INTENSIFICATION OF MASS TRANSFER IN THE GAS-LIQUID MEDIUM OF A VORTEX APPARATUS

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Annotatsiya. Ushbu maqolada havo yordamida suvni bug‘latib sovitish jarayonida uyurmali kontaktli issiqlik almashinish apparatida kechadigan massa almashinuvi jarayonlarining eksperimental tadqiqot natijalari bayon etilgan. Tadqiqotda massa almashinuvi koeffitsientlarini aniqlash hamda havo oqimining tezligi va suyuqlik sarfining jarayon jadalligiga ta’siri o‘rganilgan. Eksperimental ma‘lumotlar asosida empirik bog‘lanishlar ishlab chiqildi va ularning muhandislik hisoblarida qo‘llanishi mumkin bo‘lgan asosiy qonuniyatlari belgilandi. Tadqiqot natijalariga ko‘ra, issiqlikning asosiy qismi havoga suvning bug‘lanishi orqali o‘tadi, bu esa massa almashinuvini jarayonning asosiy mexanizmi sifatida ko‘rsatadi.

Kalit so‘zlar: bug‘latib sovitish, uyurmali apparat, massa almashinuvi, massa almashinish koeffitsienti, Nusselt diffuziya kriteriyasi, Reynolds kriteriyasi, namlik miqdori.

Аннотация. В статье представлены результаты экспериментального исследования процессов массообмена при испарительном охлаждении воды воздухом в вихревом контактном теплообменнике. Основное внимание уделено определению коэффициентов массообмена и влиянию параметров воздушного потока и расхода жидкости на интенсивность процессов. Получены эмпирические зависимости, обобщающие экспериментальные данные, и установлены основные закономерности, которые могут быть использованы для инженерных расчётов. Установлено, что основная часть тепла от воды к воздуху передаётся за счёт испарения, что делает массообмен ключевым механизмом в рассматриваемом процессе.

Ключевые слова: испарительное охлаждение, вихревой аппарат, массообмен, коэффициент массообмена, диффузионный критерий Нуссельта, критерий Рейнольдса, влагосодержание.

Abstract. This article presents the results of an experimental study on mass transfer processes during the evaporative cooling of water by air in a vortex contact heat exchanger. The focus is on determining mass transfer coefficients and examining the effect of air flow parameters and liquid flow rate on process intensity. Empirical relationships were derived from experimental data, establishing key patterns that can be used for engineering calculations. It was found that the main portion of heat is transferred from water to air through evaporation, making mass transfer the primary mechanism in this process.

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Keywords: evaporative cooling, vortex apparatus, mass transfer, mass transfer coefficient, diffusion criterion, Nusselt, Reynolds, moisture content.

Introduction

Evaporative cooling of water with air is an energy-efficient heat transfer method in which a significant portion of the heat is removed from the liquid through phase transition. Unlike traditional heat exchangers, vortex heat exchangers ensure intense phase interaction due to the high velocity and turbulence of the gas flow [1-2]. This facilitates rapid renewal of the interfacial surface and increases the driving force for mass transfer. Under conditions of incomplete air saturation, evaporation is accompanied by active mass transfer from the liquid to the gas phase, necessitating a detailed study of these processes and the determination of corresponding calculation dependencies for equipment design and optimization.

RESEARCH METHODOLOGY

Experiments were conducted in a vortex contact apparatus, in which hot water came into direct contact with unsaturated air entering at an axial velocity. Water and air mass flow rates, temperatures, relative humidity at the apparatus inlet and outlet, and moisture content were measured. Calculation formulas based on dimensionless criteria were used: Sherwood for mass transfer, Reynolds for air and liquid film, as well as energy and material balance equations. The mass transfer coefficient was determined based on the moisture content of the air before and after passing through the apparatus, taking into account the difference in saturated water vapor pressure and barometric pressure. Calculating the enthalpy of air and water allowed us to account for the total heat load and confirm the predominance of evaporation as the primary heat transfer mechanism. Results were analyzed using graphical dependencies, experimental data approximation, and the construction of generalized empirical formulas.

