Revisiting assessment of heat and mass transfer in contact apparatus for steam treatment of air

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Abstract. Modified methods are proposed for determining the surface area of heat and mass transfer in the contact apparatus in the humidification, cooling, dehumidification of air with water, as well as dehumidification of air with solid drying agent, based on the number of transfer units. The number of transfer units is determined by the method of graphical integration using I-diagram of humid air to evaluate both heat and mass transfer process.

1. Introduction
In air conditioning systems (ACS), contact apparatus is used for steam treatment of air with water when creating a micro-climate of premises of various purposes, etc. Contact apparatus is structurally manufactured in the form of nozzle spray chambers of honeycomb irrigation [1]. In the chambers, the air flow is in direct contact with water by spraying water through mechanical nozzles and the use of irrigated nozzle (sheet-, ring-like, etc.). As a result of heat and mass transfer, the air can be humidified, cooled, or dehumidified. In many cases the use of basic heat and mass transfer equations for the calculation of contact apparatus is complicated due to the impossibility of direct determination of the heat and mass transfer surface value.

Performance efficiency assessment and thermotechnical calculation of nozzle spray chambers and other contact apparatus is done using the efficiency coefficients, based on graphic constructions of the process of steam treatment of air flow at the I-diagram of humid air [1, 2]. The efficiency coefficients featuring the ratio between heat transfer in a real process and the maximum possible heat transfer at different orientation of ideal processes have not been obtained as a result of any mathematical conclusion or analysis [2]. The analysis of such methods revealed that they were based on functional dependencies and empirical equations obtained on test benches, simulating a certain type of irrigation nozzle chambers. Typical dependences represent the specific features of the aerodynamic situation in the rain area of the irrigation chamber, being its technical characteristics and are given in the directories and catalogues of such equipment manufacturers. Each of the methods deals with the calculation of a certain type of irrigation nozzle chambers.

2. Research and discussion
E. V. Stefanov proposed a method for evaluating the performance efficiency of nozzle chambers when processing the experimental data using the numbers of transfer units of sensible heat NTUs and total
heat NTU [2, 3]. These indicators are widely used for calculations of processes and apparatus of chemical technology, both abroad [4] and in Russia [5].

It is proposed to use the method of assessing the contact apparatus performance efficiency for steam treatment of air using the digits of transfer units for the purpose of their dimensioning and checking calculation [6].

In Russian publications the letter symbol N or n [5] is adopted to mark the number of transfer units. We shall use the Nt symbol to indicate the number of total heat units transfer, symbol Nt to indicate the sensible heat units transfer, Nt to indicate the number of mass units transfer.

It is recommended to determine the number of transfer units by graphic method, in particular, by graphic integration method [5].

This method consists of the following stages:

1. Construction of the operating and equilibrium lines of the process in the appropriate coordinate system.

It is proposed to use I-d-humid air diagram as a coordinate system. The following shall be the graphic constructions for contact apparatus at the I-d-diagram [6]:
   - saturated air curve $\varphi = 100\%$ (equilibrium line);
   - a direct process line that characterizes the steam treatment of air (operating line).

Figure 1, a, b represents graphic constructions at I-d-diagram of humid air to determine operating and equilibrium values.

(a) 
(b)

Figure 1. Determination of equilibrium ($t^*$) and operating ($t$) values of temperature, equilibrium ($I^*$) and operating ($I$) values of air enthalpy.

As a basic option, Figure 1a presents the construction of the adiabatic (isoenthalpic) process of air cooling and humidification as a straight line 1 - 2. Point 1 features the initial air condition, i.e. at the entrance to the contact apparatus, point 2 corresponds to the final air condition, i.e. at the exit of the apparatus. The determination of equilibrium air temperature values for points 1, 2 and for intermediate X - points is shown generally, in the form of arrows. Determination of the operating and equilibrium values of the air enthalpy is shown in Figure 1b.

Based on this data, graphic dependencies are constructed:

$$
\frac{1}{(t - t^*)} = f(t) ; \frac{1}{(I - I^*)} = f(I).
$$
Stage 2 - construction of a graphic dependency $\frac{1}{Y - Y^*} = f(Y)$ based on operating and equilibrium process line (Figure 2).

Here $Y, Y^*$ - respectively, operating and equilibrium parameters, characterizing the air flow condition during the steam treatment of air.

