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Some Aspects of Improving the Efficiency of Air Treatment in the Contact Units of HVAC Systems

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Abstract. One of the main issues of improving the efficiency of air treatment in ventilation and air conditioning systems (HVAC systems) is development of methodology for the realization of energy-efficient air treatment processes in the contacting units. This paper investigates the thermodynamic models of "air-water" system, considering some features of the transition area at the interface, including surface phases and boundary layers of air and water. It has a great impact on the efficiency of processes of heat and moisture exchange in the contact units HVAC systems. The paper presents the results of experimental studies to determine the air-water interfaces temperature when achieving a state of thermodynamic balance condition in contacting media (air and water) in the working space of contact units. It was found that the surface temperature is determined by state of the surface phase and depends on the direction process of heat and moisture exchange (condensation or evaporation). The temperature factor $k = T_{dry}/T_s$ as a criterion for determining the effect of the state transition area on the processes of heat and moisture exchange, was used. Processing of results from experimental researches in the processes of heat and mass transfer is presented in the form of criterial equations for Nu, Nu_θ. Results of the performed research are the basis for the formulation of theoretical ideas about the energy efficient processes and the development of a new method for calculation of the contact units HVAC systems.

Keywords: humidity potential, heat and moisture exchange, contact units.

Conference topic: Energy for Buildings.

Introduction

One of the ways to improve the energy efficiency of HVAC systems is the developing of methodology for the realization energy-efficient air treatment processes in the contact units.

As it is known the interaction of the air and water in the contacting units HVAC systems is attended by the progress of heat and moisture exchange processes, connected with each other through quantitative correlation, which are determined by the equations of heat balance. However, this connection has further consequences, which can be implemented through thermodynamic understanding of the exchange processes progress mechanism, taking into consideration the effects on the boundary media interface and the conditions for achieving a state of thermodynamic balance in different direction processes (Bogoslovsky, Poz 1983; Bogoslovsky, Gvozdkov 1985; Gvozdkov 2014a; Gogosov *et al.* 1984).

A lot of attention is payed to the study of the air treatment issues in the contacting units HVAC systems. Different physical and mathematical models while describing the heat and moisture exchange processes take into account the existence of boundary layers and bulk phases by air and water (Bogoslovsky, Poz 1983; Blagojevic, Bajsic 1996; Jaycock, Parfitt 1984; Gvozdkov 2006; Pandelidis *et al.* 2015).

As the factors that determine of the heat and moisture exchange processes progress, the hydrodynamic and hygrothermal conditions of interaction are usually considered. The description of heat and moisture processes is presented in the form of criterial function (1) as follows:

$$Nu, Nu' = f(\mathrm{Re}, \mathrm{Pr}, \mathrm{Pr}', Sh, Sp, Ar, k, p.......) \tag{1}$$

where: Nu, Nu' – thermal and diffusion the Nusselt number; Re, Ar – hydrodynamic criteria of Reynolds and Archimedes; Pr, Pr' – thermal and diffusion the Prandtl number; Sh – Sherwood number; Sp – Stefan criterion accounting for the influence of cross-flow of moisture; k, p – parametric criteria to account for the initial conditions of cooperation.

Analysis of criteria characteristic curves, obtained by different authors, shows that they are private and correct only for calculating the heat and moisture exchange processes for particular conditions of the contacting media interaction (Iskra, Simonson 2006; Khudheyer 2011; Lee, Saylor 2010).

In some cases, it is invited to use the parametric criterion, called temperature factor – k = Tdry/Ts, that considers the parameters of the contact surface, particularly its temperature (Gukhman 1954) to take into account the initial parameters of the contacting media when determining Nu, Nu'.

It is known that there is a transition region at the interface of air and water called the surface phase. Its condition determines the contact surface temperature and influence on the heat and moisture exchange processes (Bogoslovsky, Gvozdkov 1985; Gogosov *et al.* 1984; Gvozdkov 2014b; Jaycock, Parfitt 1984).

In the foregoing articles dedicated to the study of the heat and moisture exchange processes, there is no analysis of the conditions for interaction at the interface. In particular, while studying processes of heat and moisture exchange, there is assumed that a thin saturated layer of air is formed over the surface of water, and the determination of the surface temperature is conditional, because it does not take into account the state of the surface phase (Iskra, Simonson 2006; Khudheyer 2011; Lee, Saylor 2010).

