Methods for forming interfacial heat-mass exchange surface in flowing air contact with water

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Abstract. A review of methods for forming interfacial heat-mass exchange surface in contact devices for air steam treatment is given. An effective method for creation of heat-mass exchange surface in air flow contact with water in the course of adiabatic wetting in air conditioning systems is proposed: by use of a plate head-piece with a mechanical vibration exciter. A method of defining area of the interfacial heat-mass exchange surface for these conditions is developed on the base of number of transfer units. The criterion equations to describe heat and mass transfer which occur when a plate head-piece with a vibration exciter is used for adiabatic air wetting are obtained. Use of a plate head-piece with vibration exciter as a contact device reduces energy consumption due to reduction of aerodynamic resistance of the air path and process intensification.

1. Introduction
In air conditioning systems, the following methods are used to form interfacial heat-mass exchange surface in the contact devices for steam treatment of air [3]:

1) **spraying water in the air chamber using mechanical nozzles**, for example, in the spraying nozzle chamber (SNC); in this case, interfacial heat-mass exchange surface area is equal to the total water droplets surface area.

2) **air flow film contact with water film in the air chamber equipped with a head-piece** (honeycomb wetting chamber). Under these conditions, the interfacial heat-mass exchange surface area is equal to the total surface area of all water films flowing down along the nozzle.

3) **spraying water in the air chamber with mechanical nozzles and, in addition, crushing formed water droplets at contact with the plane of horizontal grids (spraying grid chamber - SGC)** [2]. At that, the interfacial heat-mass exchange surface is equal to the total surface of water droplets formed due to nozzle spraying and water droplets formed additionally at the droplets crushing on the plane of the horizontal grid.

2. Body
According to Kokorin O. Ya. [3, p. 46], consumption of power for water spraying in the nozzle chamber is 25 times greater than in case of supplying water in the chamber with the head-piece. Therefore, method 2 of forming interfacial heat-mass exchange surface in contact devices for air steam treatment is the most effective, and honeycomb spraying chambers which use this method are increasingly used as contact devices in centralized air conditioners. Layout of honeycomb spraying chamber is shown in Figure 1.
Figure 1. Layout of honeycomb spraying chamber: a – schematic diagram; b – general view of the honeycomb head-piece

The chamber is shaped as a rectangular parallelepiped and is equipped with a fan 6 for air supply. Throughout the height of the chamber assembly, a honeycomb head-piece made of corrugated hygroscopic plates 2 is installed.

The spraying water dispenser 3 made in the form of a perforated plate with through holes for uniform water distribution over the chamber (head-piece) section is mounted on the head-piece top. The lower part of the head-piece is located above the pallet of the chamber 4 which is used as a water tank. The chamber is equipped with a pump 5 which provides water recirculation: water from the pallet through the hose is fed to the spraying water dispenser; from the dispenser water enters the corrugated hygroscopic plates of the honeycomb head-piece. Water wets the plates of the head-piece and in the form of water film flows down by gravity into the pallet of the chamber. At that, the water temperature is stabilized at the level of the wet air thermometer temperature. Due to operation of the fan, air passes through the head-piece gaps, contacting the flowing water film, where it is adiabatically wetted (cooled), and leaves the chamber. The heat-mass exchange surface area between air and wetted surface is defined by the size (area) of the water film in the head-piece layer.

As it has been noted above, an advantage of adiabatic wetting (cooling) of air with water in the spraying layers is a significant reduction in power consumption by the water pump drive compared to the energy consumption in the nozzle chambers. In the honeycomb wetting chamber assembly, required pump pressure depends on the height of spraying water dispenser over the head-piece wetting assembly and is less by several times than the required pump pressure in the case when water is sprayed through mechanical nozzles. Also, decrease in power consumption for the water pump drive is due to decrease in the spraying coefficient – μ, i.e. water consumption per unit of treated air. [3].

Disadvantages of adiabatic air wetting with water in the honeycomb wetting chamber assembly include large air path aerodynamic resistance which increases energy consumption to drive the fan unit, and also increases the fan size.

To increase heat-mass exchange surface area between air and water in a unit volume of the honeycomb wetting chamber while reducing the aerodynamic resistance of the air path and, accordingly, improving efficiency of adiabatic air wetting and cooling at reduced specific water consumption for air treatment (spraying coefficient), the authors propose to use a plate vibration head-piece.

It is known [1, p. 212] that vibration effect on the working units, in particular, effect of targeted mechanical vibrations with a relatively small amplitude and frequency in the range 10...103 Hz, allows significant increasing the phases contact surface area and reducing diffusion resistance in mass transfer processes.

To achieve this technical result in the chamber assembly, the honeycomb head-piece was replaced by a plate head-piece assembly fixed to a spring vibration base and containing a mechanical vibration exciter with electric drive.

According to the mass transfer equation [3], increase in the heat-mass exchange surface area leads to the process intensification, i.e. to increase in the mass of steam passing into the air:
\[ dM = k \cdot dF \cdot \Delta_{av} \cdot dt, \]  

where \( dM \) – increment of steam amount, kg;  
\( k \) – mass transfer coefficient, s/m;  
\( dF \) – increment of heat and mass transfer surface area, m\(^2\);  
\( \Delta_{av} \) – average driving force of mass transfer, Pa;  
\( dt \) – time increment, c.

General view of the plate head-piece assembly with vibration exciter is shown in Figure 2.

