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A mass transfer model for dimensioning a centrifugal absorber in an air cleaning plant

HELENA UDDHOLM

Environmental Department, K-Konsult, S-117 80, Stockholm, Sweden

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Abstract—This paper describes a mathematical model, which is developed to fit a new kind of absorber designed for air purification purposes. The model includes velocity and mass transfer equations which are solved numerically. The absorber consists of rotating, helical surfaces, which induce the action of the centrifugal force in the system. Model predictions show good agreement with the experimental results obtained from a pilot plant in a pharmaceutical industry.

1. INTRODUCTION

IN ORDER to find a satisfactory procedure to capture and recover solvents in the exhaust air from industrial processes, an absorption system has been developed by Armand *et al.* [1, 2]. Polluted air is led by a fan through an absorber and brought into contact with an absorbent. The contaminated absorbent is led to an evaporator designed to evaporate solvents. The solvent vapours leaving the evaporator are condensed and recovered in a cooler. The system makes use of rotary driven absorbers and evaporators, which are designed to optimize the contact surface between the process air and the absorbent, without causing a large pressure drop. The contact surfaces are collected in 0.2 m high units, each consisting of 12 spirals wound together around the drive shaft as shown in Fig. 1. The distance between the spirals is kept constant by springs, which also help maintain the turbulent air flow.

An almost uniform continuous distribution of the absorbent is achieved by the central distributor which consists of radial holes in the axle. Centrifugal action causes the absorbent to be formed into a film which adheres on to the surface of the spiral blades. The distribution is shown in Fig. 2.

The absorption of gases and vapours in liquids is encountered in numerous chemical engineering applications. Different kinds of models are developed to fit these applications, which typically encompass falling film, spray, trayed or packed towers. However, these models cannot be used to describe the mass transfer processes under way in the devices developed since a centrifugal force, other than gravitational acts on the system. This paper presents a model to calculate the amount of absorber units required for different air purification purposes. The model, with some modification, can also be used to calculate the units needed in the evaporator. In view of the experimental data available, for comparison with calculated data, the discussion will be limited to the absorber.

2. MODEL AND EQUATIONS

The forces acting on the liquid in the system are centrifugal

$$F_c = \frac{\Phi \cdot v_{sp}}{r} \tag{1}$$

and gravitational

$$F_g = \Phi \cdot g. \tag{2}$$

The absorbent is distributed at an angle perpendicular to the direction of the air stream. The film will flow at an angle perpendicular and counter to the direction of the air flow and will be pushed into a direction opposite to that of rotation, as is shown in Fig. 3.

The following are general assumptions made in formulating the equations valid for liquid film and the gas bulk:

(1) The liquid is incompressible.

(2) The velocity component in the radial direction is zero.

(3) There will be no Coriolis force acting in the system.

(4) The heat transport in the system is neglected. The heat released when the gaseous solvents condense has a negligible effect on the absorbent temperature; hence, the absorbent maintains a constant temperature throughout the absorption process.

(5) The gas flow is turbulent.

(6) Entrance and end effects are not considered.

Radius R_1 is a function of the angle Θ:

$$R_1 = \frac{inc}{2 \cdot \pi} \cdot \Theta + R_0 \tag{3}$$

where R_0 is the radius at the spiral and axle connection.

Because of the spiral configuration, the centrifugal force will also act in the direction of the angle, which leads to the following momentum equation:

