CHEMICAL ENGINEERING TRANSACTIONS

VOL. 43, 2015

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Chief Editors: Sauro Pierucci, Jiří J. Klemeš

ISBN 978-88-95608-34-1; **ISSN** 2283-9216

DOI: 10.3303/CET1543192

Purification Apparatuses with New Types of Regular Packings for Chromium Salts Production

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The new design of gas-dust purification apparatuses with regular mobile packings has been proposed. The submitted constructions furnished with packing units in the form of plates, spheres, tubes, etc. were investigated in laboratory conditions, whereby the basic hydrodynamic and mass transfer characteristics and parameters have been defined. The investigations have been carried out in the wide range of operational and constructive parameters. On the basis of the results of laboratory studies the new effective purifying apparatuses have been designed and implemented to the enterprises for productions of chromic anhydride, chromium oxide and chrome tanning agent. Results of operation showed increased dust collection efficiency and absorption degree under significantly decrease of the energy consumption. The semi-empirical expressions for calculating the main characteristics of work efficiency and design parameters of the new types of apparatuses have been also obtained.

1. Introduction

Mass transfer and dust collecting apparatuses are widely used in almost all industries, but they are the most claimed on the chemical, petrochemical, refining and metallurgical plants. Mass transfer and dust collecting apparatuses used in the Republic of Kazakhstan are remarkable for great variety of structures and principles of work and at the same time they do not meet the current stringent ecological and economic requirements, as many of them were developed in the 60s-70s (Herbert Vogel, 2005).

At present time the new designs of purifying apparatuses whose operation is based on well-known principles are continuing to develop (Calis et al., 2001). Unfortunately, there is still no generally accepted methodology for their development, which prevents the creation of high-performance apparatuses for general industrial use. It also makes it difficult to choose the most optimal design for engineers (Serikuli et al., 2014).

Hollow nozzle type scrubbers and packed towers with Raschig rings or chord packings are widely used in enterprises of chromium compounds as absorption and dust collection equipment (Dil'man et al., 2012). The effectiveness of these apparatuses is low (Haroun et al., 2012). In addition, the hollow scrubbers require significant maintenance costs for nozzles service (Puschke and Preisig, 2011), and packed towers tend to be overgrown by solid sediments. Replacement of these devices after reaching the specified service life by similar apparatuses is associated with high material costs (Preisig, 2013). This is because the operating speed of the gas in the apparatus is small (1-1.5 m / s) and therefore the scales of apparatuses are considerable (Lapkin and Plucinski, 2010).

These considerations stimulate the search for modern and more advanced equipment designs that is capable of with minimal material costs significantly increase the efficiency of gas purification schemes (Ismailov et al., 2002). This article describes the new constructions of apparatuses studied in this work with regular movable packings with units in the form of plates, bowls, tubes and etc. The results of the study in the laboratory are

Please cite this article as: Volnenko A., Balabekov O., Korganbaev B., Sarsenbekuly D., 2015, Purification apparatuses with new types of regular packings for chromium salts production, Chemical Engineering Transactions, 43, 1147-1152 DOI: 10.3303/CET1543192

submitted. Moreover, the basic hydrodynamic and mass transfer characteristics, as well as parameters of dust collection efficiency have been obtained.

2. Laboratory studies

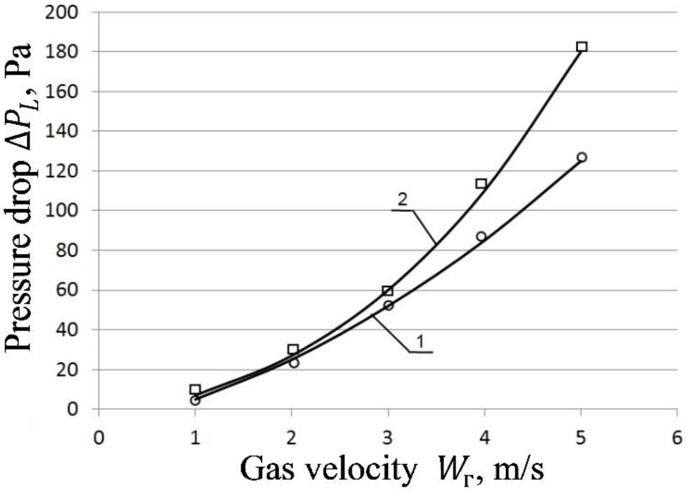
The study of hydrodynamic, mass transfer characteristics and parameters of the dust collecting apparatuses with regular movable packing (RMP) was carried out on experimental installations for columns with a diameter of 0.35 m and 1.0 m. The movement of gas (air) and liquid (water) streams was carried out in counter-current mode. The installation includes the blowers which provides the gas flow rate in the work zone of apparatuses of $W_r =$ 1-5 m/s, and pumps allowing to create irrigation density of L = 10 -75 m^3/m^2h. The research installations were equipped with instruments for measuring the velocity of the gas phase and pressure drops, psychrometers for measuring moisture content in the gas stream, thermometers, measuring cups, and dust hopper and allonges for dust sampling. The laminas and cylinders were chosen as packing units inasmuch as the similar construction was putted into the industrial installation. The pressure drop of the apparatus, ΔP_L, was measured by micro-manometers. To determine the mass transfer coefficients in the gas phase referred to the cross section of the apparatus β_{rs} or to its volume β_{rv} the well-known technique based on the study of the process of adiabatic evaporation of water in the air was used. In studying the process of dust collection for powders spraying into the gas tube the special dust supplying device was used.