Thus, suggested analysis shows that the mechanism of heat and moisture exchange processes is still not completely defined, especially in non-isothermal conditions. The regularities of thermodynamic processes are not taken into account, in particular, the conditions for achieving a state of thermodynamic balance contacting media. And the question of determining the contact surface temperature in the implementation of different direction of (evaporation or condensation) heat and moisture exchange processes is still open.

Current research conducted with the use of the humidity potential theory are the basis for new solutions which helps to improve the thermodynamic efficiency of the contacting units HVAC systems and to develop the modern methods of their calculation.

Subject of study

When considering the heat and moisture exchange processes behaviour the thermodynamic approach was used. It is based on the humidity potential theory (Bogoslovsky, Gvozdkov 1985).

According to the humidity potential theory, the driving force of moisture exchange process is the gradient or difference of moisture potentials.Being a full thermodynamic potential, the humidity potential makes it possible to assess the water conditions in all phases, including analysis of the conditions of interaction at the interface, on the water side as well.

The "air-water" system can be generally presented in the form of the thermodynamic model including bulk, boundary and surface phases from both the air and water (Fig. 1).

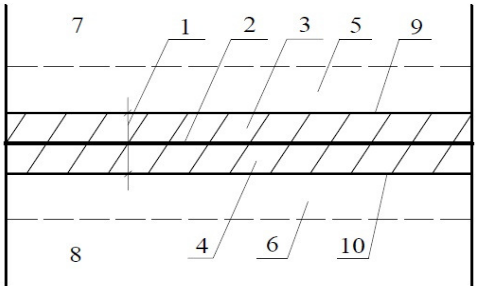


Fig. 1. The thermodynamic model of the "water-air" system: 1 – surface phase; 2 – interface surface; 3, 4 – surface phases of air and water; 5, 6 – boundary layers of air and water; 7, 8 – bulk phases of air and water; 9 – the position of interface surface (at moisture condensation from the air); 10 – the same at moisture evaporation from the water surface

As the Figure 1 shows, there is a transition area on the contact of media. This area includes the boundary layers and surface phases from the sides of air and water. Within the limits of the area the characteristics of media varies from the values in one of them to the values in other phases (Gvozdkov 2014b). Within a surface phase the interface is located. The mechanical and thermodynamic features of the transition area are significantly different from the features in the bulk phases, so they are considered as a series of separate phases (Jaycock, Parfitt 1984).

For describing the "water–air" system (Fig. 1) and for the thermodynamic analysis of the surface phase condition we used a unified thermodynamic state equation relative to the change of the Gibbs free energy F (2) (Bogoslovsky 1985) as:

$$dF = -SdT + \theta dm \tag{2}$$

where: S – entropy of heterogeneous system; T – temperature of heterogeneous system; θ – full thermodynamic potential of moisture condition in the system, humidity potential; m – mass of moisture.

Expression (3) for the humidity potential has a form:

$$\theta = -\frac{p}{\rho} + \mu + \sum \mu_i + \theta_g + \sum \theta_i \tag{3}$$

where: p – pressure of heterogeneous system; μ – the chemical potential of moisture; $\sum\mu_i$ – components of chemical potential of moisture due to availability of the dissolved substances; θ_g – the humidity potential as a result of action of gravitational field; $\sum\theta_i$ – the humidity potential by the actions of other force fields.

Based on the results of the thermodynamic analysis, it was found that the balance ($F = F_{min}$, $dF = 0$) within the surface phase can be achieved by the particular place of the interface. This place is defined by the number of molecules in the surface phases from both the air and water (Bogoslovsky, Gvozdkov 1985).

In this case, from an energy point of view, the surface phase can be located in the saturated and unsaturated condition depending on the direction of heat and moisture exchange processes.

Particularly, in condensation processes the water molecules denseness in the surface phase will be maximum, and its condition will be (Fig. 1, item 9) close to saturated.In the processes of evaporation the water molecules denseness in the surface phase will be minimal, and its condition (Fig. 1, item 10) will be unsaturated.In order to provide the evidence of the thermodynamic analysis the experimental researches of the heat and moisture exchange processes in the "air-water" system were made, shown in Figure 1.

Methodology and results

The aim of the experimental research is to resolve the following problems:

- Temperature pattern and humidity potential in boundary layers of air and liquid research;
- Surface phase parameters determination and research of special aspects of heat and moisture exchange processes (taking into consideration the thermodynamic model of contact areas and surface phases existence);
- Determination of local and medium surface coefficients of heat and moisture exchange processes while hydrodynamic and hygrothermal conditions;
- Receiving of criterion correspondence for Nu and NuΘ' for heat and moisture exchange processes calculating.