NOMENCLATURE

D^l diffusion coefficient of the absorbate in solution [m^2 s^{-1}]
g gravitational acceleration [m s^{-2}]
h_D mass transfer constant [m s^{-1}]
inc spiral inclination [m]
K equilibrium constant [(kg absorbate) (kg air)$^{-1}$ (kg absorbate)$^{-1}$ (kg solution)]
k_G mass transfer coefficient in gas [s m^{-1}]
L absorber length [m]
M molecular weight [kg kmol^{-1}]
N amount of absorbed vapour [kg s^{-1}]
P pressure [Pa]
Q air flow [kg s^{-1}]
R gas constant [kJ kmol^{-1} K^{-1}]
Re Reynolds number
Re_l Reynolds number in the laminar boundary in the gas phase
r coordinate in the radial direction [m]
T temperature [K]
v velocity [m s^{-1}]
xa concentration of absorbate in solution [(kg absorbate) (kg solution)$^{-1}$]
xa'' concentration of absorbate in solution at the gas interface [(kg absorbate) (kg solution)$^{-1}$]
ya concentration of absorbate in gas [(kg absorbate) (kg gas)$^{-1}$]
ya^* equilibrium concentration of absorbate in gas [(kg absorbate) (kg gas)$^{-1}$]
ya'' concentration of absorbate in gas at the liquid interface [(kg absorbate) (kg gas)$^{-1}$]
z coordinate in air flow direction [m].

Greek symbols
β incline rising gradient [rad]
Γ wet perimeter flow [kg m^{-1} s^{-1}]
ε coordinate in the mass transfer direction [m]
Θ coordinate in the angular direction [rad]
μ viscosity [kg m^{-1} s^{-2}]
π tension force [N m^{-2}]
Φ density [kg m^{-3}]
Ω angular velocity [s^{-1}].

Subscripts
g gas
l liquid
sp spiral.

Superscripts
g gas
l liquid.

$$\frac{1}{r^2}\frac{\delta(r^2\cdot\pi_{r\Theta})}{\delta r}=\frac{1}{r}\cdot\frac{\delta p}{\delta\Theta}\approx\frac{\Phi\cdot\Omega^2\,inc}{2\pi}. \quad (4)$$

Since we have no information as yet about the momentum flux at the interface, we introduce here the radius R_x, at which there will be a maximum in the velocity curve. This maximum will occur in the less viscous phase, the gas bulk. The following boundary conditions then apply:

$$v^l_\Theta=0 \quad \text{at } r=R_1 \quad (5a)$$

$$v^g_\Theta=\Omega\cdot R_3 \text{ at } r=R_3 \quad (5b)$$

$$\pi^g_{r\Theta}=0 \quad \text{at } r=R_x. \quad (5c)$$

The momentum equation is solved and the velocity profiles in the liquid and in the gas are given by

$$v^l_\Theta=\frac{r\Omega^2\,inc}{12\pi\mu_l}\left[(\Phi_g\cdot R_x^3+(\Phi_l-\Phi_g)R_2^3)\left(\frac{1}{r^2}-\frac{1}{R_1^2}\right)+2\Phi_l(r-R_1)\right]-\Omega\cdot r \quad (6)$$

$$v^g_\Theta=\frac{r\Phi_g\Omega^2}{12\mu_g}\left[R_x^{2g}\left(\frac{1}{r^2}-\frac{1}{R_3^2}\right)+2\cdot(r-R)\right]-\Omega\cdot r. \quad (7)$$

We assume that the momentum transport is continuous throughout the interface between the gas and the liquid fluid and make use of the following boundary condition:

$$v^l_\Theta=v^g_\Theta \text{ at } r=R_2. \quad (8)$$

R_x can then be solved

$$R_x^3=\left[\frac{\Phi_g}{\mu_g}(R_2-R_3)-\frac{\Phi_l}{\mu_l}(R_2-R_1)-\left(\frac{\Phi_l-\Phi_g}{2\mu_l}\right)\left(\frac{1}{R_2^2}-\frac{1}{R_1^2}\right)R_2^3\right]\Big/\left[\frac{\Phi_g}{2\mu_l}\left(\frac{1}{R_2^2}-\frac{1}{R_1^2}\right)-\frac{\Phi_g}{2\mu_g}\left(\frac{1}{R_2^2}-\frac{1}{R_3^2}\right)\right]. \quad (9)$$

The downward velocity due to the gravitational force acting on the liquid can be derived from the following equation:

$$\frac{1}{r}\frac{\delta(r\pi^l_{rz})}{\delta r}=\Phi^l\cdot g_z \quad (10)$$

with the following boundary conditions, assuming a maximum velocity at the radius R^l_x:

