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1. Introduction

The process of complex cleaning of gases, injected into the atmosphere, for instance, by thermal power plants, metallurgical, chemical or other industrial enterprises, from dust and harmful gaseous admixtures by means of their irrigation by wash liquids (water or specially selected water solutions) is considered. This process can be implemented in gas pipes or gas-cleaning apparatuses (direct flow or counter flow jet scrubbers) [1]. The process of gas cleaning from dust and gas admixtures is carried out in the following manner. The fluid dispersed by jets is introduced into the dust-vapor-gas flow in the form of droplets, interacts with it, and under nonisothermal conditions the increased moisture content leads to intensive condensation of liquid vapors on particles, their significant enlargement and efficient absorption of liquid droplets due to collisions of the latter with particles [2]. Simultaneously, the liquid droplets and condensate on particles absorb harmful gas components, dissolving them and removing from the vapor-gas flow.

The authors failed to find the mathematical description of this complex process in literature. From the engineering point of view the importance of development of generalized mathematical models, which reflect properly the interaction of heat and mass transfer with the effects of gas components removal and dust capture by the droplets of irrigating liquid in jet scrubbers and reactors, is undisputable, and it is determined by significant opportunities for optimization of operation conditions and constructions of energy-intensive and large-scale equipment in various industries both in terms of reducing of material and energy costs.
2. Problem statement, main equations and assumptions

In the current work we suggest the model for mathematical description of the above process with the following assumptions:

1. droplets and particles are considered monodispersed with equivalent sizes, equal to mass-median by distributions;
2. concentrations of droplets of irrigating liquid, dust particles and harmful gas components are low, what allows us to use the Henry’s law for equilibrium of gas components in liquid and gas phases at the interface and assume that the solution in droplet is ideal;
3. the mean-mass temperature of droplets and temperature of their surfaces are equal because of their small sizes [3];
4. the typical time of gas component dissolution in droplet is significantly less than the typical time of mass transfer processes, commonly occurring in the apparatus;
5. the motion velocities of particles with condensate on their surface (“formations”) and vapor-gas flow are equal;
6. the moisture content in the flow can be high, what requires consideration of the Stefan correction in mass transfer equations for evaporation-condensation process on droplets and “formations”;
7. we do not take into account the evaporation-condensation correction for the resistance and heat transfer coefficients of droplets and “formations”, it is insignificant and becomes obvious only at the initial stages of the process at high moisture contents [4];
8. in equation of droplet motion we take into account variability of its mass;
9. the radiant component in the process of heat transfer is neglected because of low temperatures of droplet, “formations” and flow;
10. mutual coalescence of droplets and “formations” is not taken into account, and merging of droplets and “formations” due to collision is the basis of condensation-inertial mechanism of dust capture in jet scrubbers [2].

Under the above conditions equations of model system will take the following form:

Motion equation of a mass-median droplet with variable mass

\[
\frac{d\vec{V}_d}{d\tau} = \vec{R}_d + \vec{g} - \frac{\vec{V}_d}{m_d} \frac{dm_d}{d\tau};
\]  

(1)

equation of heat transfer between droplet and vapor-gas flow
equation of mass transfer between droplet and the i-th component of vapor-gas flow

\[
\frac{d m_{id}}{d \tau} = -\beta_{id} \pi \delta_i^2 (\rho_{id} - \rho_i);
\]

continuity equation for i-th reacting components, including vapor of liquid

\[
\frac{\partial \rho_i}{\partial \tau} + \text{div} (\rho_i \mathbf{U}) = -\frac{d m_{id}}{d \tau} \eta_{id} - \frac{d m_{id}}{d \tau} \eta_{id};
\]

continuity equation for (mass concentration) of non-reacting component of the vapor-gas mixture

\[
\frac{\partial \rho_j}{\partial \tau} + \text{div} (\rho_j \mathbf{U}) = 0;
\]

continuity equation for (mass concentration) of “formations”

\[
\frac{\partial \rho_\delta}{\partial \tau} + \text{div} (\rho_\delta \mathbf{U}) = \sum \frac{d m_{id}}{d \tau} \eta_i \rho_i V_i \pi \delta_i^2 \eta_{sk} \eta_{id} / 4;
\]

continuity equation for (mass concentration) of droplets

\[
\frac{\partial \rho_d}{\partial \tau} + \text{div} (\rho_d \mathbf{V}_d) = \frac{d m_{id}}{d \tau} \eta_d;
\]

equation of heat transfer between “formation” and vapor-gas flow

\[
c_p m_{id} \frac{dT_d}{d \tau} = -\alpha \pi \delta_i^2 (T_d - T) + \sum r_i \pi \delta_i^2 c_{is} \rho_s V_s \frac{\pi \delta_i^2}{4} \eta_{sk} (T_s - T_0);
\]
\[ \bar{n}_{d} \frac{dT_d}{dT} = -\alpha_d \pi \delta^2 (T_d - T) + \sum \tilde{\tau}_d \frac{dm_d}{dt}; \] (9)

equation of convective heat transfer between vapor-gas flow and droplets and “formations”

\[ \rho \frac{d\tilde{n}_d(T - T_0)}{dt} = \alpha_d \pi \delta^2 (T_d - T) \tilde{n}_d + \alpha_d \pi \delta^2 (T_d - T) n_d; \] (10)
general rate of droplet mass change due to evaporation-condensation and absorption of removed gas components (droplet collision is assumed unlikely) and “formation” absorption

\[ \frac{dm_d}{dt} = \sum \frac{dm_d}{dt} + \rho V \frac{\pi \delta^2}{4} \eta_{sk} \] (11)
general rate of “formation” mass change (“formation” collision is assumed unlikely )

\[ \frac{dn_d}{dt} = \sum \frac{dn_d}{dt}; \] (12)
continuity equation for (mass concentration) of dry particles

\[ \frac{\partial \rho_p}{\partial t} + \text{div}(\rho_p \bar{U}) = -\rho_p V \frac{\pi \delta^2}{4} \eta_{sk} n_d; \] (13)

The following closure relationships shall be added to equations (1-13):

for the force of droplet aerodynamic resistance per a unit of droplet mass,

\[ \tilde{R}_d = \tilde{\xi} \left( \bar{V}_d - \bar{U} \right) \] (14)

where relative coefficient of droplet resistance is \( \tilde{\xi} = \xi / \xi_c \), \( \xi_c = 24 / Re_d \),

\[ \tilde{\xi} = 1 + 0.197 Re_d^{0.63} + 2.6 \cdot 10^{-4} Re_d^{-1.38} \text{ for } 0.1 \leq Re_d \leq 3 \cdot 10^5 \] (15)

\[ \tilde{\tau}_d = \frac{\rho V \delta^2}{18 \mu} Re_d = \frac{V \delta^2 \mu}{\mu} \] (16)
coefficient of “formation” entrainment according to the empirical formula of Langmuir–Blodgett with Fuchs correction on engagement effect [1]

\[
\eta_{Sk} = \left( \frac{Stk}{Stk + 0.5} \right)^2 + 2.5 \frac{\delta}{\delta_d},
\]

\[
Stk = \frac{V}{\delta_d}, \quad \tau_{Sk} = \frac{\rho_{Sk} \delta^2}{18 \mu} \left( \rho_{Sk} \approx \rho_f \right),
\]

where \(\rho_{Sk}\) is efficient density of “formation”;

mass transfer coefficient of the \(i\)-th component with droplets both via evaporation-condensation and absorption-desorption [2]

\[
Nu_{id} = \frac{\beta_{id} \delta_d}{D_i} = 2 \left( 1 + 0.276 Re_d^{0.5} Sc_i^{0.33} \right) K_{ci, Sc_i} = \frac{\mu}{\rho D_i},
\]