The following are proposed to be determined as operating and equilibrium parameters [6]:
- temperature (to estimate sensible heat transfer);
- enthalpy (to estimate total heat transfer);
- partial steam pressure, humidity content (to assess the mass transfer process)

(a) (b)

Figure 2. Graphic dependencies for determining the number of transfer units

Determination of equilibrium partial steam pressure values during humidification and dehumidification of air are recommended to be performed based on graphic constructions of processes at the $I-d$ diagram of humid air, shown in Figure 3.
Figure 3. Graphic constructions to determine the operating and the equilibrium partial steam pressure values in the adiabatic humidification mode (line 1-2), polytropic dehumidification of air (line 1*2*) in the contact apparatus.

Stage 3 - determination of the number of transfer units \( n \) or \( N \) or \( n_m \) by equations:

\[
n_t = \int_{t_1}^{t_2} \frac{dI}{I - I^*} = \frac{f m}{m_2};
\]

(1)

\[
N_t = \int_{I_1}^{I_2} \frac{dI}{I - I^*} = \frac{f m}{m_3};
\]

(2)

\[
n_{m(p)} = \int_{P_1}^{P_2} \frac{dP}{P - P^*} = \frac{f_p m_2 m_6}{m_5};
\]

(3)

where \( t, t^* \) - respectively, operating (current) and equilibrium air temperature, °C (Fig. 1, a); \( I, I^* \) - respectively, operating (current) and equilibrium air enthalpy, kJ/kg (Fig. 1, b); \( P, P^* \) - respectively, operating (current) and equilibrium partial steam pressure in the air flow, kPa (Fig 3); \( f, F, f_p \) – respectively, area of curved trapezoid within the adopted values (Figure 2); \( m_1, m_2; m_3, m_4; m_5, m_6 \) - respectively, the scales of the measured values along X and Y axis (Figure 2).

In works [3, 6] it is shown:

\[
n_t = \frac{a F}{G c} = \frac{t_1 - t_2}{\Delta t};
\]

(4)

\[
N_t = \frac{b F}{G} = \frac{I_1 - I_2}{\Delta I};
\]

(5)

\[
n_{m(d)} = \frac{b_p F}{G} = \frac{d_1 - d_2}{\Delta d};
\]

(6)

\[
n_{m(d)} = \frac{b_p P_2 F}{0.622 G} = \frac{P_1 - P_2}{\Delta P};
\]

(7)
where \( \alpha \) - heat exchange coefficient, \( W/(m^2\cdot{}°C) \); \( \beta_c, \beta_d, \beta_p \) - mass transfer coefficients, referred, respectively, to the difference in concentrations, humidity content and partial pressures, \( kg/m^2 \) (units double force); \( F \) - surface heat and mass transfer, \( m^2 \); \( G \) - air flow, \( kg/s \); \( c \) - heat capacity of humid air, \( J/(kg\cdot{}°C) \); \( t, I, d, P \) - respectively, temperature, \( °C \); enthalpy, \( kJ/kg \), air humidity content, \( g/kg \) dry. air. and the partial steam pressure, \( kPa \) (index 1 corresponds to the initial condition, index 2 - the final condition of air); \( \Delta p_t \) - average temperature difference between air and water (the driving force of the process), \( °C \); \( \Delta p_P \) - the average partial steam pressure difference at the surface of the water phase and in the air, \( kPa \); \( P_b \) - barometric pressure, \( kPa \).

Determination of kinetic heat transfer and mass transfer coefficients in the equations (4)-(7) is performed based on the similarity theory using heat and diffusion similarity criteria [5]:

\[
\alpha = \frac{Nu}{l} \frac{\lambda}{l}; \tag{8}
\]
\[
\beta = \frac{Nu}{l} \frac{D}{l}, \tag{9}
\]

where \( l \) - characteristic length, \( m \); \( \lambda \) - air heat conductivity coefficient, \( W/(m\cdot{}°C) \); \( D \) - air steam diffusion coefficient, \( m^2/c \); \( Nu, Nu' \) respectively, Nusselt criterion for heat and diffusion (mass transfer) process.

Nusselt criteria are determined by the criterion equations given in [5-7]. To calculate the heat and mass transfer from the drops’ surface under forced convection, it is proposed to use the following equations (when \( Re = 1..220 \) ) [8]:

\[
Nu = 2 + 1.07 Re^{0.48} Pr^{0.33} Gu^{0.175}; \tag{10}
\]
\[
Nu' = 2 + 0.85 Re^{0.52} Pr'^{0.33} Gu^{0.135}, \tag{11}
\]

where \( Re \) - the Reynolds criterion; \( Pr, Pr' \) respectively, the Prandtl number heat and diffusion; \( Gu \) – Gukhman criterion.