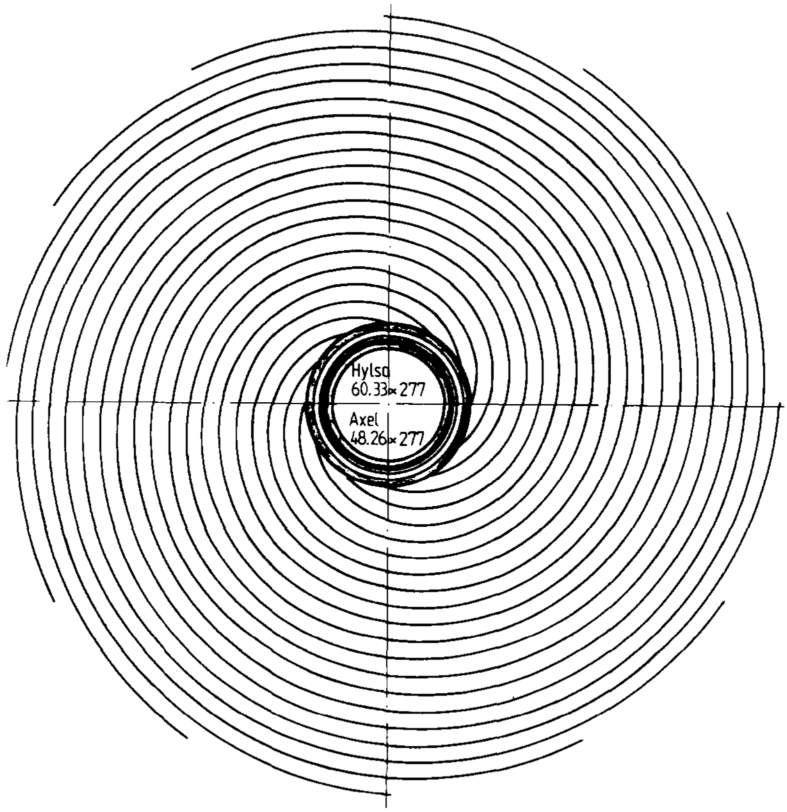

FIG. 1. One rotating unit in section.

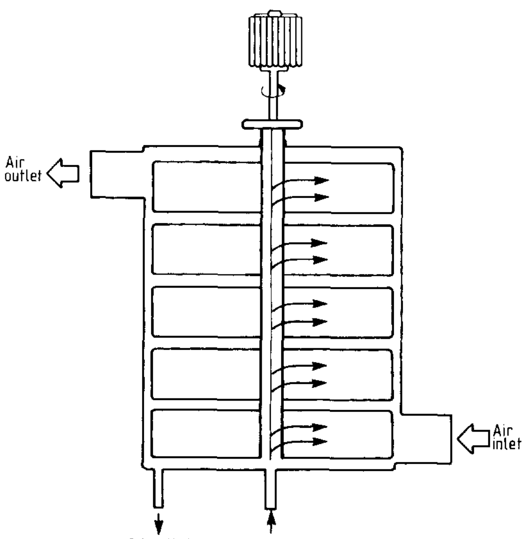

FIG. 2. The distribution of absorbent in the absorber.

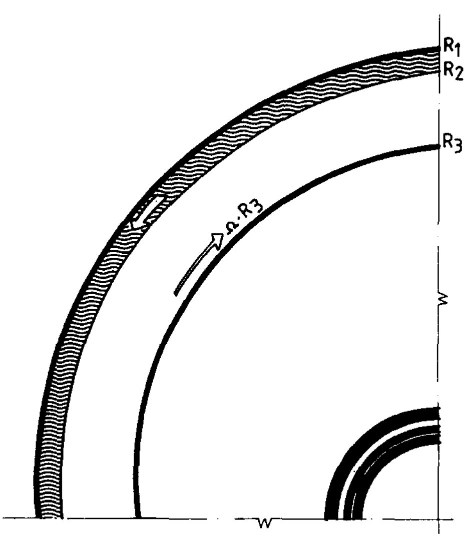

FIG. 3. The direction of the film flow and rotary movement of the spiral.