Stefan correction on increased moisture content

\[
K_{\bar{n}} = 1 + \frac{P_{id} + P_i}{2B};
\]

barometric (total) pressure

\[
B = P_g + \sum P_i;
\]

density of vapor-gas mixture

\[
\rho = \rho_g + \sum \rho_i;
\]

state equation for gas components and vapor of liquid

\[
\rho_g = \frac{M_g P_g}{RT}, \quad \rho_i = \frac{M_i P_i}{RT}, \quad \rho_{id} = \frac{M_{id} P_{id}}{RT_d}, \quad \rho_{id} = \frac{M_{id} P_{id}}{RT_d};
\]

diffusion coefficient of the \(i\)-th component in non-reacting component of the vapor-gas flow (we assume that its fraction in the flow is predominant)
\[ D_i = D_0 \left( \frac{B_0}{B} \left( \frac{T}{T_0} \right)^{1.75} \right), \quad B_0 = 0.1 \text{ MPa}, \quad T_0 = 273 \text{ K}; \]  

(24)

coefficient of droplet heat transfer according to Drake’s formula

\[ \text{Nu}_d = \frac{\alpha_d \Delta \lambda}{\lambda} = 2 + 0.459 \text{Re}_d^{0.8} \text{Pr}_d^{0.3}, \quad \text{Pr} = \frac{\mu C_p}{\lambda}; \]  

(25)

countable concentrations of droplets and “formations”

\[ n_d = \frac{n_d}{m_d}, \]  

(26)

\[ n_\delta = \frac{n_\delta}{m_\delta}; \]  

(27)

heat and mass transfer coefficients of “formations”

\[ \alpha_\delta = 2 \frac{\lambda}{\delta} \left( \text{Nu}_d = 2 \right), \quad \beta_\delta = 2 \frac{D_\delta}{\delta} \left( \text{Nu}_\delta = 2 \right), \]  

(28)

heat capacity of the vapor-gas mixture

\[ c = \sum \frac{\rho_i c_v}{\rho_i}; \]  

(29)

specific heat of gas absorption with the made assumptions [6]

\[ r = M_i^{-1} RT^2 \frac{d \ln m_{ps,i}}{dT}, \]  

(30)

it can be assumed for water vapors that \( r = 2500 \text{ kJ/kg} \) [2-4];
according to Henry’s law for partial saturation pressure at the interface between i-th gas components, the equilibrium condition is [6]

\[ P_{id} = m_{px,i} x_{id} \], \[ P_{i\delta} = m_{px,i} x_{i\delta} \],

(31)

\[ x_{id,\delta} = \frac{c_{mid,\delta}}{M_i} \frac{1}{M_{dis}} \frac{d}{d} \]

(32)

where \( x_{id,\delta} \) is a molar part, equal to the number of moles of dissolved gas per the total number of moles in solution, \( M_{dis} \) is the molar mass of dissolvent.

The equation for mass concentration of dissolved i-th gas component in the kilogram per 1 kg of dissolvent in the droplet and “formation” is written as

\[ \frac{dc_{mid,\delta}}{d\tau} = \frac{dm_{mid,\delta}}{d\tau} \frac{6}{\pi \delta_{i,f}^3 \rho_f} \],

(33)

Diameters of specific spherical volume of dissolvent for “formation” \( \delta_i \) and droplet \( \delta_d \) are calculated by equations:

\[ \frac{d}{d\tau} = \frac{6}{\pi \rho_f} \], \[ \delta_d = \sqrt[3]{\frac{3m_f}{\pi \rho_f}} \],

(34)

“formation” diameter is

\[ \delta = \sqrt[3]{\frac{6m_{\delta}}{\pi \rho_s}} + \delta_i^3 \left( \rho_s \approx \rho_f \right) \],

(35)

where \( \rho_s \) is solution density, kg/m³.

The reactive force in equation (1) is neglected because of evaporation-condensation and absorption [2]. In equation (2) specific heat capacity \( c_f \) is taken constant and equal to specific heat capacity of dissolvent because of low concentrations of absorbed dust and absorbed gases. For small particles and significant amount of condensate on them [2] we will take \( c_{\delta} \) equal to specific heat capacity of dissolvent \( c_f \). In this equation the first summand in the right determines convective heat transfer between the droplet and flow, the second summand de-
termines the total heat of phase transitions due to evaporation-condensation and absorp-
tion-desorption of gas components, and the third summand determines heat introduced by
“formations” into the droplet due to their absorption at collision. In equations (3) and (4)
\[
d_{m_d} / d\tau, \quad d_{m_o} / d\tau
\]
are the rates of droplet and “formation” mass change due to the process-
es of evaporation-condensation or absorption-desorption of the i-th gas component. In rela-
tionships (16) dynamic viscosity of the vapor-gas flow \(\mu\) is calculated by generalized
Wilkey’s formulas, in our case on the basis of research performed in [2] and [4] with consid-
eration of low concentrations of reacting gas components we will determine \(\mu\) by Sutherland
formulas [2, 4] for a non-reacting component of the vapor-gas mixture. The coefficient of
mixture heat conductivity \(\lambda\) will be calculated similarly by Sutherland formula [2, 4] in for-
mulas (25) and (28). The diffusion components of the vapor-gas flow will be determined by
their dependences on temperature in the non-reacting component by formula (24). The cor-
rection for Stefan flow of gas components is not taken into account because of their low con-
centrations \((K_{ci} = 1)\). In the current study we will consider water as the absorbent and
\(m_{px,i}\) will be taken from tables depending on temperature [6]. If there are no data for some gases
in [6], for instance, for \(\text{SO}_2\), we suggest to recalculate volumetric \(q_s\) and weight \(q_i\) solubility
[7] as the limit ones by \(m_{px,i}\), this will be described in detail in this work.

3. Numerical implementation of the model, comparison of calculation
results with experimental data

As it is shown in [2], in most technically implemented situations it is possible to use a single-
dimensional model for calculation of heat and mass transfer in irrigation chambers, what is
determined by the vertical position of apparatuses (hollow jet scrubbers HJC); at their hori-
zontal position it is determined by high velocities of cleaned gases, dust particles and drop-
lets (Venturi scrubber VS), when the gravity force, influencing the flow components and
causin its 2D character, is low in comparison with the inertia forces.

The calculation scheme of the problem for the vertical construction of apparatus is shown in
Fig. 1а). The scheme of interaction between a droplet of washing liquid dispersed by the jets
with vapor-gas flow and dust particles is shown in Fig. 1b).

The hollow jet scrubber HJS can have direct-flow and counter-flow construction. In the di-
rect-flow scheme the initial parameters of the vapor-gas flow, irrigating liquid and dust are
set on one side (inlet) of apparatus, and the resulting parameters are achieved at the appara-
tus outlet. In the counter-flow scheme the parameters of vapor-gas flow and dust are set on
one side of apparatus, the parameters of irrigating liquid are set on the opposite side (at ap-
paratus outlet). Scheme 1а) is attributed to the counter-flow. From the point of numerical
implementation the direct-flow scheme is the Cauchy problem, and the counter-flow
scheme is the boundary problem. Let’s perform calculations for the direct-flow scheme ac-
cording to the known experimental data for generalized volumetric mass transfer coeffi-
cients, shown in [6, p. 562], for different gases absorbed on dispersed water. The calculation
scheme is shown in Fig. 2 (it is conditional, the construction can differ).
The problem will be solved in the stationary statement. The boundary conditions are set at $x=0 \ (t=0)$ in the following manner:
for the vapor-gas flow \( U = U_0 \), \( d_d = d_{d0} \), \( d_i = d_{i0} \), \( T = T_{00} \);
for dispersed liquid \( V_d = V_{d0} \), \( d = d_{d0} \), \( q = q_{d0} \), \( T_d = T_{d0} \);
for dust \( \rho_d = \rho_{d0} \), \( d = d_{0} \).