A detailed description of the experimental setup is presented in [3]. The diameter of the working chamber of the vortex apparatus D=0,056 m, the height of the working zone H=0,61 m, their ratio was H/D=10,9. The dimensions of the rectangular tangential gas swirlers: height h=56 mm, width b=19,625 mm.

The experiments were carried out under the following initial operating parameters:

- average axial gas velocity in the apparatus w_0=12÷26 m/s;
- the ratio of the mass flow rates of liquid and gas entering the vortex apparatus, in the range L/G=0,45÷3;
- hot water with a temperature of 61,2-62,8 °C and atmospheric air, the temperature of which at the entrance to the vortex apparatus was about 34,5-37,9 °C, and the relative humidity varied from 20 to 38%, were used as working media;
- air mass flow rate varied from 0.037 to 0.088 kg/s;

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- experiments were carried out at gas Reynolds numbers 37333÷112000;
- experiments were carried out at Reynolds numbers for a liquid film 17401÷1188 (turbulent film flow $Re_{ж}$>1600).

Experimental studies of mass transfer processes in a vortex contact apparatus with gas-liquid flows were conducted to obtain calculated relationships for determining mass transfer coefficients. It should be noted that when hot water is cooled by unsaturated air in direct contact, heat transfer is accompanied by water evaporation, i.e., mass transfer from one phase to another.

The procedure for processing experimental data for studying the intensity of contact mass transfer in a vortex apparatus is given below.

1. Nusselt diffusion criterion (or Sherwood criterion) [4; p. 483, 5; p. 4]:

$$Nu_D=Sh=\frac{K_M D}{D'} \quad (1)$$

where K_M-mass transfer coefficient, m/s;
D'-diffusion coefficient, m^2/s.

2. The obtained results of experimental data in the contact vortex apparatus are generalized in the form of empirical equations:
- by mass transfer [6; p. 76, 7; p. 425]

$$Nu_D=Sh=ARe_г^n Re_ж^m (L/G)^z Sc_г^c \quad (2)$$

3. Reynolds criterion for air [7; p. 61]:

$$Re=\frac{w_0 D\rho}{\mu} \quad (3)$$

where is the average axial velocity of gas in the working chamber of the vortex apparatus, m/s; w_0
D- diameter of the vortex apparatus, m;
$\rho_г$- air density, kg/m^3;
μ-dynamic viscosity environment, Pa·s or kg/(m·s).

4. Reynolds criteria for liquid film [8; p. 222]:

$$Re_ж=\frac{4\Gamma}{\mu} \quad (4)$$

where G is the irrigation density, kg/(m·s);
μ-dynamic viscositywater, .Pa·s

5. Moisture content of air kg moisture/kg at the inlet and $x_н$ $x_к$ at the output of the apparatus [6; p. 76]:

$$x_н=\frac{0{,}622\varphi_н P_{н.н}}{P_б-\varphi_н P_{н.н}},\ x_к=\frac{0{,}622\varphi_к P_{н.к}}{P_б-\varphi_к P_{н.к}} \quad (5)$$

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where $\varphi_н$ and $\varphi_к$ - accordingly, the relative humidity of the airat the input and output of the apparatus, %;

$P_{н.н.}$ and $P_{н.к}$ - respectively, the pressure of saturated water vaporat the input and output of the apparatus, Pa;

$P_б$ - barometric pressure, $P_б$=101300 Pa.

6. Saturated water vapor pressureat the entrance and exit of the apparatus in the air were determined by the equation [6; p. 77]:

$$P_{н.н}=1000e^{\frac{16,57t_{гн}-155,72}{233,77+0,997t_{гн}}}, \quad P_{н.к}=1000e^{\frac{16,57t_{гк}-155,72}{233,77+0,997t_{гк}}} \tag{6}$$

where $t_{гн}$ and $t_{гк}$ are the air temperatures at the inlet and outlet of the apparatus.