$$v_z^l = 0 \text{ at } r = R_1 \tag{11a}$$

$$\pi_{z\Theta}^l = 0 \text{ at } r = R_x^l. \tag{11b}$$

The air velocity depends on the pressure fall over the absorber which is calculated from the air flow as well as liquid flow and friction factors [3]. Hence air velocity can be derived from the following equation:

$$\frac{1}{r}\frac{\delta(r\pi_{rz}^g)}{\delta r} = \frac{\Delta P}{\Delta L}. \tag{12}$$

As the vertical air flow runs in a direction opposite to the liquid flow which is caused by gravitation, there will also be a maximum velocity in the gas bulk and the following boundary conditions apply:

$$v_z^g = 0 \text{ at } r = R_3 \tag{13a}$$

$$\pi_{z\Theta}^g = 0 \text{ at } r = R_x^g. \tag{13b}$$

The equations are solved and allow the velocity in the film to be calculated from

$$v_z^l = -A\left[\frac{1}{2}(r^2 - R_1^2) + R_x^{l^2} \ln\frac{R_1}{r}\right] \tag{14}$$

where

$$A = \frac{\Phi_l \cdot g}{2 \cdot \mu_l} \tag{15}$$

and in the gas bulk

$$v_z^g = -B\left[\frac{1}{2}(r^2 - R_3^2) + R_x^{g^2} \ln\frac{R_3}{r}\right] \tag{16}$$

where

$$B = \frac{\Delta(P/L)}{2\mu_g}. \tag{17}$$

Also in this direction we assume that the momentum transport is continuous through the interface between the gas and the liquid fluid, which leads to the following boundary conditions:

$$\pi r_z^l = \pi r_z^g \text{ at } r = R_2 \tag{18a}$$

$$v_z^l = v_z^g \text{ at } r = R_2. \tag{18b}$$

We calculate R_x^l and R_x^g

$$R_x^{g^2} = \frac{(b_4 b_1 - b_3 b_2)}{(b_4 - b_2)} \tag{19}$$

$$R_x^{l^2} = \frac{b_4 b_1}{b_2(b_4 - b_2)} - \frac{b_3}{(b_4 - b_2)} - \frac{b_1}{b_2} \tag{20}$$

where

$$b_1 = R_2^2\left(1 - \frac{\Phi_l \cdot g}{\Delta(P/L)}\right) \tag{21a}$$

$$b_2 = \frac{\Phi_l \cdot g}{\Delta(P/L)} \tag{21b}$$

$$b_3 = \frac{\frac{\Phi_l \cdot g \cdot \mu_g}{\Delta(P/L) \cdot \mu_l}\left(\frac{R_1^2 - R_2^2}{2}\right) - \left(\frac{R_3^2 - R_2^2}{2}\right)}{\ln\frac{R_2}{R_3}} \tag{21c}$$

$$b_4 = \frac{\Phi^l \cdot g \cdot \mu_g \ln\frac{R_2}{R_1}}{\Delta(P/L) \cdot \mu_l \ln\frac{R_2}{R_3}}. \tag{21d}$$

To simplify the mass transfer calculations we introduce a mass transfer direction ε, where

$$d\varepsilon = \sqrt{(dx^2 + dz^2)} \tag{22}$$

$$dx = \frac{R_0 \cdot d\Theta}{\cos\beta} \tag{23}$$

where

$$\beta = (\arctan(inc/2R_0\pi)). \tag{24}$$

The radius R_2 and hence the film thickness can be calculated from equation (25)

$$\frac{\Gamma}{\Phi_l(R_1 - R_2)} = v_\varepsilon^l = \sqrt{(v_\Theta^{l^2} + v_z^{l^2})}. \tag{25}$$

The mass transfer equation is then

$$v_\varepsilon^l \frac{\delta xa}{\delta\varepsilon} = D^l \frac{\delta^2 xa}{\delta r^2}. \tag{26}$$

