects which was weight depending on the amount of value.

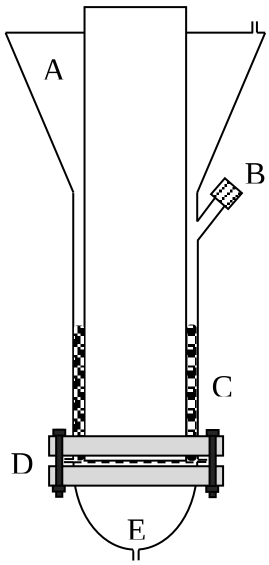


Fig 1. Annular Fluidized Bed Reactor Containing Activated Carbon Adsorbent Particles (A: Expanding Area, B: screw Cap, C: Activated Carbon Particles, D: Flange, Gasket and gas Distribiuter, E: Gas Inlet

MATERIALS AND METHODS

Fluidized bed reactor design: An annular fluidized bed reactor was designed to investigate the activated carbon particles adsorption (Fig.1). For construction the reactor a 50 (cm) length pyrex cylinder with ID=60 (mm) was used and a 55 (cm) length cylinder with OD= 55 (mm) was installed inside that. For uniform distribution of the gas flow a stainless steel gas distributor with 6 (cm) diameters and 100-140 ASTM standard screen mesh was designed for the lower part of the reactor. The distributor contained 12 holes of 2 (mm) diameter. To prevent loss of activated carbon particles from the lower part of the reactor. As shown in Fig. 1 a flange with four bolts and nuts were used for discharged of AC particles from the bottom of the reactor and the flanges were sealed with silicone gasket.

In order to calculate U_{mf} the average diameter of AC particle were considered 126.5 (μm), particle density were considered ρ= 480 (kg/m^3) and AC particles spherical ration also were considered φ=0.8 [15]. For particles with average size of 126.5 (μm), bed void space in minimum fluidization velocity was considered ε_{mf} = 0.69 [15]. In all the tests in order to calculate the pressure drop of the bed an inclined manometer (Airflow Lufttechnik GmbH 5308) were used.

To prevent particles from leaving the fluidized bed reactor, in the upper part of the reactor-settling chamber were designed same as a cone (Fig.1). In this mechanism, by increasing the outer wall diameter, the superficial gas velocity are decreased, so the probably escaped particles reach to settling velocity in this section and come back to bed again. In order to prevent the deposition of the particles on the surface of the designed cone, the cone's slope experimentally were considered 80 degrees. To add AC particles a screw cap were designed in the body of the reactor (Fig. 1).

Calculating minimum fluidization velocity of AC particle: The commercial activated carbon with an average particle size of 50-100 μm (100-140 ASTM meshes) was used as a fluidized bed adsorber. To produce 1(kg) of activated carbon in this mesh size, 5 (kg) cylindrical pellets with length of 4 (mm) were used.

Cylindrical pellets activated carbon initially was crushed by roller crusher and reduced the size to 1 (mm). Then, the particle was crushed and screened by laboratory ball mill and standard sieve (ASTM), and the process continued until the desired particle size achieved. In crushing process, at each step, the crushed particles were separated from residue particles by standard sieve and vibration devices. This prevents Excessive crushing of desired size particles.

There are different methods to calculate the minimum fluidization velocity of particles (U_{mf}), each one has its own precision [15, 23]. In order to calculate the minimum fluidization velocity, Ergun equation has been used (Equation 1) [15].

Eq.1

$$\frac{1.75}{\varepsilon_{mf}^3\varphi_s}\left(\frac{d_p\, u_{mf}\, \rho_g}{\mu}\right)^2+\frac{150(1-\varepsilon_{mf})}{\varepsilon_{mf}^3\varphi_s}\left(\frac{d_p\, u_{mf}\, \rho_g}{\mu}\right)=\frac{d_p^3\,\rho_g\left(\rho_s-\rho_g\right)g}{\mu^2}$$

In order to generate stable desired concentrations of VOC, saturation vapors method was used according to the method described in the article references [24]. Concentration of styrene in inlet and outlet of the reactor, were measurements every 15 minutes by direct reading PhoCheck (model 5000, made in England) which work by Photo ionization detector (PID) mechanisms. In order to ensure the accuracy of the measured data, some samples measurement was repeated by gas chromatography (Philips PU-4410) equipped with a FID detector. Removal efficiency of the adsorber was calculated by concentration difference between input and output of the reactor as it indicated in Equation 2. The obtained isotherms were analyzed by two Langmuir and Freundlich models [16].