Continuity equations (6) and (8) in stationary single-dimensional case can be reduced to the following, as in [2], analytical dependences:

\[
U = U_0 \frac{T}{T_{00}} \frac{B - \sum P_j}{B - \sum P_j + \frac{K_{ave} + d_{\Sigma}}{\rho_{d0}}},
\]

\[
\rho_d = \rho_{d0} \frac{V_{d0}}{V_{d0}} \frac{m_d}{m_{d0}}, \quad \rho_{d0} = \rho_{d0} \frac{U_0}{V_{d0}}, \quad m_d = \rho_d \frac{\pi d_i^3}{6}, \quad m_{d0} = \rho_d \frac{\pi d_{i0}^3}{6},
\]

where

\[
K_{ave} = \frac{1}{k} \sum K_i, \quad K_i = \frac{M_i}{M_g},
\]

\( k \) is the number of reacting components, including liquid vapors, \( M_g \) is molecular mass of a non-reacting component of gas;

\[
d_{\Sigma} = \frac{1}{B} \sum \frac{K_i P_i}{1 - \frac{1}{B} \sum P_i} \approx K_{ave} \frac{1}{B} \sum \frac{P_i}{1 - \frac{1}{B} \sum P_i},
\]

efficiency of dust capture and gas component removal is determined by relationships:

\[
\eta_p = 1 - \frac{\left( \rho_{d0} U \right)_{d0}}{\rho_{d0} U_0},
\]

\[
\eta_i = 1 - \frac{\left( \rho_{d0} d_{d0} U \right)_{d0}}{\rho_{d0} d_{d0} U_0}.
\]
3.1. Calculation with the use of $m_{px}$ [6] or Henry’s coefficient $E$ [7]

Calculation results on absorption of $\text{CO}_2$ by water droplets in the direct-low hollow jet scrubber are shown in Fig. 3. There are no any restrictions for calculations by solubility limit (concentration of gas dissolving in the droplet). However, the solubility limits exists as the experimental fact for gases, presented in tables of Hand-books as absorption coefficient $\alpha$, in volumetric fractions reduced to $0 ^\circ\text{C}$ and pressure of $0.1 \text{ MPa}$ or in the form of solubility coefficient $q_r$ in mass fractions to solution or dissolvent [8, 9]. Thus, in [9] for $\alpha(T)$, m$^3$ of gas/ m$^3$ of water, for CO$_2$ and CH$_4$ the following data are shown (Table 1).

<table>
<thead>
<tr>
<th>$T$, $K$</th>
<th>273</th>
<th>283</th>
<th>293</th>
<th>303</th>
<th>313</th>
<th>323</th>
<th>333</th>
<th>353</th>
<th>373</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{\text{CO}_2}$</td>
<td>1.713</td>
<td>1.194</td>
<td>0.878</td>
<td>0.665</td>
<td>0.530</td>
<td>0.436</td>
<td>0.359</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>$\alpha_{\text{CH}_4} \times 10^3$</td>
<td>55.6</td>
<td>41.8</td>
<td>33.6</td>
<td>27.6</td>
<td>23.7</td>
<td>21.3</td>
<td>19.5</td>
<td>17.7</td>
<td>17.0</td>
</tr>
</tbody>
</table>

Table 1. Absorption coefficients for CO$_2$ and CH$_4$, m$^3$/m$^3$ of water at $\beta=0.1$ MPa and $T_p=273$ K

It follows from this table that the limit value of CO$_2$ concentration in a water droplet is...
\[ c_{\text{meo}} \text{,lim} = \alpha_{\text{co2}}(T) \cdot \frac{M_{\text{co2}} \cdot B_0}{R \cdot t_0} = \alpha_{\text{co2}} \cdot \frac{44 \cdot 10^{1325}}{8, 314 \cdot 10^3 \cdot 273} = 1,964 \cdot 10^{-3} \cdot \alpha_{\text{co2}}(T), \quad \text{kg CO}_2 \text{kg water}, \]

(43)

where \( \alpha_{\text{co2}}(T) \) is the table value of absorption coefficient for CO\(_2\) (Table 1).

This value shall limit concentration of CO\(_2\) dissolved in the droplet. It can be seen in Fig. 3a) that according to Table 1 calculated value of \( c_{\text{mid}} \) does not reach the solubility limit and it is one order lower. Thus, \( c_{\text{mid}, \text{lim}}(T_d=278, 63 \text{ K}, \text{see Fig. 3c}) = 2.81 \cdot 10^{-3} \text{ kg of CO}_2/\text{kg of water.} \) It can be seen in Fig. 3b) that as a result of water vapor condensation and CO\(_2\) absorption the size of droplet increases insignificantly, less than by 0.05 %, i.e., a small amount of water vapors condenses on the droplet and a small amount of CO\(_2\) is absorbed by the droplet, Fig. 3a). The calculated amount of the mass of gas component absorbed by liquid droplets in the scrubber is determined by formula, kg/h \( \cdot \) m\(^2\),

\[ W_{i, \text{th}} = \rho_{\text{d, a}, 0} \cdot d_{\text{co2}, 0} \cdot U \cdot \eta \cdot 3600. \]

(44)

For calculated situation with consideration of partial density of dry air at the inlet \( \rho_{\text{d, a}, 0} = 1.0363 \text{ kg/m}^3 \), gas content \( d_{\text{CO2}, 0} = 0.2 \text{ kg/kg of dry air,} \) \( U_0 \text{=0.25 m/s and} \eta_{\text{CO2}} \text{=0.022262 according to formula (44) we will obtain} \)

\[ W_{i, \text{th}} = 1.0363 \cdot 0.2 \cdot 0.25 \cdot 0.022262 \cdot 3600 = 4,153 \text{ kg/h \cdot m}^2. \]

(45)

Let’s compare the obtained result with the value achieved via the empirical volumetric mass transfer coefficient, shown in [6, p. 562] (in our nomenclature):

\[ \beta_{i, p} = 720U_0^{0.5}Q^{0.45}H^{-0.65} \left( \frac{D_{\text{co2}, 0}}{D_{\text{NH3}, 0}} \right)^{0.67}, \text{1/h.} \]

(46)

Here \( Q \) is irrigation density, m/h, \( D_{\text{NH3}, 0}=0.198 \text{ 10}^{-4} \text{ m}^2/\text{s} \) is coefficient of methane diffusion in air at \( T_d=0.1 \text{ MPa and} T_0=273 \text{ K}, \) \( H \) is calculated scrubber height, m.

Let’s write down the value of obtained coefficient per an area unit of apparatus cross-section via coefficient \( \beta_{i, p} \) in the following form, kg/h \( \cdot \) m\(^2\):

\[ W_{i, \text{sp}} = \beta_{i, p} \Delta \rho \cdot l, \]

(47)
where $\Delta \rho_i$ is calculated concentration pressure on the way of gas component obtaining $x=l$, where $l$ corresponds to the coordinate, where thermodynamic equilibrium is achieved for the $i$-th component in the flow.

Substituting (46) into (47) and assuming $l=H$, as it was made at treatment of experimental data in [6], we get

$$W_{i,e} = 720U_0^{0.9} \left(3600U_0q\right)^{0.45} H^{0.25} \Delta \rho_i \left(\frac{D_{i,0}}{D_{\text{NH}_3,0}}\right)^{0.67}, \text{kg/h} \cdot \text{m}^2,$$  

(48)

where $q$ is irrigation coefficient, $\text{m}^3$ of water/ $\text{m}^3$ of vapor-gas flow at apparatus inlet.

Let’s transform formula (48), and finally for calculation we obtain dependence

$$W_{i,e} = 28685,9 \left(0,25\right)^{1.35} \left(0,015\right)^{0.45} \left(7\right)^{0.35} \left(0,004614 \frac{0,138}{0,198}\right)^{0.67} \approx 4,772 \text{ kg/h} \cdot \text{m}^2$$  

(49)

For the considered situation $D_{i,0}=D_{\text{CO}_2,0}=0, 138 \cdot 10^{-4} \text{m/s}$ [6].