The investigations were conducted on a test bench. Its working chamber has the section of 150×150 mm, length – 1000 mm and a liquid pan. The temperature in the air layer over the liquid surface and in the temperature the liquid with adjoin layer at the depth was measured with copper-constantan thermocouples (diameter – 0.08 mm, the distance from the front edge of the pallet with water – 65, 100, 150, 200 and 300 mm respectively).

During the research it was planned to study polytropic and isenthalpic conditions in the "air-water" system in regard to surface phases at the media contact.

Temperature fields and humidity potential fields in the boundary layers of air and water were investigated under different combinations of initial parameters of media in bulk phases. Experimental conditions were defined on the relation $P = f(\theta, t)$ and I–d–θ–diagram (Bogoslovsky, Gvozdkov 1985).

The water temperature was changed within 10÷24 °C, the relative humidity changed from 30÷80%, air flow speed changed from 0.79÷2.4 m/s.

Considering that there are surface phases at the media contact and it is difficult to measure the true interface parameters, the graphic way of its determination based on test data concerning temperature and humidity potential distribution in the boundary layers has been applied.

The results of the experiments if θ = const. The following parameters defined its conditions:

- Bulk phase of air – $t_{dry} = 27.4$ °C, $t_{wet} = 22.35$ °C;
- Bulk phase of water – $t_w = 15.3$ °C;
- Air velocity – $v = 0.79$ m/s;
- Distance from the front edge of the pan – $1 = 0.2$ m.

The values measurement for t_{dry}, t_{wet}, t_w (Table 1) was done in the boundary layers of air and various ranges from interface. As the result, the temperature (t) distribution lines and the humidity potential (θ) lines in the boundary layers were plotted in the coordinates H–t, H–θ (H – the altitude distance from the interface to the measurement point). The results are presented in Figure 2 (a, b).

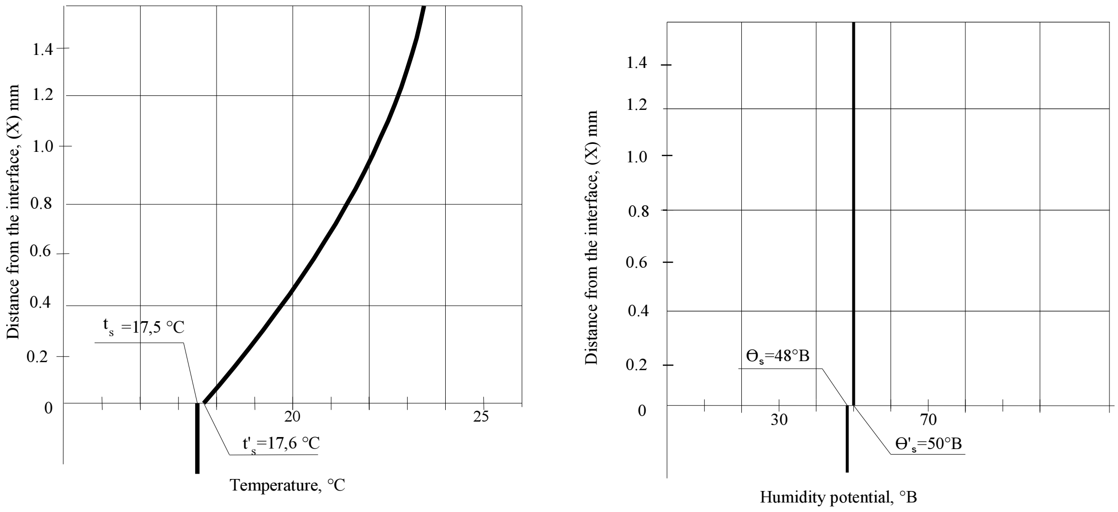
The interface parameters were determined at the crossing point of an extension of distribution lines t and θ with the interface ($H = 0$). In the test under study – $t_s = 17.6$ °C, $\theta_s = 48$°B.

From plotting in Figure 2 (a, b) it will be noted that the surface temperature, measured in the experimental practically corresponds to the temperature as a result of the graphic plotting with regard to thickness of the boundary layers. The same is true concerning the humidity potential. Thus, there are no parameters jumps at the interface.

The absence of the parameters jump at the interface is explained by the energetically saturated condition of the surface phase which is conforming to the conclusions of theoretical research. Also experimental study isenthalpic state of medium at I = const was carried.