As the gas flow is turbulent, the mass transfer coefficient can be calculated from ref. [3] as

$$\frac{h_D}{v_\varepsilon^g} = 0.037Re^{-0.2} + Re^{-1}(0.646Re_l^{0.5} - 0.037Re_l^{0.8}) \tag{27}$$

where

$$Re = \frac{v_\varepsilon^g \cdot \Phi_g \cdot d\varepsilon}{\mu} \text{ and } Re_l \approx 1 \times 10^5.$$

The mass transfer in the system can then be calculated from the relations

$$dN = k_g dA(ya^* - ya'') = Q\Delta ya^* = \Gamma \cdot L\Delta xa^* \tag{28}$$

where

$$k_G = h_D \frac{M}{R \cdot T} \tag{29}$$

and

$$xa'' = K \cdot ya''. \tag{30}$$

3. SOLUTION

The differential mass equation is discretized and solved using the Crank–Nicolson method. The concentrations ya'' and ya^* are adjusted until the relations in equation (28) are equal. The computer program developed consists of a main program with procedures

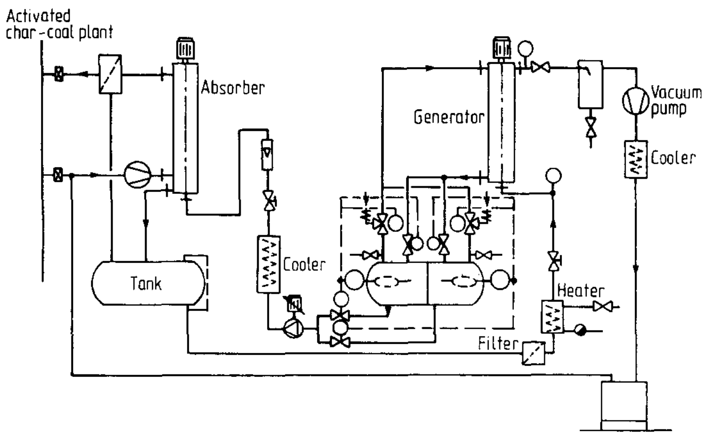

FIG. 4. The test plant at the pharmaceutical industry.

for calculating the film thickness, air and film velocities at different positions along the absorber in the length and angle direction. The program also includes subprograms with procedures for solvent properties. The computer program is written in Pascal and stored in a minidisk type MD 2S. Input variables to the program are wet perimeter flow, air flow, concentration in the inlet process air and absorbent and rotational speed.

4. RESULTS AND DISCUSSION

The capacity of the absorber has been evaluated at a pharmaceutical company in Sweden. The experimental set-up is shown in Fig. 4. The process air that was led through the absorber contained primarily methylene chloride, but also small amounts of isopropanol, acetone, ethyl acetate, butyl acetate, trichloroethylene and toluene. The process air flow varied between 90 and 550 m^3 h^{-1} and the absorbent flow between 0.06 and 0.6 kg s^{-1}, which meant proportions of absorbent flow to air flow (liquid/gas) between 1 and 24. The evaporator pressure varied between 10 and 120 mbar. A silicone oil with a viscosity of 50 cSt was used as absorbent. The absorber in the pilot plant contained four wetted units.

Experimental results according to methylene chloride are presented in Fig. 5. Regression analyses show rather good correlations at concentrations above 4 g m^{-3} air between absorber efficiency and liquid/gas proportions, but poor correlations at lower concentrations. Using the described model to calculate absorber efficiency at comparable conditions, rather good agreements were achieved between measured and calculated efficiencies in the liquid/gas range of 5–15.