$$\text{Eq.2} \qquad \text{Removal Rate (\%)} = \frac{\text{Input styrene concentration} - \text{output styrene concentration}}{\text{Input styrene concentration}}$$

Fixed and fluidized bed absorber comparison: Two VOCs controlling system which worked by the AC absorption technology, are compared in Various environmental, engineering and economic aspects [16]. Economic criteria were divided into three categories: capital cost (Included equipment, installation, engineering, etc.), operating cost (Included utilities, maintenance and expected equipment lifetime) and engineering criteria were divided into five categories: (Included construction of reactor, pressure drop, heat distribution, particles abrasion, recovery operation), and environmental criteria also were divided into three categories: (Included removal efficiency, waste production and sound pressure level).

In order to compare comprehensively all the criteria, based on the multifactorial nature of the subject, one of multi criteria decision-making techniques was used. There are various compensatory and non-compensatory techniques in decision-making process. Since in the selection of air pollution control equipment, high score of one criteria cannot offset weaknesses of other criteria, So a non-compensatory techniques were used. In the non-compensatory techniques, there are not allowed to trade-off between the criteria and each criterion is compared with itself. The advantage of the non-compensatory techniques is their simplicity, which conform to limited data of the DM. Hence, techniques named “Maximin” were used. Maxmin means maximizing minimal available profitability. In the method, several important parameters or all parameters may be compared [25]. In these techniques, each evaluation value of attribute “i” given by resident “j” or “r_{ij}” is assigned a score between numbers 1 to 9. Better criteria get higher score. The weight of each criteria is determined in accordance with the situation where the system is been operating like rules and regulations, economic status technology development, the desired level of health etc. In order to compare alternative, the criteria should have same scale. Therefore it is necessary to transform the elements of column “x_1” using $n_{ij}=\frac{r_j^{min}}{r_{ij}}$ and other columns using $n_{ij}=\frac{r_{ij}}{r_{ij}^{*}}$. In the maximin techniques, the most appropriate “r_{ij}” is selected using the following method [25]:

$$\underset{(I)}{\text{Max}} \rightarrow \underset{(J)}{\text{Min}} \rightarrow n_{ij}$$

So each indicator are split on the highest scores of each column to make it dimensionless. Then in order to find best cases, the minimum score of the system are compared [25]. Thus decision maker (DM) can choose the best option.

Attribute / Alternative	x_1	x_2	…	x_j
A_1	r_{11}	r_{12}	…	r_{1j}
A_2	r_{21}	r_{22}	…	
.	.	.	…	.
.	.	.	…	.
.	.	.	…	.
A_i	r_{i1}		…	r_{ij}

Where:
A_j= alternative of problem
x_1= attribute of problem
r_{ij} = the evaluation value of attribute i given by alternative j

RESULT

In order to test the minimum fluidization velocity, the fluidized bed reactor inlet flow rate gradually increased and the static pressure of the reactor inlet were measured continually. Figure 2 indicates that the bed’s pressure drops ($KN.m^{-2}$) versus the inlet flow rate ($Lit.min^{-1}$). Test results indicated that in the flow rate less than 0.25

($Lit.min^{-1}$), gas slowly passes through the bed's particles void spaces. As indicated in the curves, the pressure drop of 10 (g) of AC in flow rate of 0.1 and 0.2 ($Lit.min^{-1}$), are 44 and 108 ($KN.m^{-2}$), respectively. As long as the bed of AC are fixed, by increasing inlet flow rate, the pressure drop of the bed linearly increase. If the inlet gas velocity increased further, particles separate from each other and some particle start to vibrate in their places. This condition is called "expanded bed". By increasing the inlet flow rate from 0.3 (Lit/min^{-1}), bubbles start to formed in the bed and the bed pressure drop decrease. The inlet air velocity which bed start to fluidize are referred as minimum fluidization velocity (U_{mf}).