Table 1. The results of the experimental study of the temperature fields and humidity potential in the boundary layers of air and water (1 = 0.2 m, v = 0.79 m/s, θ = const), test No. 40

Parameters of the bulk phase	measure-ment point	1	2	3	4	5	6	7	8
	H, mm	–0.4	–0.2	0.0	0.2	0.4	0.6	0.8	1.0
Air:									
t_{dry} = 27.4 °C	t_{dry}	–	–	–	18.5	19.1	19.8	20.5	21.0
t_{wet} = 22.35 °C	t_{wet}	–	–	–	18.5	18.8	19.2	19.6	19.9
Water:									
t_w = 15.3 °C	t_w	17.5	17.5	17.5	–	–	–	–	–



a) b)

Fig. 2. a) Temperature distribution in boundary layers of air and water at v = 0.79 m/s, 1 = 0.2 m (data of Table 1); b) Humidity potential distribution in boundary layers of air and water at v = 0.79 m/s, 1 = 0.2 m; t_s, θ_s is interface parameters from plotting of temperature and humidity potential fields; t'_s, θ'_s is interface parameters measured in the experiment

The results of the experiments if I = const (Table 2). The following parameters defined its conditions:

- Bulk phase of air –t_{dry} = 19.6 °C, t_{wet} = 8.7 °C;
- Bulk phase of water –t_w = 8.8 °C;
- Air velocity – v = 0.79 m/s;
- Distance from the front edge of the pan – 1 = 0.2 m.

Table 2. The results of the experimental study of the temperature fields and humidity potential in the boundary layers of air and water (1 = 0.2 m, v = 0.79 m/s, I = const), test No. 36

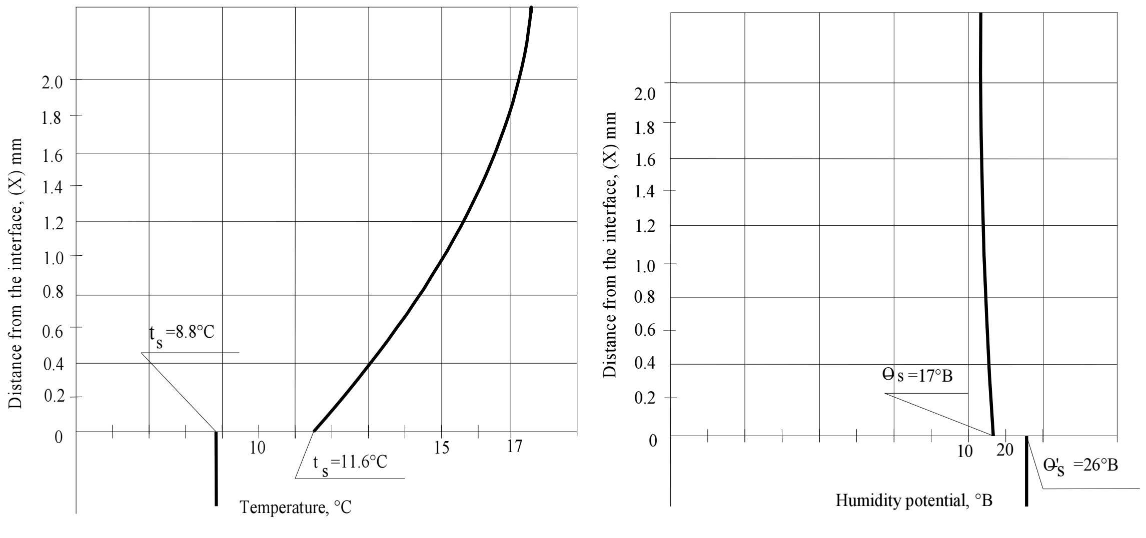
Parameters of the bulk phase	measure-ment point	1	2	3	4	5	6	7	8
	H, mm	–0.4	–0.2	0.0	0.2	0.4	0.6	0.8	1.0
Air:									
t_{dry} = 19.6 °C	t_{dry}	–	–	–	12.3	13.0	13.7	14.3	14.9
t_{wet} = 8.7 °C	t_{wet}	–	–	–	8.7	8.7	8.7	8.7	8.7
Water:									
t_w = 8.8 °C	t_w	8.8	8.8	8.8	–	–	–	–	–

By analogy with the above-considered test at θ = const, on the basis of the given measurements of t_{dry}, t_{wet} and t_w at the boundary layers of air and water, the lines of temperature (t) distribution and the humidity potential (θ) at I = const (Fig. 3a, b) have was plotted. The parameters of the transition phase – t_s = 11.6 °C, θ_s = 17°B have been specified and the experimental values of interface parameters –t'_s = 8,8 °C, θ'_s = 26°B have also been plotted on the line H = 0.