In Fig. 6 calculated values are compared with values from test runs at liquid/gas proportions of 8 at evaporator pressures of 50–80 mbar. At liquid/gas proportions lower than 5, predicted absorber efficiencies are significantly higher than those measured. The reason for lower measured efficiencies might be, for

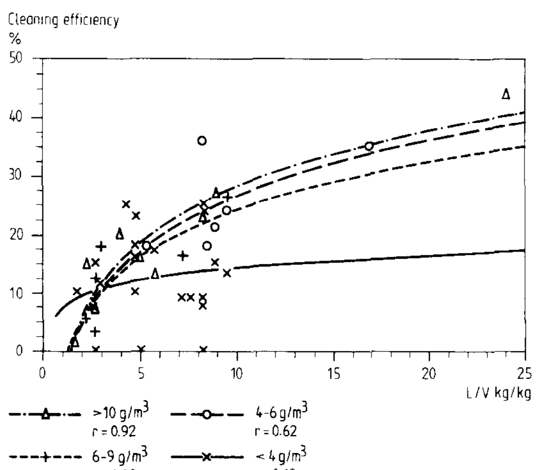

FIG. 5. Experimental data from test runs with methylene chloride.

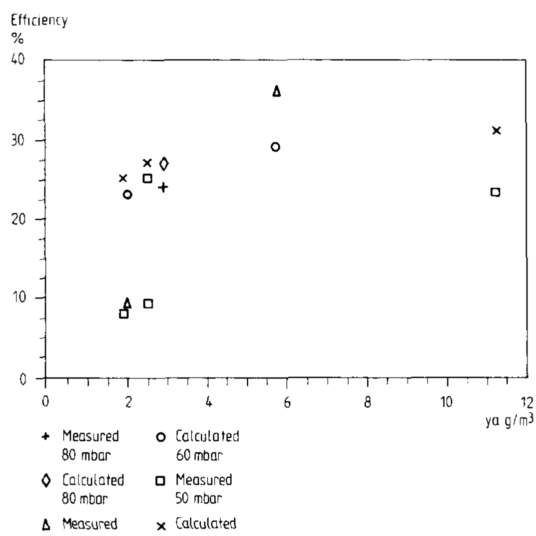

FIG. 6. Calculated and measured absorber efficiency at varying inlet air concentration of methylene chloride.

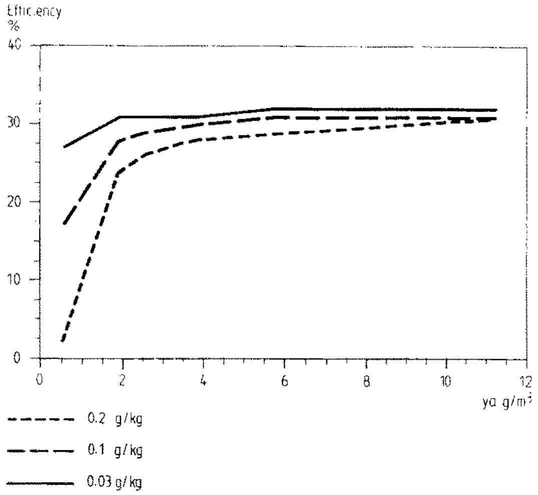

FIG. 7. Absorber efficiencies as a function of inlet absorbent concentrations.

instance, poor wetting of the spiral blades at low liquid flows. At liquid/gas proportions higher than about 15, the predicted efficiencies are somewhat lower. This might be due to end effects which have not been considered in the model, i.e. the counter flow of air and absorbent at the outlet of the spiral blades. The influence of the evaporator pressures and temperatures can be verified, by calculating at varying inlet absorbent concentrations corresponding to varying evaporator conditions. The results of calculations with inlet concentrations of 0.00003, 0.0001 and 0.0002 kg kg^{-1} are shown in Fig. 7. It appears that at lower air concentrations, the evaporator conditions have a strong effect on the absorption capacity. This is in accordance with the experimental results in Fig. 5, where good correlations were found between efficiencies and high inlet concentrations (above 5 g m^{-3}) and no correlations at all at lower inlet concentrations.