in order to evaluate the effect of weight of adsorber on the bed's pressure drop, the pressure drop of different weight of AC samples were measured. For this purpose different weights of AC from 6-20 (g) with 50-100 µm (100-140 ASTM mesh) were poured into annular reactor and the pressure drop of each sample were measured. As it shows in the curves of Fig. 3, the pressure drop of 6 (g) of AC in minimum flow rate of fluidization were 20 ($KN.m^{-2}$). However, the pressure drop of 10 and 20 (g) of AC were 150 and 420 ($KN.m^{-2}$) respectively. So increasing the weight of AC bed, increase the reactor pressure drop. However the pressure drop in the minimum flow rate of fluidization were almost constant in all weights form 6, 8, 10, 12, 14, 16 and 20 (g). In minimum flow rate for all weights, the bed pressure drop are suddenly reduced in minimum fluidization velocity (U_{mf}).

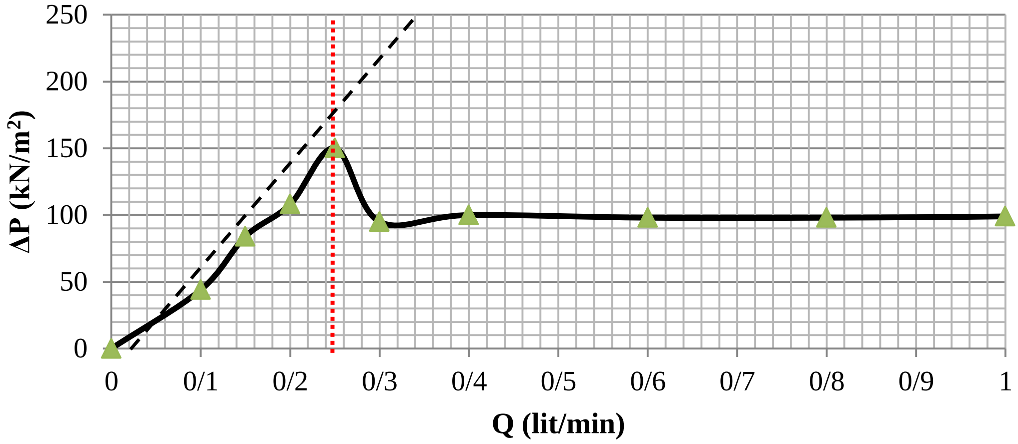


Fig 2. Inlet flow rate effect on reactor pressure drop (ΔP= static pressure of the activated carbon bed, Q= flow rate adjusted by flow meter)

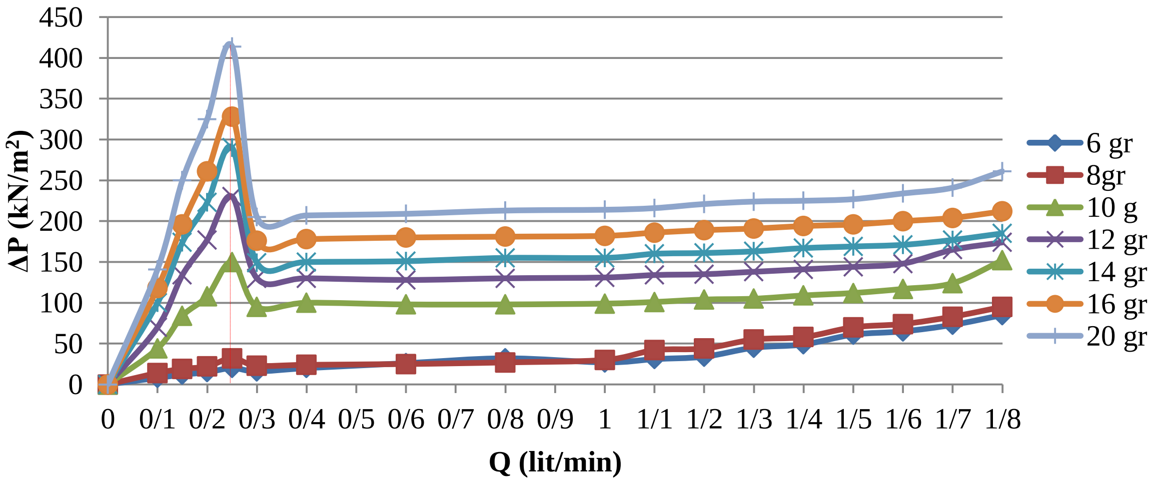


Fig 3. Mass effect on bed's pressure drop of reactor with 50-100 µm (100-140 ASTM mesh) AC particle (ΔP= static pressure of the activated carbon bed, Q= flow rate adjusted by flow meter)