Let’s take the average experimental data of [6] as the calculation working height of absorber $H_{\text{ave}}=(H_{\text{min}}, H_{\text{max}})^{1/2}=(4,3, 12)^{1/2}=7$ m, then for calculated value $\Delta \rho_{\text{CO}_2}=\rho_{\text{d,av}} \Delta \rho_{\text{CO}_2}$ 

$$W_{i,e} = 28685,9 \left(0,25\right)^{1.35} \left(0,015\right)^{0.45} \left(7\right)^{0.35} \left(0,004614 \frac{0,138}{0,198}\right)^{0.67} \approx 4,772 \text{ kg/h} \cdot \text{m}^2$$  

(50)

since $D = \frac{B_0}{\beta_0} \left(\frac{T}{T_0}\right)^{1.75}$ and total multiplier $\frac{B_0}{\beta_0} \left(\frac{T}{T_0}\right)^{1.75}$ in (50) is reduced.

Calculated (45) and experimental (50) results differ by $\Delta=13 \%$. If we take $H=4.3$ m, then $W_{i,e}=4, 024 \text{ kg/h} \cdot \text{m}^2$ and $\Delta=3 \%$. At $H=12$ m, $W_{i,e}=5, 76 \text{ kg/h} \cdot \text{m}^2$ and $\Delta=28 \%$.

It follows from formula (42) for calculated concentration difference at apparatus inlet and outlet that

$$\Delta \rho_{i,\text{cal}} = \left(\frac{U_{\text{out}}}{U_0} - 1\right) \rho_{i,\text{in}} + \Delta \rho_i,$$

where calculated value is $\Delta \rho_{i,\text{cal}}=\eta_i \rho_{i,\text{in}}$. Thus, for $U_{\text{out}}= U_0$ $\Delta \rho_{i,\text{cal}}=\eta_i \rho_{i,\text{in}}$ = $\Delta \rho_i$ i.e., the calculated value of concentration difference coincides with real value $\Delta \rho_i$. Therefore, we can make a conclusion that efficiency of dust capture and mass transfer shall be calculated not
by the measured difference of dust concentrations and extracted gas components at the inlet and outlet, but by difference of their mass fluxes in accordance with the law of mass conservation, and if velocities at the inlet and outlet are equal or close efficiencies can be calculated by real concentration difference. Distribution of mass flux of CO₂ along the scrubber height is shown in Fig. 3d). It is obvious from Figs. 3c) and 3d) that the process of absorption completes long before the flow escape from the scrubber, for the given version of calculation at x/H ≈ 0.1 (=1.3 m). Hence, the residual height of the scrubber is excessive, and it can not be determined experimentally.

Previous comparison can be made in the relative form, what will prove the validity of calculation of mass transfer coefficient as a measure determining process intensity, on the basis of model in comparison with its experimental expression [6]:

\[
\frac{W_{i,th}}{W_{i,e}} = \frac{\rho_{d.a,d} U_0 \eta_3 3600}{28685,9 U_0^{0.35} q^{0.45} H^{0.35} \Delta \rho} = \frac{0.1255}{q^{0.45} \left( H U_0 \right)^{0.35} \left( \frac{D_{i,0}}{D_{NH_3,0}} \right)^{0.67}},
\]

(51)

where it is assumed that \( \Delta \rho_i = \eta_i \rho_{d.a,d} \beta \rho \). Thus, for our case \( \frac{W_{i,th}}{W_{i,e}} = \frac{0.1255}{0.616 \cdot 0.151 \cdot H^{0.35} \cdot 0.785} = \frac{1,72}{H^{0.35}} \approx 0, 87 \) at \( H=7 \) m and \( \frac{W_{i,th}}{W_{i,e}} = 1, 03 \) at \( H=4.3 \) m.

Here \( \Delta \rho_i \) has the meaning of efficient drop of gas concentration, not real, but corresponding to extraction of the gas component due to absorption on a liquid droplet. Real drop of CO₂ concentrations at the inlet and outlet at the example of Fig. 4 is even negative: \( \Delta \rho_{CO_2} = \rho_{CO_2, in} - \rho_{CO_2, out} = 0, 1245 - 0, 2099 = -0, 0854 \) kg/m³, here \( U_0 = U_0 = 0.25 \) m/s, \( U_w = 0.1439 \) m/s.

Extractions per a total volume of apparatus can be presented as, kg/h,

\[
\Delta G_{i,th} = \beta_{i,th} \Delta \rho_i \beta \pi D^2 H;
\]

\[
\Delta G_{i,e} = \beta_{i,e} \Delta \rho_i \beta \pi D^2 H.
\]

(52)

(53)

On the other hand

\[
\frac{\beta_{i,th}}{\Delta \rho_i \beta \pi D^2 H} = \frac{\rho_{d.a,d} U_0 \eta_3 3600 \pi D^2}{\Delta \rho_i \beta \pi D^2 H}.
\]

Hence, with consideration of formulas (46) and (53) we will obtain the relationship for volumetric mass transfer coefficients (theoretical and experimental ones)
\[
\beta_{\text{te,th}} = \frac{3600 U_i \Delta \rho_i \pi D^2}{28685, 9 U_0^{1.35} q^{0.45} H^{-0.65} \Delta \rho \left( \frac{D_i,0}{D_N H_i,0} \right)^{0.65} \pi D^2 H},
\]

after elementary reductions in numerator and denominator this corresponds to formula (51). Here \( D \) is apparatus diameter.

Calculations results for the same situation as in Fig. 3 are shown in Fig. 4, but for the increased moisture content \( d_0 = 0.5 \text{ kg/kg of dry air} \). The theoretical value of absorbed \( \text{CO}_2 \) is:

\[
W_{i, th} = 0, 6226 \cdot 0, 2 \cdot 0, 25 \cdot 0, 029136 \cdot 3600 = 3, 265 \text{ kg/h•m}^2.
\]

Calculation by formula (48) for height \( H = 4.3 \text{ m} \) gives the following

\[
W_{i,e} = 28685, 9 \cdot (0, 25)^{1.35} (0, 15)^{0.45} (4, 3)^{0.35} 0, 0363 \cdot 0, 785 = 3, 165 \text{ kg/h•m}^2,
\]

what differs from the theoretical value by 3 %. Here \( \Delta \rho_{\text{CO}_2} = 0, 00363 \text{ kg/m}^3 \) by calculation (\( \Delta \rho_{\text{CO}_2} = 0, 029136 \)). We should note that even for the increased moisture contents the size of droplets increases slightly due to condensation and absorption (less than by 1 %) (Fig. 4b). For calculated scrubber height \( H_{\text{av}} = 7 \text{ m} \) \( W_{i,e} = 3, 75 \text{ kg/h•m}^2 (\Delta = 15.6 \%) \).

According to comparison, the model agrees well with the experimental data.
In calculations tabular data \( m_{pr} \) for water solution of \( \text{CO}_2 [6] \) were approximated by temperature dependence \( T \),

\[
m_{pr} = \left( 2.389T^2 - 994.6T + 100765 \right) 10^4, \text{Pa.} \tag{54}
\]

Partial pressures of saturated water vapors on droplet and “formation” surfaces were calculated by formula [2] (the partial pressure of saturated vapors of gas components were not taken into account)

\[
P_{ad,\delta} = P_c \exp \left( A_1 \ln \frac{T_{d,\delta}}{T_{cr}} + A_2 f_2 \right), \tag{55}
\]

where

\[
f_2 = \left( \frac{T_{d,\delta}}{T_{cr}} - 1 \right) \frac{4(T_{d,\delta} - 1)}{T_{cr}} + f_1 - 5 \ln \frac{T_{d,\delta}}{T_{cr}}
\]

\[
f_1 = \left( \frac{T_{d,\delta}}{T_{cr}} - 1 \right) \left[ \frac{T_{d,\delta}}{T_{cr}} + 1 \right]^{1/2} + 0.3
\]

\[P_c = 221.29 \times 10^5 \text{ Pa}; \quad t_{cr} = 374.1 \ ^\circ\text{C}; \quad A_1 = 7.5480; \quad A_2 = 2.7870.\]

For hydrogen sulfide \( m_{pr} \) for water solution [6] was approximated by dependence:

\[
m_{pr} = \left( -0.0251T^2 + 148.73T - 36374 \right) 10^4, \text{Pa.} \tag{56}
\]

Calculation results on absorption of hydrogen sulfide on a water droplet from the vapor-gas flow are shown in Fig. 5.