Characteristic criteria are calculated by the formulas:

\[
Re = \frac{vl}{\mu} = \frac{vl}{\upsilon}; \tag{12}
\]
\[
Pr = \frac{\mu c}{\lambda} = \frac{\upsilon}{a}; \tag{13}
\]
\[
Gu = \frac{T_h - T_i}{T_m}; \tag{14}
\]
\[
Pr' = \frac{\mu p}{D'}, \tag{15}
\]

where \( \upsilon \) - linear speed of air flow, \( m/s \); \( \rho \) - air density, \( kg/m^3 \); \( \mu \) - air dynamic viscosity coefficient, \( PA\cdot{}c \); \( \mu c \) - kinematic air viscosity coefficient, \( m^2/s \); \( c \) - specific air heat, \( J/(kg\cdot{}°C) \); \( a \) - air thermal conductivity coefficient, \( m^2/c \); \( T_e \) - air flow temperature by dry thermometer, \( K \); \( T_m \) - air flow temperature by wet thermometer, \( K \).
Stage 4 - defining the heat and mass transfer surface. The required heat transfer surface in the contact apparatus, corresponding to the segment 1-2 (Figure 1), in accordance with equation (4) is:

\[ F = \frac{Gcn}{\alpha} , \]  

(16)

Required mass transfer surface for this process based on equation (7):

\[ F = \frac{0.622Gn_m}{\beta \rho P_A} , \]  

(17)

For the purpose of complete assessment of heat and mass transfer in ACS devices, E. V. Stefanov introduced the concept of process perfection [2]:

\[ \xi = \frac{n_t}{n_m} . \]  

(18)

The process of heat and mass transfer in the apparatus is considered perfect if \( \xi = 1 \). It is emphasized [3] that in practice there are cases when \( \xi \neq 1 \). Such cases appear when the surface areas of heat and mass transfer are different. The given method additionally provides for the analysis of such situations.

Drying agents based on solid sorbents, i.e. adsorbents, can be used as basic equipment in ACS. Standard apparatus is called adsorbers. In practice, adsorbers with a fixed adsorbent layer are widely used [5, 9].

Silica gel, i.e. hydrated amorphous silica, is the effective adsorbent of steam. Its formula \( \text{SiO}_2 \cdot n\text{H}_2\text{O} \). It is a granular vitrification, obtained by treating liquid glass with mineral acid. To dehumidify the air, KCM silica gel is used with grain sizes of 1...3 mm [9].

The final state of the adsorption process, as well as other mass transfer processes, is the equilibrium state.

Air dehumidification by silica gel is accompanied by the release of adsorption heat and wetting heat, which increases the temperature of the operating bodies, i.e. silica gel and air flow. During heat removal from the adsorber the steam sorption process can be isothermal, in case of no heat removal, the process is isoenthalpic or adiabatic, and the process beam at the I-d- diagram of humid air is depicted by the line I – const [9]. Specific features of the sorption process shall be taken into account when applying the method of standard equipment calculation [11].

At the same time, the analysis of the calculation methods of adsorbers with a fixed adsorbent layer reveals that the adsorption isotherm is automatically proposed as the base curve, i.e. the process conditions are not specified [5]. It is obvious that in case of isoenthalpic air dehumidification process isoenthalpy adsorption (adiabatic line) should be used as a base curve.

For graphic construction of the steam isoenthalpy adsorption from the air flow by the silica gel, the authors suggest applying the I-d-diagram of humid air, which has additional isometric lines \( D^* \) of equilibrium humidity content the KCM silica gel (Figure 4) [10].

As mentioned above, chemical technology has developed methods for calculating equipment based on the number of transfer units [4, 5]. This methodology is proposed for the conditions described above.

- **benchmark data is set** (adsorber operates without heat removal; dehumidification air flow \( G \), kg/s; initial air parameters, e.g. temperature \( t_1 \), °C, relative humidity \( \varphi_1 \), % or other combinations of two air parameters: temperature \( t_1 \), °C, humidity content \( d_1 \), g/kg; temperature \( t_1 \), °C, enthalpy \( I \), kJ/kg, etc.; final air parameter after dehumidification, e.g., temperature \( t_2 \), °C or humidity content \( d_2 \), g/kg of dry air).
- **the process of air dehumidification is built at the I-d-diagram of humid air**, e.g., line segment 1-2 (Figure 4).