Asorption capacity of 6 (g) of activated carbon in three concentrations of 400, 500 and 600 (ppm) were measured at 25 ($^{\circ}$C). In order to examine the maximum styrene weight which adsorbed on the AC bed, the weight difference of the activated carbon bed before and after saturation were measured? Finally, the obtained isotherms were analyzed by two Langmuir and Freundlich models. Freundlich model equation and the linear form are described by equation 3 and 4 respectively:

$$Y=kP^{\frac{1}{n}} \qquad \text{Eq.3}$$

$$\text{Log}\,Y=\text{Log}\,K+\left(\frac{1}{n}\right)\text{Log}\,P \qquad \text{Eq.4}$$

In this model, “Y” is the amount adsorbate per unit mass of adsorbent, “P” is gas partial pressure and “k, n” is the equation constants, which depends on the temperature. In this model, the adsorption is assumed non-homogeneous.

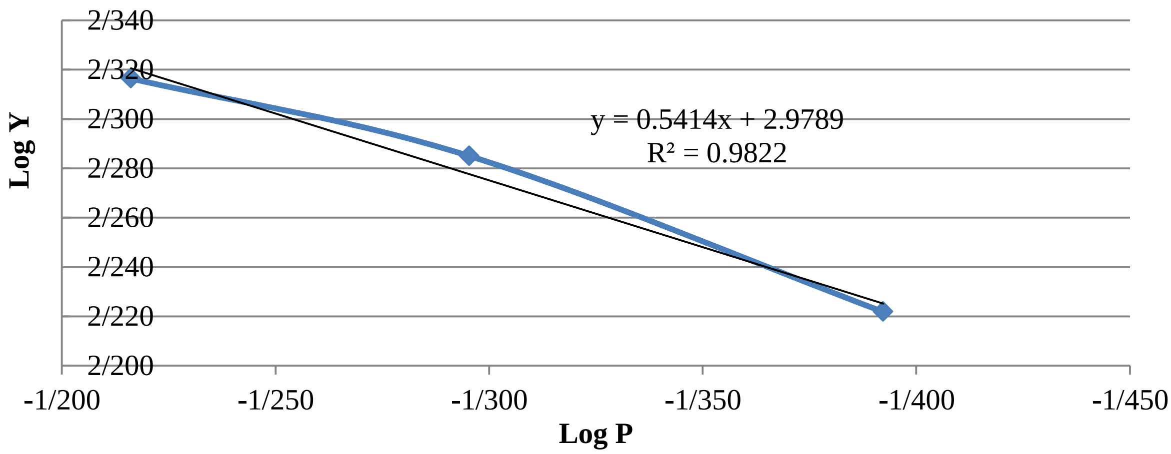
The Langmuir adsorption model is described by Equation 5. The constants “a, b” are characteristic of the system under consideration and are evaluated from experimental data. Their magnitude also depends on the temperature. At any temperature the validity of the Langmuir adsorption equation can be verified most conveniently by first dividing both sides of this equation by “p” and then taking reciprocals. The result is described by Equation 6:

$$Y=\frac{ap}{(1+bp)} \qquad \text{Eq.5}$$

$$\frac{p}{Y}=\frac{1}{a}+\frac{b}{a}\,P \qquad \text{Eq.6}$$

Adsorption isotherm curves of styrene monomer indicated that AC adsorption capacity increases by increasing concentration. As indicated in Fig. 4 and 5 the correlation coefficients of both isotherm models are greater than R ≥0.9.