The constructions in Figure 3a, b shows that $\Delta t = t_s - t'_s = 2.8$ °C, and $\Delta\theta = \theta'_s - \theta_s = 9$°B. That is the surface temperature measured in the test does not correspond to that from the constructions of temperature fields in theboundary layers. The same is true in concerning to the humidity potential. There is a parameters jump at the media interface.

The similar results were obtained also at the other initial interaction conditions. It should be noted, that in the explored range under the simulation of the condition I = const, $\Delta t = t_s - t'_s$ makes up 2.5÷3.8 °C, and $\Delta\theta = \theta'_s - \theta_s$ – 4÷10°B.

In order to generalize results of studies of heat and moisture exchange there was accepted the criterial form of the dependence of the Nusselt's thermal and diffusion criterion from hydrodynamic and hygrothermal interaction conditions.



a) b)

Fig. 3. a) Temperature distribution in boundary layers of air and water at v = 0.79 m/s, 1 = 0.2 m (data of Table 2); b) Humidity potential distribution in boundary layers of air and water under v = 0.79 m/s, l = 0.2 m; t_s, θ_s is parameters of interface out of temperature and humidity potential fields plotting; t'_s, θ'_s is parameters of interface, measured in the experiment.

For heat and moisture exchange processes there was established relationship in the following form (4):

$$Nu, Nu'_\theta = f(\mathrm{Re}, \mathrm{Pr}, \mathrm{Pr}'_\theta, k), \qquad (4)$$

where: Nu, Nu'_θ– determinable number; Re, Pr, Pr'_θ, k – determining criteria.

The relationship between the determinable and the determining factors was established graphically, on the basis of that has been learned mathematical expressions that describe heat and moisture exchange processes between air and water.

As a result of the processing of the experimental data the criteria's dependencies were received with using the potential to determine local values of heat and moisture exchange coefficients with regard to the surface phases at the media interface as follows (5–6):

$$Nu = c_1 \cdot \mathrm{Pr}^{0.33} \cdot \mathrm{Re}^{0.74} \cdot k^{0.17} \qquad (5)$$

$$Nu_{\theta'} = c_2 \cdot (\mathrm{Pr}_{\theta'})^{-2} \cdot \mathrm{Re}^{1.08} \cdot k^{-0.28} \qquad (6)$$

where: Nu, Nu_θ' – Nusselt number; Pr, Pr_θ' – Prandtl number; k = 1.018÷1.033; c_1 = 0.046÷0.052; c_2 = 0.0061÷0.006.

The temperature factor (k) was used in the criteria's dependencies, it presents ratio between temperature by dry-bulb thermometer in the bulk phase of air and temperature of interface as well it determines the degree of impact of surface phase's condition on the processes of heat and moisture exchange in the "air-water" system.

Now consider features of the interaction in the "water–air" system in the contacting units.

In conditions of developed turbulence interacting flows, which is typical for the work of the contacting units, boundary layers from the side air and water are destroyed, contributing to a more intensive progress of processes of heat and moisture exchange between the air and water (Bogoslovsky, Poz 1983; Gvozdkov 2014b).

In this case, in the conditions state of thermodynamic balance, the final parameters of the air and water are completely determined by the state of the surface phase at the interface of the contacting media that finally determines the temperature of the media interface.

The most interesting in terms of the calculation of heat and moisture exchange is to establish the conditions to achieve thermodynamic balance of finite parameters of air and water at the outlet of the contact units.

Taken into account the mentioned above fact, we will consider the thermodynamic model of the “air–water” system, which takes into account the existence at the interface only the surface phase, within which there is the interface (Fig. 4).