Theoretical value of \( W_{i,th} \) for \( \text{H}_2\text{S} (\rho_{d,a,0}=1, \ 0029\text{kg/m}^3) \) is

\[
W_{i,th} = 1.0029 \times 0.2 \times 0.25 \times 0.062478 \times 3600 = 11.28 \ \text{kg/h m}^2. \tag{57}
\]

Calculation by formula (48) with experimental mass transfer coefficient gives for \( H=4.3 \text{ m} \)
\[ W_{i,e} = 28685.9 \cdot 0.1539 \cdot 0.151 \cdot 1.66615 \cdot 0.01253 \cdot 0.7426 = 10,335 \text{ kg/h m}^2, \]  

where \[ \frac{D_{H_2S}}{D_{NH_3}} = \left( \frac{0.127}{0.198} \right)^{0.67} = 0.7426, \]  

\[ \Delta \rho_{H_2S} = \eta \rho_{SO_2} = 0.22031 \cdot 0.01253 \cdot 0.7426 = 0.01253 \text{ kg/m}^3. \]  

Difference between results of (57) and (58) is \( \Delta \approx 8\% \). For calculated height \( H = 7 \text{ m} \) \( W_{i,e} = 12,257 \text{ kg/h m}^2 \) and \( \Delta \approx 8\% \) on the other hand. In calculations for \( H_2S \) the limit of concentration (solubility) in water is not exceeded (solubility for 20 °C is about \( 3.85 \times 10^{-3} \text{ kg of } H_2S/\text{kg of water} \)) (see Fig. 5a)). According to the diagrams, here absorption is completed at 1.3 – 1.5 m from the scrubber inlet.

**Figure 5.** Calculation of hydrogen sulfide absorption: \( H = 12.75 \text{ m}; q = 0.015 \text{ m}^3/\text{m}^2; \delta_0 = 700 \mu\text{m}; V_0 = 24.5 \text{ m/s}; U_0 = 0.25 \text{ m/s}; T_{in} = 278 \text{ K}; T_{wa} = 293 \text{ K}; d_i = 0.02 \text{ kg/kg of dry air}; d_{H_2S,0} = 0.2 \text{ kg of } H_2S/\text{kg of dry air}; \eta_{H_2S} = 0.062478 \)

3.2. Calculation of absorption by solubility of \( l \) and \( q_s \)

If there are no tabular data for \( m_{air} \) (or \( E \)) of any gas, and solubility information is available in the handbook, for instance, for \( l, \text{ m}^3 \) of gas/\( \text{m}^3 \) of water and for \( q_s, \text{ g of gas/100 g of water} \), we can relate \( l \) and \( q_s \) to the limit density of saturated gas on the droplet surface \( \rho_{id,lim} \), \( \text{kg/m}^3 \), taking into account that the process of its dissolution occurs in droplet volume fast, i.e., the typical time of gas dissolution is significantly less than the typical time of droplet stay in the working volume of scrubber. Then,
Thus, in [8, p. 260-261] there are tabular data for \( \text{SO}_2 \) for \( l \) and \( q_s \), where we have shown re-calculation of \( \rho_{\text{SO}_2,d,\lim} \) by formula (59) in the last line of Table 2:

\[
\rho_{\text{SO}_2,d,\lim} = 10 \frac{q_s}{T}.
\]  

\( (59) \)

Table 2. Volumetric \( l \) and weight \( q_s \) solubility coefficients for \( \text{SO}_2 \)

<table>
<thead>
<tr>
<th>( T, \degree C )</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l )</td>
<td>79.8</td>
<td>56.7</td>
<td>39.4</td>
<td>27.2</td>
<td>18.8</td>
</tr>
<tr>
<td>( q_s )</td>
<td>22.8</td>
<td>16.2</td>
<td>11.3</td>
<td>7.8</td>
<td>5.41</td>
</tr>
<tr>
<td>( \rho_{\text{SO}_2,d,\lim} )</td>
<td>2.8571</td>
<td>2.8571</td>
<td>2.8680</td>
<td>2.8676</td>
<td>2.8777</td>
</tr>
</tbody>
</table>

According to this Table, \( \rho_{\text{SO}_2,d,\lim} \approx 2.9 \text{ kg/m}^3 \) and it is almost constant value.

First, for this case we calculate \( m_{px} \):

\[
P_{ad,\lim} = \frac{P_{S\text{O}_2,d,\lim}}{\rho_{\text{SO}_2,d,\lim}} = \frac{RT_d}{M_{\text{SO}_2}} = 2.8655 \times 10^3 \left( \frac{8.314}{64} \right) T_d; \tag{60}
\]

\[
\left( m_{px} \right)_{\text{SO}_2} = \frac{P_{\text{SO}_2,d,\lim}}{x_{\text{SO}_2,d,\lim}}; \tag{61}
\]

\[
x_{\text{SO}_2,d,\lim} = \frac{q_s 10^{-2}}{M_{\text{SO}_2}} + \frac{1}{M_{\text{water}}}; \tag{62}
\]

As a result, the following approximation was obtained by formula (61) for \( \text{SO}_2 \)

\[
\left( m_{px} \right)_{\text{SO}_2} = 2976.58 T^2 - 1594158 + 215090898; \tag{63}
\]

Knowing \( \left( m_{px} \right)_{\text{SO}_2} \) we determine specific heat of \( \text{SO}_2 \) absorption by water:
Following calculation is performed by the general scheme (formulas (31)–(35)). Results of calculation are shown in Fig. 6 at ventilation of air humidity \( d_0 = 0.02\) kg/kg of dry air, \( d_{\text{SO}_2,0} = 0.2\) kg/kg of dry air. Other parameters are shown in captions to the figure. It was obtained for this calculation version that \( \eta_{\text{SO}_2} = 51.1\%\), \( \eta_{\text{CH}_4} = 0.08\%\). The limit value of \( \text{SO}_2 \) concentration in a droplet is not achieved even for \( \text{CH}_4 \). According to tabular data on absorption coefficient \( \alpha \), m\(^3\)/m\(^2\) of water (see Table 1):

\[
c_{\text{mid}, \text{lim}} = 717 \cdot 10^{-6} \alpha, \text{ kg of CH}_4/\text{kg of water.}
\]

According to calculation of extracted \( \text{SO}_2 \) for the given case (\( \rho_{d,a,0} = 0, 8121\) kg/m\(^3\)):

\[
W_{i,th} = 0, 8121 \cdot 0, 2 \cdot 900 \cdot 0, 51072 = 74, 656 \text{ kg/h•m}^2;
\]

\[
W_{i,e} = 28685, 9 \cdot 0, 1539 \cdot 0, 151 \cdot (12)^{0.35} \cdot 0, 8121 \cdot 0, 2 \cdot 0, 51072 \cdot 0, 715 = 94, 34 \text{ kg/h•m}^2
\]

for \( H = 12\) m,

\[
W_{i,e} = 28685, 9 \cdot 0, 1539 \cdot 0, 151 \cdot (7)^{0.35} \cdot 0, 8121 \cdot 0, 2 \cdot 0, 51072 \cdot 0, 715 = 78, 13 \text{ kg/h•m}^2
\]

at \( H_{\text{ave}} = 7\) m (\( H_{\text{ave}} = \sqrt{4, 3 \cdot 12} = 7\) m). Here \( \left( \frac{\text{DSO}_2,0}{\text{DNIT}_1,0} \right)^{0.67} = 0, 715 \).

Comparison of \( W_{i,th} \) and \( W_{i,e} \) for \( \text{SO}_2 \) proves good agreement between theory and experiment.