This device is well established for its reliability, high level of particles disintegration, adjustable performance depending on the flow of gas supplied per unit of time. In addition, this device is recommended for conducting a comparative assessment of wet flue gas purifying. In determining the overall effectiveness of the dust collection the method of internal filtration was used. The allonges were filled with glass wool. Gas flow through the allonge can be calculated on the condition of iso-kinetic capture. To measure the particulate composition of dust in the gas flow the seven-stepped impactor with twin steps was used.

As a standard dust the quartz powder, additionally milled on a vibratory mill was used. In all experiments, the concentration of dust at the inlet of the apparatus is maintained at about 2 g/m^3.

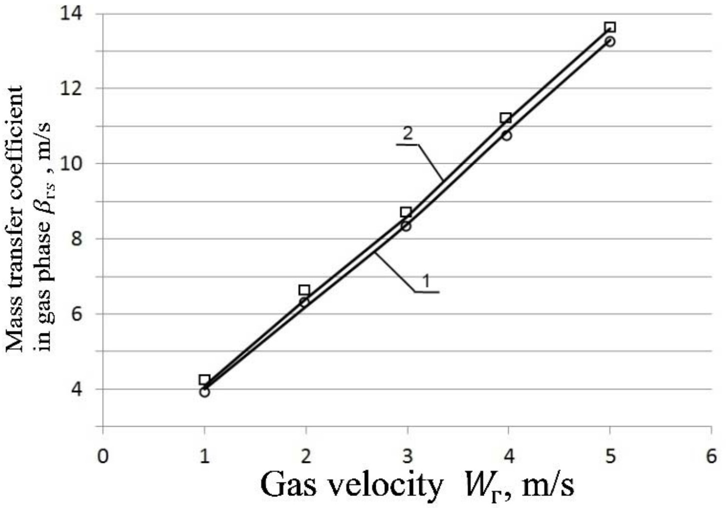
We have carried out the investigations in a wide range of operating and design parameters. While investigating the role of design parameters the possibility of reaching the modes of simultaneous vortices, which for laminas and cylinders correspond to vertical steps between packing units of $t_v/b=2$ and 4 appropriately, has been shown. The optimal distance between strings in the radial direction is $t_r/b=2$.

The main results of investigations of the pressure drop, mass transfer coefficients on gas phase and the efficiency of dust collection as functions of regime parameters are shown in Figures 1, 2, 3.



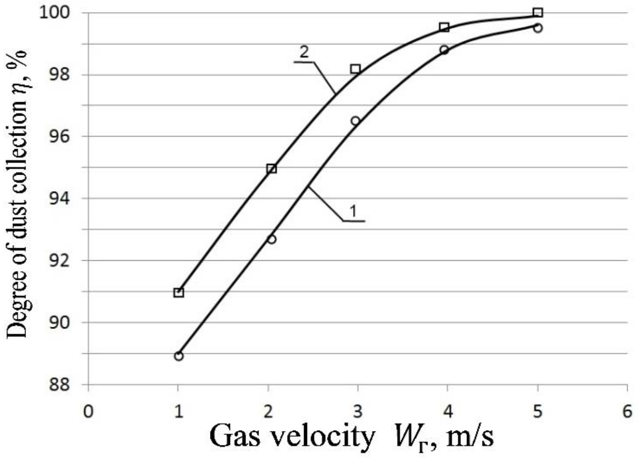
$t_в/b=2$; $t_р/b=2$; L =25 $м^3/м^2 \cdot ч$.
1 - laminar packing; 2- cylindrical packing

Figure 1: Dependence of pressure drop on gas velocity



$t_в/b=2$; $t_р/b=2$; L =25 m^3/m^2h
1-laminar packing; 2- cylindrical packing

Figure 2: Dependence of mass transfer coefficient in gas phase on gas velocity



$t_в/b=2$; $t_р/b=2$; L =25 m^3/m^2h
1 - laminar packing; 2- cylindrical packing

Figure 3: Dependence of the degree of dust collection on gas velocity

As it can be seen from Figures 1-3, with increasing gas velocity an increase of the all studied parameters is observed. Factors limiting the choice of high gas velocity are high pressure drops and a high level of droplets leaving the apparatus, which becomes important at gas velocities higher than 4 m/s.