Fig 4. Freundlich isotherm model for styrene adsorption on AC adsorbent 50-100 (µm)



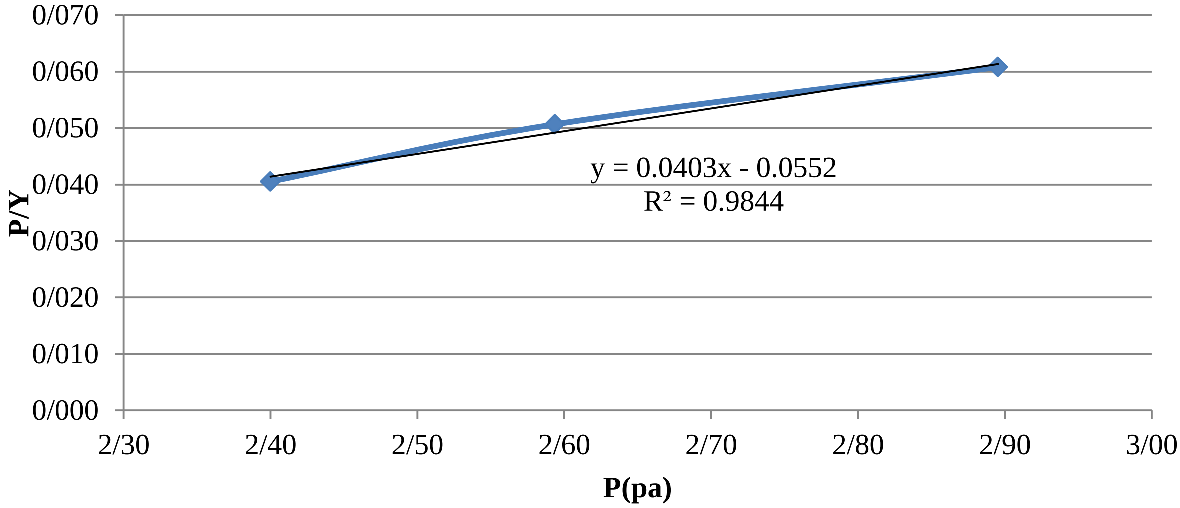


Fig 5. Langmuir isotherm model for styrene adsorption on AC adsorbent 50-100 (μm)

Comparison of fixed and fluidized bed absorber in terms of environmental, engineering and economics factors is illustrated in Table 2. Depending on the importance of each criterion a value were assigned according to terms of use, industrial conditions and law restrictions of the country. Thus, it is possible that same controlling equipment is given different value on different country. In this method, each criterion, which are illustrated as X_1 to X_{17}, are assigned score from 1 to 9 so that the better indicator get higher value. For example, "X_{11}" which represents the amount of pressure drop which known as the effective engineering criteria are assigned 3 in fixed bed and 8 in fluidized bed, respectively.

Table 1. Comparison of fixed and fluidized bed absorber with small particles 50-100 (μm)

Bed Type		Economic									Engineering					Environmental		
		Capital Cost					Operating Cost											
		Equipment		Installation			Utilities											
		Reactor Costs	Fan Size	Space Occupied	Weight	Engineering	Electricity Consumption	Cost Adsorbent	Maintenance	Expected Equipment Lifetime	Construction of Reactor	Pressure Drop	Heat Distribution	Particles Abrasion	Recovery Operation	Removal efficiency	waste Production	Sound pressure level
		x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}
Fixed Bed	A_1	8	3	6	7	7	3	5	6	7	6	3	3	6	4	9	7	8
Fluidized Bed	A_2	5	6	6	5	6	6	6	5	7	5	8	8	3	7	8	7	8

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In order to eliminate the effect of dimension of criteria, each value were divided into the maximum values of the column. Thus an index number smaller than the 1 were obtained. Table 2 shows comparison of fixed and fluidized bed absorber with dimensionless criteria. As indicated in table 2, the minimum score of A_1 row are “0.37” and minimum score of A_2 are “0.5” which indicated that A_2 is more suitable choices according to the defined conditions.

Table 2. Comparison of fixed and fluidized bed absorber with dimensionless criteria using maxmin techniques

Attribute / Alternative	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	Min Score
A_1	0.57	1	0.37	0.37	1	1	1	0.83	0.5	1	1	1	0.5	1	1	1	1	0.37
A_2	1	0.5	1	1	0.83	1	0.83	1	1	0.85	0.71	1	1	0.62	0.88	1	1	0.5

DISCUSSION

Fluidized bed adsorber has many advantages. As shown by increasing the inlet flow rate over the fluidized bed, pressure drop does not change significantly, however in fixed beds by increasing the inlet flow rate, the pressure drop usually linearly increases. Review of the different fluidization studies indicates that in minimum fluidization velocity, the compressive force of the upper particles disappears and the bed pressure drop approximately are equal to the weight of the gas and suspended particles [15].