According to calculation, Fig. 6c), methane is not absorbed by water. However, even for methane comparison of calculation with experiment yields satisfactory agreement:

\[
W_{i,th} = 0, 1624 \cdot 900 \cdot 0, 00079541 = 0, 11626 \text{ kg/h•m}^2;
\]

\[
W_{i,e} = 28685, 9 \cdot 0, 1539 \cdot 0, 151 \cdot 0, 1624 \cdot 0, 00079541 \cdot 0, 715 = 1026 \text{ kg/h•m}^2
\]

at \( H = 4.3\) m, \( \Delta = 11.75\% \). At \( H = 7\) m, \( W_{i,e} = 0, 1217 \text{ kg/h•m}^2 \) and \( \Delta = 4.5\% \).

We should note that absorber height \( H \) in experimental dependence for \( \beta_{e} \) is taken improperly. The optimal and calculated height of setup should equal path \( l \), where the process of component extraction is completed. In most cases of calculations, it completed earlier at the height less than the accepted height of absorber \( H = 12.75\) m. Therefore, at comparison of calculation and experimental data in experimental dependence for mass transfer coefficient we have varied the calculated height in the range of the heights of tested setups from 4.3 to 12 m [6].

For \( \text{CH}_4 \) \( m_{\text{in}} \) is approximated by dependence
\[ m_{ps} = (-47, 154T^2 + 35490T - 5962310) \times 10^4 \text{, Pa.} \] (65)

\[ \frac{\delta}{\delta_d} \]

\[ T, K \]

\[ \rho_{\text{LI}}, \text{kg/s m}^2 \]

\[ c_x \times 10^5, \text{kg of SO}_2 / \text{kg of water} \]

\[ c_x \times 10^5, \text{kg of CH}_4 / \text{kg of water} \]

\[ \rho_{\text{LI}}, \text{kg/s m}^2 \]

Figure 6. Calculation of SO$_2$ and CH$_4$ absorption in direct-flow jet scrubber: \( H = 12.75 \text{ m} \); \( q = 0.015 \text{ m}^2/\text{m}^3 \); \( \delta_d = 700 \mu\text{m} \); \( V_d = 24.5 \text{ m/s} \); \( U_d = 0.25 \text{ m/s} \); \( T_d = 278 \text{ K} \); \( T_0 = 293 \text{ K} \); \( \delta_c = 0.02 \text{ kg/kg of dry air} \); \( d_{\text{SO}_2,0} = 0.2 \text{ kg/kg of dry air} \); \( d_{\text{CH}_4,0} = 0.2 \text{ kg/kg of dry air} \); \( \eta_{\text{SO}_2} = 0.51064 \); \( \eta_{\text{CH}_4} = 0.00079541 \)

3.3. Calculation of combined absorption-condensation dust-gas cleaning

Calculations of combined condensation dust capture and absorption extraction of hydrogen sulfide from the vapor-air flow in direct-flow hollow scrubber are shown in Fig. 7. Calculated parameters are shown below the figure. According to Fig. 7a), even at increased moisture content the size of droplets increases weak due to condensation. Therefore, for similar processes the equation of droplet motion can be calculated with a constant mass.

An increase in the size of “formations” is more significant due to condensation of water vapors on them: for \( \delta_0 = 0.01 \mu\text{m} \) it is 2.1, for \( \delta_0 = 0.1 \mu\text{m} \) it is 2.3, and for \( \delta_0 = 1 \mu\text{m} \) it is 32 and more for the same total concentration of dust at the inlet of 1.72 g/m$^3$. In the first case, particles are not caught, in the second case, about 5.76% of particles are caught, and in the third case, 100% of particles are caught at the inlet to the apparatus. For this version of calculation the stable state by concentrations of H$_2$S dissolved in droplets and in condensate on “formations”
occurs far from the flow escape from the scrubber. For particles water vapor condensation at flow escape from the scrubber has been also competed already (see Fig. 7g). Therefore, in this case the height of absorber above 1.5 m is excessive, and in construction it can be limited by 2 m. According to Figs. 7d) and 7e), concentration of \( \text{H}_2\text{S} \) dissolved in condensate on the particle and in droplets increases, but it does not exceed the solubility limit (in this case it is about \( 3.85 \times 10^{-3} \) kg of \( \text{H}_2\text{S} \)/kg of water).

![Graphs and images](image)

Figure 7. Calculation of combined air cleaning from submicron dust and hydrogen sulfide in direct-flow scrubber: \( H = 2 \) m; \( q = 0.015 \text{ m}^3/\text{m}^2 \); \( \delta_{d0} = 700 \) μm; \( V_{d0} = 24.5 \text{ m/s} \); \( U_0 = 0.25 \text{ m/s} \); \( T_{d0} = 278 \text{ K} \); \( T_{00} = 333 \text{ K} \); \( \rho_{d} = 0.2 \text{ kg/kg of dry air} \); \( d_{\text{H}_2\text{S},0} = 0.2 \text{ kg/kg of dry air} \); \( \rho_{p0} = 1.72 \text{ g/m}^3 \); \( \delta_{p} = 1 \) μm; \( \eta_{\text{H}_2\text{S}} = 0.075411 \); \( \eta_p = 1.0 \)

3.4. Calculation of absorption and condensation dust capture in Venturi scrubber

Calculation results on \( \text{H}_2\text{S} \) absorption and condensation capture of dust with different sizes in Venturi scrubber are shown in Fig. 8. As an example the Venturi scrubber with following parameters was chosen for calculations: diameter of Venturi tube mouth \( d_m = 0.02 \) m, diffuser...
length \( l = 0.2 \) m, diffuser opening angle \( \alpha = 6^\circ \) \((\alpha = 6\text{–}7^\circ, l/d_m = 10\text{–}15\) are recommended for normalized Venturi tube [6, 10]), vapor-gas flow velocity in the tube mouth \( U_0 = 80 \) m/s, initial velocity of droplets in the tube mouth \( V_{d0} = 4 \) m/s, irrigation coefficient \( q = 0.015 \) m\(^3\)/m\(^3\), temperature of the vapor-gas flow and droplets in the tube mouth \( T_0 = 333 \) K and \( T_{d0} = 278 \) K, respectively, concentration of dust particles at the inlet \( \rho_{p0} = 1.72 \) g/m\(^3\), size of dust particles \( \delta_0 = 0.1 \) μm, moisture content in water vapor at the inlet was set \( d_i = 0.2 \) kg/kg of dry air, gas content \( d_{H_2S,0} = 0.1 \) kg/kg of dry air. Efficient of \( H_2S \) extraction and dust capture were determined \( \eta_{H_2S} = 0.072959 \) and \( \eta_{p} = 0.52904 \), respectively.

The mean-mass size of droplets in the tube mouth was calculated by Nukiyama-Tanasava formula [1]:

\[
\delta_{d0} = \frac{0.585}{U_0 - V_{d0}} \sqrt{\frac{\sigma_f}{\rho_f}} + 53.4 \left( \frac{\mu_f}{\sqrt{\rho_f \sigma_f}} \right)^{0.45} q^{1.5}, \text{ m, (66)}
\]

where \( \rho_f \) (kg/m\(^3\)), \( \mu_f \) (Pa•s), \( \sigma_f \) (N/m) and \( q \) (m\(^3\)/m\(^3\)) are density, dynamic viscosity, surface tension coefficient of pneumatically atomized liquid, and irrigation coefficient.

Velocity \( U \) was calculated with consideration of diffuser expansion angle [2, 11].

Dependences of droplet size along the diffuser length are presented in Fig. 8a). It can be seen that firstly condensation of water vapors occurs intensively, then this process stops at the length of \( x/l = 0.2 \), and the size of droplets stays constant up to the scrubber outlet. At this, the quantitative droplet size changes slightly along the diffuser length (it stays almost constant; the maximal increase is a little bit higher than 0.3 %).