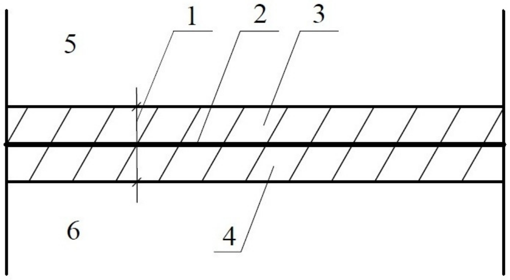


Fig. 4. Thermodynamic model of “air-water” system relating to the contacting units of HVAC system:
1 – the surface phase; 2 – interface; 3, 4 – surface phases of air and water; 5, 6 – bulk phases of air and water

As the Figure 4 shows, the conditions of thermodynamic balance of heat and moisture exchange processes will be completely determined by the state of the surface phase at the interface of the contacting media. The results of the thermodynamic analysis of the “air–water” system have shown that the condition of complete thermodynamic balance corresponds to equality of the transfer potential (temperature and humidity potential) on the interface interacting media (Gvozdkov 2014b).

It should be noted that the traditional view of heat and moisture exchange processes flow is based on the idea that the interaction of air and water is regarded as the interaction of the particular state air (unsaturated) and the saturated air layer over the surface of the water (Bogoslovsky, Poz 1983; Iskra, Simonson 2006; Khudheyer 2011; Lee, Saylor 2010).

Providing that the surface phase as this layer, it should be noted that the phase can be both in the saturated state (or close thereto) and in the unsaturated state as a “contact” resistance at the interface.

For example, consider the process of cooling and dehumidifying of air. The peculiarity of these processes is that the condition of thermodynamic balance of air and water final parameters is achieved in the area of humid air in the range $\varphi = 90–95\%$ and the final parameters of the air and water are in condition $\Theta = \text{const}$ (Fig. 5) (Gvozdkov 2014b).

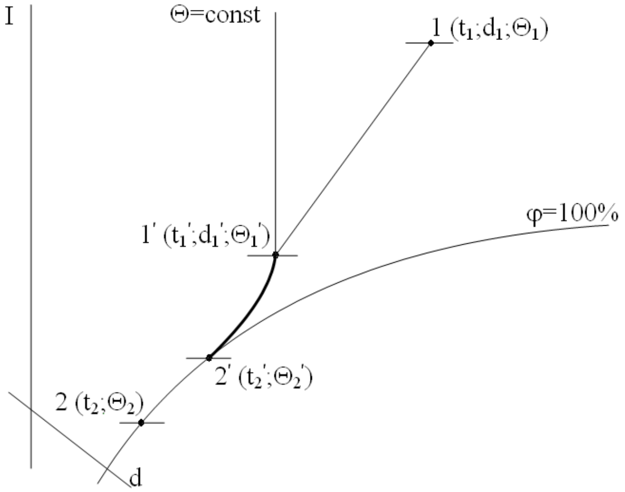


Fig. 5. The thermodynamic balanced state of final parameters of interacting media during the cooling and dehumidifying processes in the I–d–θ–diagram: t_1, t_2 – the initial parameters of air and water; t_1', t_2' – the initial parameters of air and water; $\theta = \text{const}$ – the line of constant humidity potential; $\varphi = 100\%$ – saturation line

If considering the thermodynamic model of the “water–air” system (Fig. 4) for cooling and dehumidification of air, when there is a condensation of liquid molecules from the bulk air phase, the interface will be located on the upper boundary surface phase and determines the conditions of thermodynamic balance interacting media.

In this case the state of the surface phase will be stay in unsaturated condition and parameters of interface surface will be correspond to the final parameters of the treated air. The state of interface in conditions of thermodynamic balance is characterized by the point 1' on I–d–θ–diagram (Fig. 5). The line 1'–2' describes the process of parameters changing within the surface phase, and the state of the point 2' describes the final parameters of the water in the bulk phase in thermodynamic balance in the “air-water” system at θ = const.

The results of theoretical analysis are fully consistent with the results of experimental research of the heat and moisture exchange processes in the contacting units, which have been obtained by other authors (Chan Ngok Tian 1970; Karpis 1960; Zusmanovich 1960, 1967).

Conclusions

The results of analysis of heat and moisture exchange processes between air and water are submitted in this article and based on the humidity potential theory.

The models of air and water interaction including boundary layers and surface phases on the sides of air and water were developed and the features of surface phase condition depending on a direction of heat and moisture exchange process were determined.

Relations for Nu and $Nu_{\theta'}$ in the view of influencing on exchange processes of the surface phase as the temperature factor $k = T_{dry}/T_s$ were established experimentally.

The thermodynamic common factors of heat and moisture exchange processes in contact devices and conditions of thermodynamic balance between interact areas were established.

The results received in the research are the basis for developing a uniform method of calculating contacting units which are used in HVAC system.

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