7. Mass flow rate of evaporated water into the air M, kg/s [8]:

$$M=G(x_к-x_н)=L_н-L_к \tag{7}$$

where $x_н$ and $x_к$ are the moisture content of the air before and after the vortex apparatus, kg/kg;

G - air mass flow rate, kg/h;

$L_{жн}$ and $L_{жк}$ – mass flow rates of water at the inlet and outlet of the apparatus, kg/s.

8. The heat balance equation for a vortex contact apparatus has the form [9; p.169, 5; p.4]:

$$GI_н+L_нH_н=GI_к+L_кH_к+Q_п \tag{8}$$

where $GI_н$ is the heat flow entering the apparatus with air, J/s;

$L_нH_н$ - heat flow entering with water, J/s;

$GI_к$ - heat flow leaving with air, J/s;

$L_кH_к$ - heat flow leaving the apparatus with water, J/s;

$Q_п$ - heat losses to the environment, which can be neglected under the conditions of this experiment.

9. The enthalpy of moist air at the entrance to the apparatus and at the exit from the apparatus was calculated using the equation I, J/kg [6; p. 77, 7; p. 619]:

$$I_н=(1007+1970\cdot x_н)\cdot t_{гн}+r_н x_н, \quad I_к=(1007+1970\cdot x_к)\cdot t_{гк}+r_к x_к \tag{9}$$

where $r_н$ и $r_к$-specific heat of vaporization at temperature $t_{гн}$ and $t_{гк}$, J/kg;

$t_{гн}$and $t_{гк}$- temperature air at the inlet and outlet of the device,℃.

10. The specific heat of vaporization was determined using the equation [6; p. 77]:

$$r_н=1000\cdot(2501-2,36\cdot t_{гн}), r_к=1000\cdot(2501-2,36\cdot t_{гк}) \tag{10}$$

11. The enthalpy of water at the inlet and outlet of the apparatus was determined using the equation H, J/kg [9; p. 169, 5; p. 4]:

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$$H_н=T_{жн}\cdot c_н, H_к=T_{жк}\cdot c_к \quad (11)$$

where $c_н$ and $c_к$are the specific heat capacities of water at temperatures $T_{жн}$ and $T_{жк}$, J/(kg·K);

$T_{жн}$ и $T_{жк}$- water temperatureat the input and output of the apparatus, °C.

12. The heat transferred from water to air was determined from equation (7) [9; p. 169, 5; p. 4]:

$$Q=G(I_к-I_н) \quad (12)$$

or

$$Q=L_н H_н-L_к H_к \quad (13)$$

13. The total amount of heat transferred from hot water to air is determined by the formula [5; p. 4]:

$$Q=Q_{ис}+Q_{соп}+Q_п \quad (14)$$

where $Q_{ис}=Mr$ - heat transferred by evaporation of water into the air, W;

$Q_{соп}$ - heat of contact of water with air, W;

$Q_п$ - heat loss to the environment, W;

14. In the experimental determination of the mass transfer coefficient, the following equation was used [9; p. 169, 10; p. 482, 5; p. 4]:

$$K_м=\frac{M\cdot R\cdot \Delta t_{ср}}{F_{ап}\cdot(P_{п.к}-P_{п.н})\cdot M_{H_2O}} \quad (15)$$

where R=8,314 is the universal gas constant, J/(mol·K);

$P_{п.к}=\varphi_к P_{н.к}$ и $P_{п.н}=\varphi_н P_{н.н}$- respectively, partial water vapor pressure at the input and output of the apparatus, *Pa*;

M_{H_2O}- molar mass of water, kg/mol.

RESULTS AND DISCUSSION

As noted above, the intensity of heat transfer by both contacts and evaporation depends heavily on water temperature. The higher the water temperature, the more intense the evaporative heat transfer, and the majority of heat is removed from the liquid by evaporation.

As the temperature of the liquid increases, the overall heat load increases, and heat transfer by evaporation increases significantly more than heat transfer by contact.