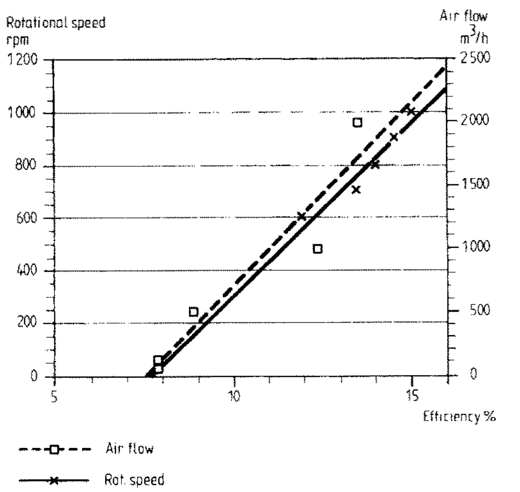

FIG. 8. Absorber unit efficiency as a function of air flow and rotational speed.

In Fig. 8 it is shown how the absorber capacity varies with the rotational speed and the air flow. The increase of absorber efficiency with increasing air flows, is due to the increase of air turbulence and consequent decrease in mass transfer resistance in the gas bulk. The increase of absorber efficiency with the increasing rotational speed is due to the thinning of the film and consequent decrease in fluid mass transfer resistance.

5. CONCLUSION

This study has focused on predicting the efficiency of a rotating absorber, constructed for air cleaning purposes. Good agreements of the model with experimental data have been found when the liquid/gas proportions range between 5 and 15. As the liquid/gas proportion in the operating absorber will be about 8, we estimate the model to be useful for predicting the efficiency of absorber designs. The next pilot plant to be built will be a device for cleaning zeolite filter regeneration air. The zeolite filter will remove about 50 mg contaminants m^{-3} (primarily butyl acetate) from about 12 000 m^3 process air per hour. The regeneration flow will be about 2000 m^3 h^{-1}. Using the above described model, we have calculated that, to achieve 95% clean regeneration air will require an absorber with 15 wet units. This corresponds to an absorber unit height of 3 m.

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UN MODELE DE TRANSFERT DE MASSE POUR LE DIMENSIONNEMENT D'UN ABSORBEUR CENTRIFUGE DANS UNE UNITE D'EPURATION D'AIR

Résumé—On décrit un modèle mathématique pour l'appliquer à un nouveau type d'absorbeur conçu pour la purification de l'air. Le modèle contient les équations de vitesse et de transfert de masse qui sont résolues numériquement. L'absorbeur comprend des surfaces hélicoïdales tournantes qui induisent une force centrifuge dans le système. Les prédictions du modèle sont en bon accord avec les résultats obtenus avec une installation pilote dans une industrie pharmaceutique.

EIN STOFFÜBERGANGSMODELL ZUR DIMENSIONIERUNG EINES ZENTRIFUGAL-ABSORBERS IN EINER ANLAGE FÜR DIE LUFTREINIGUNG

Zusammenfassung—Es wird ein mathematisches Modell zur Beschreibung eines neuartigen Absorbers für die Luftreinigung beschrieben. Die Gleichungen für die Geschwindigkeit und den Lufttransport werden numerisch gelöst. Der Absorber besteht aus rotierenden spiraligen Oberflächen, welche dazu führen, daß im System Zentrifugalkräfte auftreten. Die Berechnungen zeigen eine gute Übereinstimmung mit Versuchsergebnissen, welche an einer Pilotanlage der pharmazeutischen Industrie ermittelt worden sind.

МОДЕЛЬ ТЕПЛОПЕРЕНОСА ДЛЯ ОПРЕДЕЛЕНИЯ РАЗМЕРОВ ЦЕНТРОБЕЖНОГО АБСОРБЕРА В ВОЗДУХООЧИСТИТЕЛЬНОЙ УСТАНОВКЕ

Аннотация—Описывается математическая модель, разработанная для расчета нового вида абсорбера, предназначенного для очистки воздуха. Модель включает уравнения скорости и массопереноса, которые решаются численно. Абсорбер состоит из вращающихся спиралевидных поверхностей, вызывающих действие центробежных сил в системе. Результаты расчетов по предложенной модели хорошо согласуются с экспериментальными данными, полученными на пилотной установке для фармацевтической промышленности.