Figure 4. 1-d-diagram of humid air with isometric lines of equilibrium humidity content of silica gel ($D^*$).

- adsorber diameter is determined $D_a$:

$$D_a = \frac{G}{\sqrt{0.785 \rho_v}}, \quad (19)$$

where $v$ - air speed in the adsorber section, m/s ($v = 0.25...0.30$ m/s) [5, 7];

- sorbent layer height is determined (silica gel) $H$:

$$H = nh, \quad (20)$$

where $n$ - number of transfer units; $h$ - height of a transfer unit, m.

a) number of transfer units is determined.

In accordance with the recommendations [7] based on the figure 4, an equilibrium (adsorption isoenthalpy line) is built as well as the process operating line (figure 5).

Figure 5. Adsorption isoenthalpy line (OA) and the operating process line (1 - 2): $d$, $D^*$ - air humidity content and corresponding equilibrium humidity contents of silica gel.
The calculation of the number of transfer units performed by the formula:

\[ n = \int_{d_1}^{d_2} \frac{\bar{a}(d)}{1 - \frac{d}{d^*}} \]  \tag{21}

where \( d, d^* \) - current (operating) and equilibrium humidity content of the dehumidified air, g/kg of dry air.

Arrows at Figure 5 show the determination of the equilibrium humidity contents of the air for the corresponding operating humidity content values.

For the numerical determination of the number of transfer units by the formula (21), a graphic dependency is built of air dehumidification with silica gel:

\[ \frac{1}{d - d^*} = f(d) \]  \tag{22}

An overview of the graphic dependency is shown in figure 6.

![Figure 6. Dependency 1/(d - d*) = f(d)](image)

The number of transfer units is numerically equal to:

\[ n = f \cdot M_1 \cdot M_2, \]  \tag{23}

where \( f \) - the area of curved trapezoid, \( M_1, M_2 \) - respectively, the scale of values along X and Y axis.

\( b) \) height of a transfer unit is determined.

The calculation is made by the formula:

\[ h = \frac{G}{S_c \beta_y}, \]  \tag{24}

where \( S_c \) - adsorbent layer section area, m²; \( \beta_y \) - volumetric mass transfer coefficient in the air, c⁻¹.

\[ S_c = 0.785D_c^2; \]  \tag{25}

\[ \beta_y = \frac{Nu'D}{D_s^2}, \]  \tag{26}

where \( d_e \) - equivalent silica gel grain diameter, m.
The Nusselt diffusion criterion $\text{Nu}'$ is determined depending on the numerical value of the modified Reynolds criterion – Re:

$$\text{Re} = \frac{\nu d \rho}{\mu \varepsilon},$$  \hspace{1cm} (27)

where $\varepsilon$ - porosity of the fixed adsorbent layer ($\varepsilon = 0.3$ [5]).

With $\text{Re} < 2$, $\text{Nu}' = 0.51\text{Re}^{0.85} (\text{Pr})^{0.33}$;  \hspace{1cm} (28)

With $\text{Re} = 2...30$, $\text{Nu}' = 0.725\text{Re}^{0.47} (\text{Pr})^{0.33}$;  \hspace{1cm} (29)

With $\text{Re} > 30$, $\text{Nu}' = 0.395\text{Re}^{0.64} (\text{Pr})^{0.33}$.  \hspace{1cm} (30)

Other design dimensions of the adsorber (total height, height of the apparatus covers, etc.) are in certain ratios with the calculated basic parameters: diameter and height of the adsorbent layer [5, 7].

3. Conclusions

There were improved and scientifically substantiated methods of calculation of contact apparatus while treatment of air with water, air dehumidifiers using a solid sorbent (silica gel) based on the number of transfer units [12]. Determination of the number of transfer units is performed using the method of graphic integration, the necessary calculations are proposed to be made on the basis of graphic constructions of air treatment processes at the $I$-$d$- diagram of humid air and its modification, carrying the isometric lines of the equilibrium humidity content of silica gel. The methods allow to calculate separately and perform a comparative assessment of the required surface for the implementation of heat and mass transfer process, to perform calibration and design calculations of contact apparatus for steam treatment of air.

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