3. Expressions for engineering calculations

On the basis of experimental investigations the set of empirical expressions for engineering designing the apparatuses with packing in the form of laminas or cylinders which are threaded by the vertical oscillating strings has been obtained. The pressure drop caused by the energy dissipation of the gas flow during the formation and movement of vortices in the packed zone of the apparatus, and by change of the direction of gas flow, and due to gas friction along a surface of the packing elements and liquid films, can be calculated by the following relationship

$$\Delta P_L = \xi_L \frac{H}{t_b} \frac{\rho_g W_r^2}{2\varepsilon_0^2} \tag{1}$$

Here H - height of packing layer, m; ρ_g - gas density, kg/m^3; ε_0 - porosity of packing layer into the cross-section; ξ_L - resistance coefficient accounting the vortices interaction over vertical and radial direction and energy dissipation under the friction.

The following relationships for coefficients ξ_L have been obtained:

for cylindrical units

$$\xi_L = 0{,}24\theta_b \theta_p \operatorname{Re}_L^{0{,}2} \tag{2}$$

for laminar units

$$\xi_L = 0{,}27\theta_b \theta_p \operatorname{Re}_L^{0{,}2} \tag{3}$$

Here Re_l is the Reynolds number

$$\operatorname{Re}_L = U_L d_H / \nu_L , \tag{4}$$

where U_L = L/3600 is the liquid velocity; ν_L is the dynamical viscosity coefficient of liquid; L is the irrigation density.

Parameter d_H is the equivalent hydrodynamic diameter of packing unit. It is:

for cylindrical packing

$$d_H = \left(4t_b t_p - \pi d_c^2\right) / \pi d_c \tag{5}$$

for laminar packing

$$d_H = \left(4t_b t_p^2 - b^2\delta\right) / \left(2b(b+2\delta)\right), \tag{6}$$

where δ is the thickness of the laminas.

The coefficient for characterizing the degree of vortices interaction over the vertical direction can be defined as

$$\theta_v = 0.85 + 0.15\sin\left[\frac{\pi}{2}\left(\frac{4t_v Sl}{m_k} + 1\right)\right] \tag{7}$$

Here Sl is the Strouhal number (for cylindrical bodies $Sl = 0.2$; for laminar bodies $Sl = 0.15$)

Parameter m_k characterizes the intensity of vortices interaction and the form of packing units:

$$m_K = \kappa\left(1 - \exp(-t_b)\right), \tag{8}$$

where $\kappa = 0.44$ for cylindrical elements, and $\kappa = 0.329$ for laminar elements.

The elements which are located along a row perpendicular to the vector of gas velocity induce the vortices of the scale λ. Moreover, two different cases should be considered: 1) when $t_p > 2d$ than $\lambda = d$; otherwise $\lambda = t_p - d$.

The special coefficient θ_p for evaluating the level of vortices interaction along the radial direction taking into consideration the frequency of vortices formation reads

$$\theta_p = \left(t_p - \lambda\right) / \left(t_p - d\right) \tag{9}$$

On the basis of the Fick law and the theory of local-isotropy turbulence of Kolmogorov-Obukhov the expressions for calculating the mass transfer coefficient in a gas phase has been obtained

$$\beta_{rS} = B_{rS}\left[\frac{D_g^2 C_k U_g^3 (h_0 - h_p)}{\varphi_{cell}(t_b - h_p) d_k \nu_g}\right]^{1/4} \tag{10}$$

From experimental investigations, relations for the coefficient are found:
for the cylindrical packing $B_{rS} = 8.68(\varphi/(1-\varphi))^{1/4}$, and for laminar packing $B_{rS} = 7.8(\varphi/(1-\varphi))^{1/4}$. When analyzing the experimental data for the level of dust collection, the model of inertia-diffusion separation was used.
The general form of the appropriate relation reads

$$\eta_{gen} = 1 - (1 - \eta_{Stk})(1 - \eta_D) \tag{11}$$

Here η_{Stk} and η_D are the efficiencies of dust collecting by the inertia and diffusion ways.
The following relationship was obtained for calculating the efficiency of dust collection by the inertia way

$$\eta_{Stk} = 1 - \exp\left(-\frac{3}{2}\frac{m_y K \vartheta_{rel} t_b}{U_k d_k}\right) \tag{12}$$