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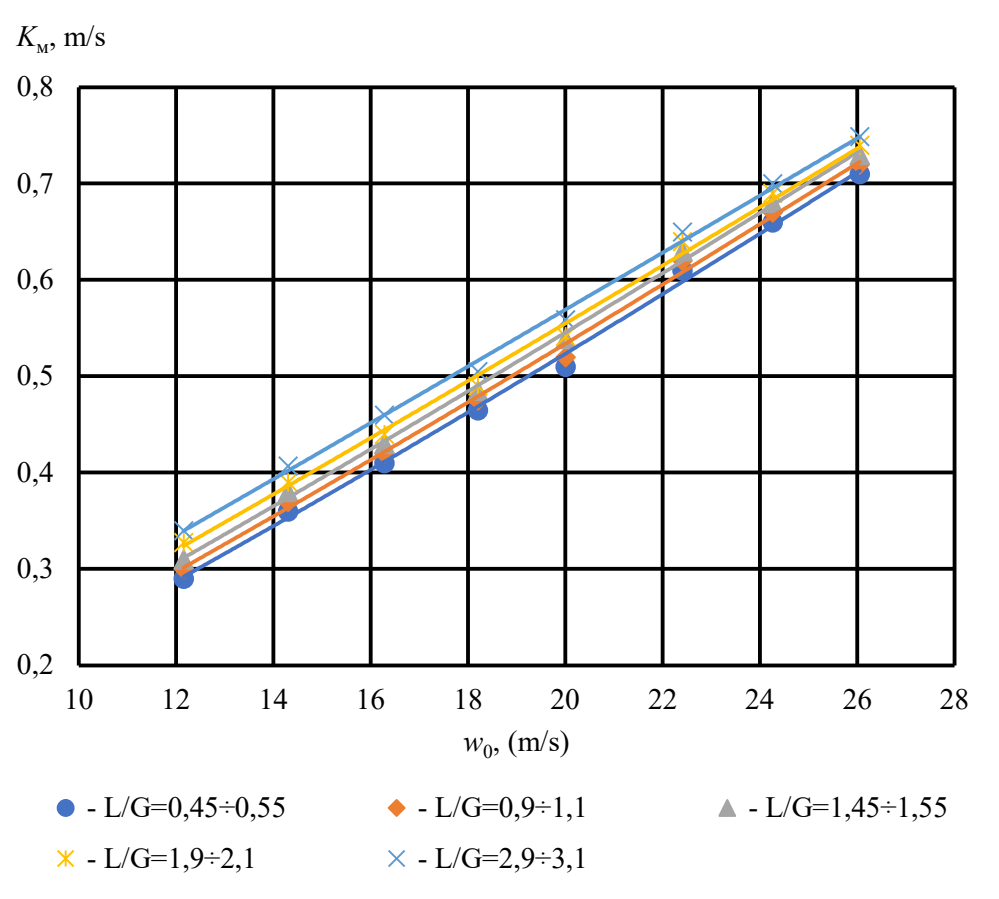


Fig. 1. Dependence of the mass transfer coefficient Km on the gas velocity w0 for different ratios of liquid and gas mass flow rates L/G