The results also indicated that by increasing the amount of adsorbent, pressure drop increase, however the amount of pressure drop increase in fluidized beds are less than that of fixed beds. Thus costs related to the fluidized bed pressure drop are lower than fixed bed and that is why it has been assigned a higher rating. Ability of using small adsorbent particles is one of the main advantages of fluidized bed adsorbers system. Because the small adsorber particle increases the pressure drop of fixed beds [15], it is not possible to use these sizes of particles in Industrial scale of fixed beds adsorber. However, the results indicated that using small size particle in fluidized bed adsorber dot not increases the pressure drop. On the other hand, the results also indicated that by reducing the average size of particles, surface area and the adsorption capacity of the adsorbent increase. Hence, the use of smaller particles of activated carbon in annular fluidized bed, in addition to overcoming the media pressure, also increases the efficiency of adsorption. Several studies were performed on new media in order to reduce expenses of absorbent system. Schaaf et al. state that the pressure drop of new designed substrate named “Versa comb” are greatly reduced compare to current system pressure drop. As a result, the size of the fan and the capital cost of system are reduced. Therefore, due to reduce in fan size the energy consumption and consumer costs are also reduced [26].

Most important criteria affecting consumer cost in adsorber systems are costs associated with activated carbon bed. As result indicated, adsorption equilibrium isotherm provide us important information about adsorption capacity. Adsorption isotherm indicates that styrene adsorption on activated carbon fit both Langmuir and Freundlich isotherm, however Langmuir model fit better. There are several studies published on AC fluidized beds adsorber for controlling of air pollution. Moradi Rad et al. in their study on kinetic and isotherm curve modeling, indicated that adsorption equilibrium data of polycyclic aromatic hydrocarbons on activated carbons well fitted by Fraundlich adsorption models [13]. In addition isotherm curves comparison indicated that fluidization had not significant effect on the adsorption capacity so in comparison of fixed and fluidized bed absorber both beds assigned same value. Aslo

Kuo et al. [27] and Chiang et al. [28], indicated that the removal efficiency of toluene vapors in the annular fluidized bed reactor containing 50-100 μm (100-140 ASTM mesh) AC particles was almost 90% in the first 100 min of the test and after 180 min, it reached zero [27].

In the conditions which several criteria have an impact on an issue simultaneously, MCDA techniques are very useful tools. As it indicated in the result section of the study comparison of fixed and fluidized bed absorber in terms of environmental, engineering and economics factors, using maximin technique, indicated that fluidized bed adsorber are at higher priority regarding to the defined parameters. Using MCDA technique indicated that for smaller particles, if all defined criteria be considered simultaneously, using fluidized bed is more suitable. Multi criteria decision-making analysis technique are used in many environmental issues as described by previews study [29].

CONCLUSIONS

Annular fluidized bed reactors are useful technique for VOCs adsorption when considering all parameters, which defined in MCDA model. Fluidized bed absorbers have much strength compared to fixed beds, so it can be considered as alternative for fixed beds adsorbent. When the adsorbent particles are smaller, fluidized bed adsorbers are more suitable to use. Fluidized bed are less attended in the field of VOCs air pollution control system Because Construction complexity, lack of sufficient knowledge, specialized in designing and installation and etc. Lack of precise estimation of parameters in decision-making may lead to incorrect decision or increases risk of error. Sometimes DMs due to the multi parameter nature of the question are hesitant in decision-making, Such as selection of air pollution control equipment. Using multi criteria, decision-making technique can help industrial hygiene DMs to choose different types air pollution control devices.

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Notation:

μ	dynamic viscosity of gas, [kg/ms]
g	acceleration of gravity, [m/s^2]
ε_{mf}	void fraction at minimum fluidization condition
d_p	Mean particle diameter
r_{ij}	the evaluation value of attribute i given by alternative j
u_{mf}	minimum fluidization velocity [m/s]
Δp	ΔP= static pressure [kN/m^2]
ρ_S	particle density (including volume of the pores), [kg/m^3]
ρ_g	gas density, [kg/m^3]
φ_S	particle shape factors (dimensionless)

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