A change in droplet temperature due to convective heat transfer between droplets and vapor-gas flow, thermal effects of water vapor condensation on droplets, and gas dissolution is shown in Fig. 8d). A change in mass concentration of \( H_2S \) dissolved in a droplet is shown in Fig. 8c). It is obvious that absorption is almost completed at the length of tube diffuser 1 for this version of calculation. The same circumstance is illustrated by mass concentration of \( H_2S \) in “formation” condensate along the diffuser in Fig. 8c). According to the figure, the solubility limit on “formations” and droplets is not achieved as in the hollow jet scrubbers. A change in “formation” size due to water vapor condensate on their surfaces is illustrated in Fig. 8f). It can be seen that firstly water vapors condense very intensively, then at the distance of about \( x/l = 0.1 \) this process completes, the size increases more than twice and stays constant until the leaving from the scrubber. Efficiency of dust capture in this version is up to 53 %. Calculation at the same parameters of the vapor-gas flow and dust at the scrubber inlet with mouth \( d_i = 0.1 \) m and constrictor length \( l = 1 \) m gives \( \eta_{p} = 0.77729, \eta_{H_2S} = 0.074965 \). It follows from the diagrams in this figure that for the calculated version it is practically reasonable to be limited by diffuser length \( x/l = 0.4 \) (\( x = 0.08 \) m), where the processes of dust capture (Fig. 8g)) and absorption are completed (Fig. 8b)). Therefore, the residual length of 0.12 m is
excessive. Figs. 8b) and 8g) illustrate distributions of dust and H$_2$S mass fluxes along the diffuser of Venturi tube.

Figure 8. Calculation of H$_2$S absorption and dust capture in Venturi scrubber (calculated parameters are presented in the text)

It is necessary to note that these calculation versions do not meet the conditions of optimal scrubber operation; they only illustrate the character of complex gas cleaning. To determine the optimal regimes, a series of calculation on the basis of suggested model should be carried out and analyzed for the specific industrial conditions.

Let’s turn to comparison of calculation results with the known experimental data. The experimental volumetric mass transfer coefficient is shown in [6] for NH$_3$ absorption in the Venturi tube with mouth diameter $d_m=0.02$ m. There no geometrical and other parameters. This coefficient is presented as

$$
\mu_{\text{NH}_3}^{\text{NH}_3} = 260 U_0^{1.56} \theta_0^{0.57},
$$

(67)
where \( q \) is irrigation coefficient in l/m\(^3\), \( U_0 \) is in m/s, and \( \beta_{iv} \) is in 1/h.

The experimental value of \( \text{H}_2\text{S} \) absorbed in Venturi tube is expressed by formula, kg/h,

\[
\Delta G_{i,e} = \beta_{iv,e}^{\text{H}_2\text{S}} \Delta \rho_{i,e} V_{\text{dif}},
\]  

where \( V_{\text{dif}} \) is diffuser volume, \( \Delta \rho_i \) is calculated drop of gas concentration along the diffuser length, kg/m\(^3\), corresponding to experimental data.

The theoretical value of mass of absorbed gas, kg/h, is

\[
\Delta G_{i,th} = \beta_{iv,th}^{\text{H}_2\text{S}} \Delta \rho_{i,th} V_{\text{dif}} \approx \Delta \rho_{i,th} U_0 \frac{\pi d_{i,th}^2}{4} \frac{3600}{4}.
\]  

Then

\[
\frac{\Delta G_{i,th}}{\Delta G_{i,e}} = \frac{\beta_{iv,th}^{\text{H}_2\text{S}} \rho_{i,th} V_{\text{dif}}}{\beta_{iv,e}^{\text{H}_2\text{S}} \rho_{i,e} \frac{\pi d_{i,th}^2}{4} \frac{3600}{4}} \Delta \rho_{i,e},
\]  

where (see Fig. 9) the volume of truncated cone is

\[
V_{\text{dif}} = \frac{\pi}{24} \frac{d_{i,th}^3}{a} \left[ \left( \frac{2l}{d_{i,th}} + \frac{\alpha}{2} + 1 \right)^3 - 1 \right].
\]  

Substituting (67), (71) into (70), at \( \alpha=6^\circ \), \( l=0.2 \) m, \( d_{i,th}=0.02 \) m, \( U_0=80 \) m/s, \( q=15 \) l/m\(^3\) we get the following, assuming that \( \Delta \rho_{i,th} = \Delta \rho_{i,e} \),

\[
\frac{\Delta G_{i,th}}{\Delta G_{i,e}} = 0.9457,
\]  

where for \( \text{H}_2\text{S} \left( \frac{D_{i,th}}{D_{\text{NH}_3,0}} \right)^{0.67} = 0.7426 \), i.e., the difference between the theory and experiment is less than 6 %, what is a good agreement, considering the assumed parameters for normalized Venturi tube.
The amount of absorbed $\text{H}_2\text{S}$ for the version of calculation in Fig. 8 ($\eta_{\text{H}_2\text{S}}=0.072959$, $\rho_{d,\text{at},0}=0.7541 \, \text{kg/m}^3$) is

$$W_{i,\text{th}} = 0, 7541 \cdot 0, 1 \cdot 0, 072959 \cdot 80 \frac{3, 14(0, 02)^2}{4} 3600 = 0, 5 \, \text{kg/h}.$$ 

For the scrubber with $d_m=0.1 \, \text{m}$, $l=1 \, \text{m}$ at the same dust and gas parameters at the inlet $W_{i,e}=12, 78 \, \text{kg/h}.$

The experimental values of efficiency of condensation capture of submicron dust are compared with results of model calculation in [2, 11, 12] at the example of deposition of ash particles from cracking gases under the industrial conditions in hollow jet scrubbers [13]; good agreement is achieved.

4. The choice of the value of calculated concentration difference for the absorbed gas component

Let’s consider this important question in detail as an addition to iss. 2 at the example of water absorption of $\text{SO}_2$, comparing calculation and experimental data [6] on volumetric mass transfer coefficient.

It follows from equation (3) that

$$W_{i,\text{th}} = - \int_0^H \beta_d \frac{\delta_d}{\delta_{d0}} (\rho_{d0} - \rho_1) n_d \, dx, \, \text{kg/s} \cdot \text{m}^2,$$  

(73)

where, according to formulas (26) and (38)
In (73) and (74), according to calculation results, it is assumed that \( \delta_d = \delta_{d0} \).

Let’s put \( \beta_d \) from (19) to (73) at \( K_{ci} = 1 \) and \( n_d \) from (74), we obtain, proved by estimates,

\[
W_{i,th} \approx -3.312 qU_{0} \int_{0}^{H} \left( \frac{\rho_d}{H} - \frac{\rho_i}{H} \right) dx, \quad \text{Re}_d^{0.67} \gg 1, \quad V_{dx} >> U_0.
\]

where

\[
\text{Re}_d = \frac{V_{dx} \delta_{d0} \rho}{\mu}.
\]

Let’s turn dependence (74) to the following form using the theorem about an average for integral:

\[
W_{i,th} \approx 3.312 qU_{0} \left( \frac{\bar{D}_{NH_3}}{\delta_{d0} V_{dx}} \right)^{0.67} \left( \frac{\bar{V}}{\bar{D}_{NH_3}} \right)^{0.22} \left( \frac{\Delta \rho_d}{\rho_d} \right) \left( \frac{D_{i,0}}{D_{NH_3,0}} \right)^{0.67}, \quad \text{kg/s} \cdot \text{m}^2,
\]

where \( \bar{v} = (\mu / \bar{p}) \) is the average value of kinematic viscosity of the vapor-gas flow in the scrubber volume, \( \text{m}^2/\text{s} \), \( \bar{D}_{NH_3} \) is the average value of diffusion coefficient of methane \( \text{NH}_3 \), \( \bar{V}_{dx} \) is average velocity of droplets on the \( 0-\text{H} \) way at motion from scrubber inlet to the outlet, \( \text{m/s} \), \( \Delta \rho_d \approx | \rho_d - \rho_i | \).