![Figure 2. Plate head-piece with vibration exciter](image)

The plate head-piece assembly consists of a set of flat parallel plates made of hygroscopic (or non-hygroscopic) material spaced at a distance of 15...20 mm and arranged along the length of the chamber.

The heat and mass transfer surface area between air and water is defined by a sum of:  
a) surface area of the water film flowing down along the plate of vibration head-piece;  
b) surface of the droplets and splashes in halo formed at water particles separation from the plates of the vibration head-piece.

It follows from analysis of Figure 2 that total area of heat and mass transfer increases significantly when a plate of vibration head-piece with a mechanical vibration exciter is used.

Aerodynamic resistance of the chamber assembly with a plate head-piece will be significantly reduced in comparison with the resistance in the honeycomb head-piece which is manufactured by foreign companies. Energy spent for air passage through the contact device is significantly reduced. In these conditions, additional energy consumption to drive the mechanical vibration exciter of the plate head-piece is small and can be of 200...300 W [1].

3. Methodical part
Calculation of heat and mass transfer surface area in the contact device which applies plate vibration head-piece is proposed using the method of graphic integration based on number of transfer units [4]:

1. Basic data for adiabatic wetting (cooling) of air (\( t_1, I_1, t_2 \) are, respectively, temperature, °C, enthalpy of inlet air, kJ/kg, and air temperature at the outlet of the contact device) were given.

2. The curve 1 – 2 for steam air treatment process was drawn in the \( I-d \) coordinate system, in accordance with Figure 3.
3. Number of transfer units $n_t$ necessary for exchange processes and number of transfer units $n_p$ necessary for mass transfer processes were defined.

On the basis of Figure 3, a curve for adiabatic wetting (cooling) of air was drawn (Figure 4).

![Figure 3](image)

**Figure 3.** Defining current ($t_i$) and balance ($t^*$) values of water temperature, current air moisture content ($d_i$) and balance ($P^*$) values of partial steam pressures in the course of adiabatic wetting and air cooling.

Calculation of number of the transfer units can be made according to the formulas:

$$n_t = \frac{1}{t - t^*} \int \left[ \frac{d_2}{d_1} \right] dt = f \cdot m_1 \cdot M_2$$ (2)

$$n_p = \frac{1}{P - P^*} \int \left[ \frac{d_1}{d_2} \right] \frac{dP}{dP} = F \cdot M_1 \cdot M_2$$ (3)

where $t, t^*$ – respectively, current (operating) and balance values of air temperature during steam treatment, °C;

$f, F$ – area of curved trapezoid in units of the used scale (Figure 4);

$m_1, m_2, M_1, M_2$ – respectively, scale of values along the abscissa and ordinate axes.

$P, P^*$ – respectively, current (working) and balance partial pressure in the course of air wetting, kPa,

$d_1, d_2$ – current air moisture content, g/kg.

4. Kinetic coefficients of heat and mass transfer were defined on the basis of thermal and diffusion similarity criteria.

Heat transfer coefficient is calculated by the formula:

$$\alpha = \frac{\lambda}{\nu}$$ (4)
Mass transfer coefficient is calculated by the formula:

\[ \beta = \text{Nu} \frac{D}{l} \]  

where \( \lambda \) – coefficient of thermal conductivity of air, W/(m·ºC);
\( l \) – defining geometric dimension, m;
\( D \) - steam diffusion coefficient in air, m²/s.

\( \text{Nu}, \text{Nu}' \) – Nusselt criterion parameter for thermal process, diffusion process, accordingly, which are defined by a criterion equations obtained by the authors on the basis of experimental studies using multiple regression method.

\[ \text{Nu} = 22.4\text{Re}^{0.11}\text{Re}_w^{0.41} \]  

\[ \text{Nu}' = 0.1\text{Re}^{0.464}\text{Re}_w^{0.195} \]  

where \( \text{Re}, \text{Re}_w \) - accordingly, Reynolds criterion parameters for air flow, criterion for aqueous phase (film) in vibration mode.

\[ \text{Re} = \frac{\nu d \rho}{\mu} \quad \text{Re}_w = \frac{\nu_w d_w \rho_w}{\mu_w} \]  

where \( \nu, \nu_w \) – accordingly, air velocity and velocity of the water film in vibration mode, m/s; \( d, d_w \) - respectively, equivalent diameter of the channel for air and equivalent diameter of the channel for water film, m; \( \rho, \rho_w \) – respectively, air density and density of the water film, kg/m³; \( \mu, \mu_w \) – dynamic viscosity coefficients for air and water film, Pa·s.

5. Required heat-mass exchange surface area in the contact device necessary for wetting in accordance with the basic data (p .1) was defined as:

\[ F^r = \frac{n_r \rho \nu}{\beta} \]  

\[ F^p = \frac{n_p \rho \nu}{\beta} \]  

4. Conclusion

Application of a plate head-piece assembly with a mechanical vibration exciter in contact devices for air steam treatment provides an effective way to form interfacial heat-mass exchange surface in contact of gas (air) flow with water flowing down along the plate vibration head-piece in the form of a water film, as well as with water droplets and splashes in halo formed at water particles separation from the surface, i. e. to provide energy saving at air wetting (cooling) in adiabatic conditions.

Advantages of the considered method for forming interfacial heat-mass exchange surface include:

- improved efficiency of air steam treatment in the course of adiabatic wetting and cooling due to increased heat-mass exchange surface area between working environments;
- reduction of specific water consumption for air treatment (spraying coefficient);
- reduction of aerodynamic resistance of the air path.

References
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