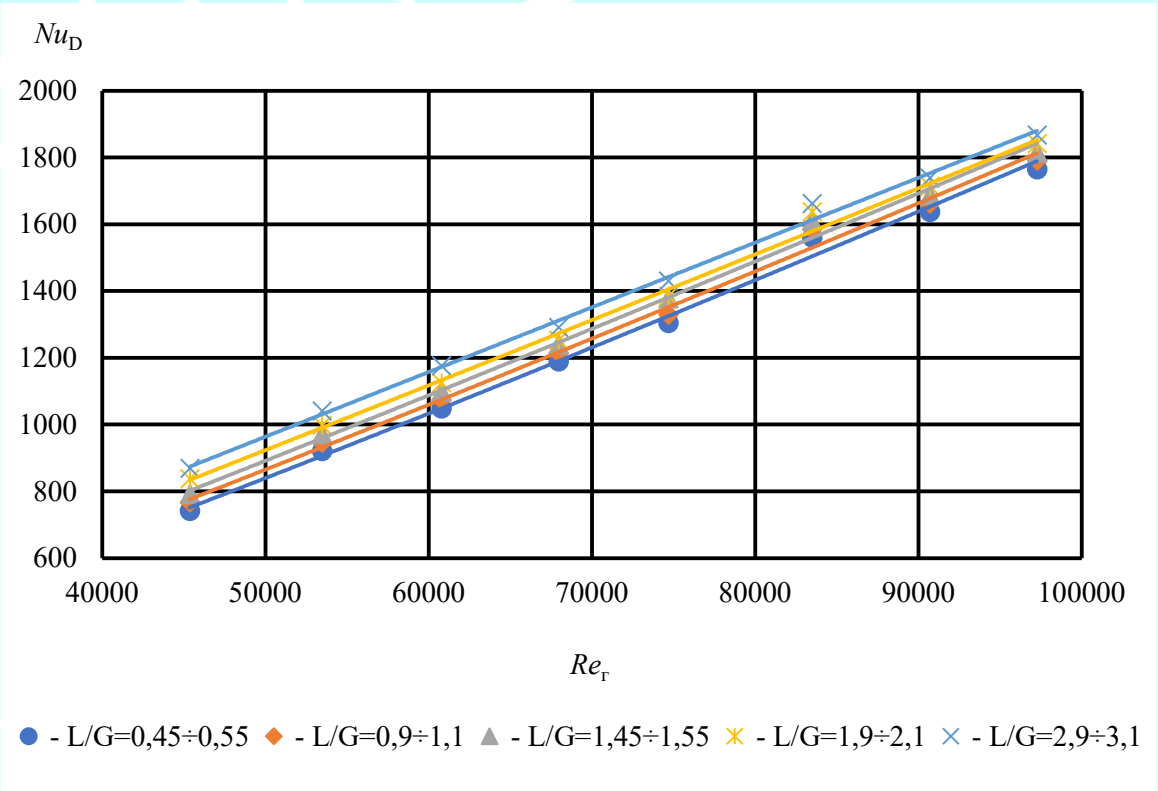


Fig. 2. Dependence of the Nusselt diffusion criterion NuD on the gas Reynolds criterion Rer for different ratios of liquid and gas mass flow rates L/G

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Under such conditions, evaporative heat transfer predominates in overall thermal loads. Therefore, studying mass transfer during evaporative cooling of water is a necessary factor, significantly affecting the intensity of the heat and mass transfer process.

The results of the experiments are presented in the form of the dependence of the mass transfer coefficient on the air velocity in Fig. 1, and in the form of the dependence of the Nusselt diffusion criterion on the Reynolds criterion of gas for different ratios of the mass flow rates of liquid and gas L/G, in Fig. 2.

An analysis of the experimental data obtained shows that with increasing gas flow rate and irrigation density, the intensity of mass transfer increases. This pattern of change in the mass transfer coefficient, firstly, confirms that the majority of heat is transferred from water to air through mass transfer (evaporation). Secondly, it is explained by the emergence and increase in the relative velocity of the gas and liquid, which facilitates rapid renewal of the water film surface and, consequently, increases the intensity of heat and mass transfer. The rotating high-speed gas flow strips vapor bubbles emerging from the depths of the water to its surface. As a result, the driving force for evaporative cooling of the water increases.

The experimental data were processed using the approximation method of experimental data on mass transfer, and the coefficients A, n, m, and z in equation (2) were determined. The experimental values of NuD were generalized using the following formula, and the approximation of the experimental data on mass transfer is shown in Fig. 3

$$Nu_D=0{,}0089\cdot Re_г^{1{,}067}\cdot Re_ж^{0{,}01}\cdot (L/G)^{0{,}04}\cdot Pr_г^{0{,}33} \quad (16)$$

The approximation accuracy is R2=0.99. The maximum relative error was 6%.