Expressing velocity \( U_0 \) and \( V_{dx} \) in \( \text{m/h} \), and assuming \( \delta_{d0} = 7 \cdot 10^{-4} \text{m} \) (700 \( \mu\text{m} \)), \( \bar{D}_{NH_3} \approx 278, 5 \text{K} \), \( 198 \cdot 10^{-4} \left( \frac{285}{273} \right)^{1.75} \) \( = 0, 205 \cdot 10^{-4} \text{m}^2/\text{s} \) (see Fig. 10 b)), \( \bar{V}_{dx} = 5, 25 \text{ m/s} \) (see Fig. 10 e)), \( (D_{SO_2,0} / D_{NH_3,0})^{0.67} = 0, 715 \), we obtain for calculation parameters of Fig. 10 \( W_{i,th} \approx 83 \text{ kg/h} \cdot \text{m}^2 \), where \( \int_{0}^{H} \Delta \rho_d dx = 0, 6437 \text{ kg/m}^2 \) is obtained via model calculation (see Fig. 11).
Figure 10. Calculation of SO₂ absorption in direct-flow jet scrubber: \( H = 12.75 \, \text{m} \); \( q = 0.015 \, \text{m}^3/\text{m}^2 \); \( \delta_{d_0} = 700 \, \mu\text{m} \); \( V_{d_0} = 24.5 \, \text{m/s} \); \( T_{d_0} = 278 \, \text{K} \); \( T_{00} = 293 \, \text{K} \); \( d_0 = 0.02 \, \text{kg/kg of dry air} \); \( d_{SO_2,0} = 0.2 \, \text{kg/kg of dry air} \); \( \eta_{SO_2} = 0.51722 \)

We should note that multiplier \( (D_{i,0}/D_{NH_3,0})^{0.67} \) was included into formula (76) as a correction like to was done for empirical dependence (46).

Numerical calculation by the model give the value of SO₂ extraction

\[
W_{i,e} = \rho_{d,e,0} d_{SO_2,0} H_i \eta_{SO_2} = 3600 \cdot 1.0743 \cdot 0.2 \cdot 0.25 \cdot 0.51722 \cdot 3600 = 100 \, \text{kg/h} \cdot \text{m}^2.
\]  

(78)

The difference is 17 %, what is a sequence of simplifications and averaging in dependence (76).

If we assume average concentration difference in accordance to average experimental height \( H = 7 \, \text{m} \); \( \Delta p_{l} = 0.6437/7 = 0.092 \, \text{kg/m}^3 \), then

\[
W_{l,e} = 28685 \cdot 9 \cdot 1539 \cdot 0.092 \cdot 0.715 = 28685 \cdot 9 \cdot 1539 \cdot 0.092 \cdot 0.715 = 86 \, \text{kg/h} \cdot \text{m}^2.
\]

The difference with \( W_{i,e} = 83 \, \text{kg/h} \cdot \text{m}^2 \) is 4.2 %.
If we take $\Delta \rho_i = \rho_{d,a,0} \Delta \rho_{SO_2}$, then $W_{i,e} = 104.5 \text{ kg/h} \cdot \text{m}^2$, what differs from result of (77) by similar 4.3% with accuracy of estimation error. This proves the fact that calculated volumetric mass transfer coefficient agrees empirical dependence (46) of [6].

On the basis of analysis performed the calculated concentration difference should be recommended for practical application as the most appropriate

$$\Delta \rho_i = \rho_{i,0} - \rho_{i,H} \frac{U_H}{U_0}$$  \hspace{1cm} (79)

at determination of the value of extracted gas component by formula (49), thus, it is necessary to measure $\rho_{i,0}$, $\rho_{i,H}$ and $U_0$, $U_H$ at apparatus inlet and outlet. Calculation of moisture content is shown in Fig. 10 c), at this, it was obtained that $U_H = 0, 2234 \text{ m/s}$, $\rho_{d,a,0} = 1, 0743 \text{ kg/m}^3$.

5. Conclusions

The suggested physical-mathematical model of complex heat and mass transfer and condensation-absorption gas cleaning from dust and harmful gaseous components is confirmed by the known experimental data and can be used for engineering calculations and optimization of construction and operation parameters of hollow jet scrubbers of direct and counter flow types. This was proved by its numerical implementation for the specific conditions. Calcula-
tions on absorption of some gases (CO₂, H₂S, SO₂, CH₄) on water droplets, dispersed by coarse centrifugal nozzles in hollow direct-flow jet scrubber and pneumatic Venturi scrubber from wet air is shown in the current paper together with calculation of combined absorption-condensation air cleaning from H₂S and various-sized fine dust in these apparatuses at an increased moisture content. The system of model equations is written at some certain conditions for the multicomponent vapor-gas mixture with particle. This makes it possible to use this system for calculation of complex gas cleaning from several harmful gas components and several fractions of dust particles and investigate regularities of this process.

Nomenclature

V → d vector of droplet velocity
U → n vector of vapor-gas low velocity
g vector of gravity acceleration
mₙ droplet mass (variable value due to evaporation-condensation and absorption), kg
cₙ specific heat capacity of liquid, J/kg•K
Tₙ mean mass temperature of droplets, K
αₙ heat transfer coefficient of droplet, W/m²•K
δₙ mass-median size of droplet, m
T temperature of vapor-gas flow, K

rₙ specific heat of absorption, evaporation-condensation, J/kg

cₙs specific heat capacity of “formation”, J/kg•K
ρₙ mass concentration of “formations’ in the vapor-gas flow, kg/m³
Vₙ = l V → d - U → l module of relative droplet velocity, m/s
ηₙst coefficient of “formation” capture by droplets
Tₙs mean mass temperature of “formations”, K
βₙid coefficient of droplet mass transfer with the i-th component of vapor-gas flow by concentration difference, m/s

ρₙd and ρᵢ partial densities (mass concentrations) of saturated vapors of dissolvent and gas components near droplet surface and far from it (in the flow), kg/m³
\( n_d \) and \( n_g \) calculated concentrations of droplets and “formations” in the flow, \( 1/m^3 \)

\( \rho_g \) partial density of non-reacting gas component, \( kg/m^3 \)

\( \rho_d \) mass concentration of droplets, \( kg/m^3 \)

\( a_0 \) heat transfer coefficient of “formation”, \( W/m^2\cdot K \)

\( \delta \) size of “formation”, \( m \)

\( \rho \) density of vapor-gas flow, \( kg/m^3 \)

\( c \) specific heat capacity of vapor-gas flow, \( J/kg\cdot K \)

\( \rho_p \) mass concentration of dry dust particles in the flow, \( kg/m^3 \)

\( \rho_f \) density of liquid (droplets), \( kg/m^3 \)

\( \mu \) dynamic viscosity of vapor-gas flow, \( Pa\cdot s \)

\( M_i \) molar masses of components of the vapor-gas mixture, \( kg/kmole \)

\( R = 8, 314 \) kJ/kmole\cdot K universal gas constant

\( D_i \) diffusion coefficient of mixture component, \( m^2/s \)

\( P_i \) partial pressure of the \( i^{th} \) component of the vapor-gas mixture, \( Pa \)

\( P_{id,0} \) partial saturation pressures of mixture components, calculated by droplet and “formation” temperature, \( Pa \)

\( m_{px,i} \) constants of phase equilibrium of solutions of \( i^{th} \) components of extracted gases, \( Pa \)

\( x_{id,0} \) mole fractions of gas components dissolved in a droplet and “formation” condensate

\( c_{mid,0} \) mass fractions of gas components in droplet and “formation” dissolvent, \( kg/kg \) of dissolvent

\( M_{dis} \) molar mass of dissolvent, \( kg/kmole \)

\( dm_{vo}/d\tau \) rate of “formation” mass change due to evaporation-condensation of liquid, \( kg/s \)

\( \delta_0 \) initial size of dust particles, \( m \)

\( \rho_s \) density of solution on “formation” due to condensation of liquid vapors and absorption of gas components, \( kg/m^3 \)

\( d \) moisture content, \( kg \) of vapors/kg of dry non-reacting component of vapor-gas mixture

\( d_i \) gas content, \( kg \) of reacting gas component/ \( kg \) of dry non-reacting component of vapor-gas mixture

\( q = Q_f / Q_{sg0} \) irrigation coefficient
\( Q \) volumetric flow rate of liquid, m\(^3\)/s

\( Q_{sg0} \) volumetric flow rate of vapor-gas mixture at apparatus inlet, m\(^3\)/s

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