Here m_y is the density of irrigation, m^2/m^3; U_k is the rate of particles sedimentation on the droplet surface, m/s; t_c is the height of the packing cell, m; K is the capture coefficient.
After analyzing the set of experimental measures the following relation for calculating the capture coefficient has been obtained

$$K_3 = \frac{Stk^2}{(Stk + 0.25)^2}\left(\exp\left(-5.1\cdot 10^{-4}\frac{d_d}{d_p}\right) - \exp\left(-4.5\tfrac{l_d}{d_d}\right)\right) \tag{13}$$

The efficiency of dust collecting by the diffusion way reads

$$\eta_D = 1 - (1 - \eta') \tag{14}$$

The efficiency of dust collection into the packing layer can be calculated with the help of the empirical relation

$$\eta' = 3.57(W_r d_d / D_T)^{-1/4} \tag{15}$$

The empirical formula for the coefficient of turbulent diffusion reads

$$D_T = 8.85\cdot 10^{-2}\xi_L^{1/3}(1 - \varepsilon_0)^{1/3}\left(H\rho_g/(t_b\rho_l h_0)\right)^{1/3} d_d^{4/3} u_g Stk \tag{16}$$

Here Stk is the Stokes criterion.

4. Conclusions

On the basis of the results of laboratory studies and of the analysis of the empirical data both the calculation method and set of recommendations for optimal design of the apparatuses with regular movable packings have been offered to engineering practice. Results of the investigations were implemented into the enterprises of chromic anhydride, chrome oxide and chrome tanning agent.
The main results obtained while testing the scrubbers with regular movable laminar packings in the scheme of gas purification for the production of chromic anhydride are the following: gas flow rate from 11.500 to 16.800 m3 / h; gas temperature after the first scrubber - from 70 to 75 °C; after the second scrubber - from 50 to 55 °C; concentration of captured components (in terms of Cr) after the first scrubber – from 0.7 to 3.65 g/m^3; after the second scrubber - from 0.0117 to 0.275 g/m^3; the efficiency of purification - 99.9 %. Ecological and economic effect was 5.18 mln. Kzt/y.
In the technological scheme of chromic production two hollow scrubbers were reconstructed by installing the regular movable laminas packing inside the tower.
On the basis of the results of laboratory studies and of the analysis of the empirical data both the calculation method and set of recommendations for optimal design of the apparatuses with regular movable packings have been offered to engineering practice. During the industrial test, the limit values of the gas flow parameters at the inlet of the apparatus were as follows: the temperature of the gas - from 500 to 800 °C; gas

flow rate – from 17,400 to 19,390 m^3/h; the dust flow rate in the gas - from 80 to 160 g/s. At the outlet of apparatus: gas temperature – from 70 to 90 °C; gas flow rate - from 21,400 to 28,700 m^3/h (gas flow rate was increased by partial evaporation of the irrigating liquid and air leaks (Golubev and Brener, 2002); the dust flow rate in the gas – from 1.25 to 4.66 g/s; dust collection efficiency - from 96.0 to 98.4 %. Ecological and economic effect was 3,51mln. Kzt/y.

In the technological scheme of the lame tanning with the help of recovering the sodium dichromate with sulfur dioxide the towers with Raschig rings were replaced onto the scrubbers with cylindrical packing. The point is that this manufacture characterizes by hard technological terms and by solid sediments availability.

Before reconstruction the limit values of operating parameters were: inlet gas flow in a scrubber – from 9500 to 10500 m3 / h; gas temperature – from 50 to 55 °C; the rate of captured components – from 2.1 to 2.5 g/s; degree of purification - of 94-96 %. After reconstruction the following limiting parameters were obtained: flow rate – from 9,800 to 11,200 m^3/h; gas temperature - from 45 to 50 °C ; the concentration of sulfur dioxide – from 0.0082 to 0.014 g/m^3; degree of purification (at concentrations in the sanitary pipe) - 98- 99 %. Ecological and economic effect was 5.31mln. Kzt/y.

On the results of the implementation of all industries increased dust collection efficiency and the high degree of absorption have been showed while significantly reducing energy costs.

So, it can be concluded that on the results of laboratory investigations as well as industrial testing the relevance of worked out apparatuses has been confirmed.

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