Using mathematical methods, the equation for calculating the mass transfer coefficient can be reduced to the following form:

$$K_м=0{,}0089\cdot Re_г^{1{,}067}\cdot Re_ж^{0{,}01}\cdot (L/G)^{0{,}04}\cdot Pr_г^{0{,}33}\cdot D'/D \quad (17)$$

For engineering calculations, a simplified empirical formula can be used:

$$K_м=0{,}027\cdot w_0^{1{,}067}\cdot D^{0{,}057}\cdot L^{0{,}05}\cdot G^{-0{,}04} \quad (18)$$

The results obtained are shown in Fig. 3 as a dependence of the ratio on the Reynolds criterion for gas.$Nu_D/(Re_ж^{0{,}01}\cdot (L/G)^{0{,}04}\cdot Pr_г^{0{,}33})$

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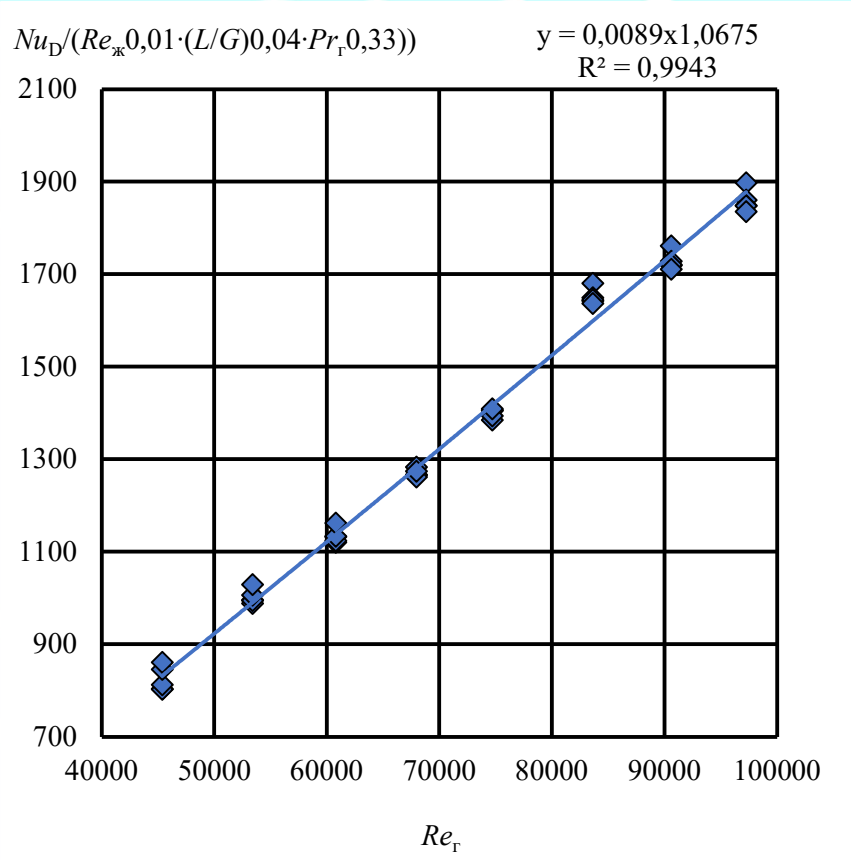


Fig. 3. Approximation of experimental data on mass transfer

As can be seen from Figure 3, the experimental values of the NuD number for the vortex apparatus are in good agreement with the results of calculations using equation (16).

CONCLUSIONS

The process of evaporative cooling of water in a vortex device is characterized by a high level of mass transfer, which determines the efficiency of heat transfer. The majority of heat is transferred through evaporation, which is especially pronounced at elevated water temperatures and increased air flow rates. The experimental relationships and empirical formulas obtained can be used in the design and optimization of heat exchange equipment with an evaporative cooling mechanism. Increased mass transfer intensity is directly related to flow parameters and ensures efficient cooling of liquids in vortex systems.

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