UDC 66.045.1 DOI: 10.70769/2181-7383.MBU.1(104).2026.14

INTENSIFICATION OF CONTACT HEAT EXCHANGE IN A VORTEX APPARATUS TO IMPROVE THE EFFICIENCY OF WET GAS CLEANING

Akhmatov A.A.,
Navoi State University of Mining and Technologies, PhD, Associate Professor

Abstract. *The article presents the results of a comprehensive experimental study on the intensification of contact heat transfer during the direct interaction of hot water and air flows in a vortex-type apparatus. The relevance of the research is determined by the increasing demand for improved energy efficiency, reduced operating costs, and enhanced environmental safety of thermal and gas-cleaning systems, as well as the transition of industry toward sustainable development principles. The objective of the study is to establish quantitative relationships between hydrodynamic parameters, liquid-to-gas mass flow ratios, swirl intensity, and their influence on the heat transfer coefficient, thermal capacity, and overall efficiency of the apparatus.*

An experimental setup with tangential injection of both gas and liquid phases was developed and implemented to ensure the formation of a stable vortex regime, an expanded interfacial contact surface, and a high level of turbulence. The experimental data were processed using the Nusselt and Reynolds similarity criteria, together with heat balance equations accounting for evaporation, condensation, and changes in air moisture content. Experiments were carried out over a wide range of Reynolds numbers and L/G ratios, allowing stable heat transfer patterns to be identified.

It was established that increasing the gas Reynolds number from 45,360 to 97,253 results in a rise of the Nusselt number from 2,300 to 15,700. Higher irrigation density intensifies heat transfer due to enhanced liquid dispersion and enlargement of the interfacial area. The obtained results can be applied in the design and modernization of energy-efficient vortex heat exchangers and wet gas-cleaning systems.

Keywords: *contact heat exchange; vortex apparatus; flow swirl; evaporative cooling; heat transfer; Nusselt number; Reynolds number; wet gas cleaning*

ИНТЕНСИФИКАЦИЯ КОНТАКТНОГО ТЕПЛООБМЕНА В ВИХРЕВОМ АППАРАТЕ ДЛЯ ПОВЫШЕНИЯ ЭФФЕКТИВНОСТИ МОКРОЙ ОЧИСТКИ ГАЗОВ

Ахматов А.А.

Навоийский государственный горно-технологический университет, Республика Узбекистан

Аннотация. *В статье представлены результаты комплексного экспериментального исследования интенсификации контактного теплообмена при непосредственном взаимодействии потоков горячей воды и воздуха в вихревом аппарате. Актуальность работы обусловлена возрастающими требованиями к энергоэффективности, снижению эксплуатационных затрат и повышению экологической безопасности теплотехнических и газоочистных систем в условиях ужесточения природоохранных нормативов и перехода промышленности к устойчивому развитию. Цель исследования заключается в установлении количественных закономерностей влияния гидродинамических параметров, отношения массовых расходов фаз и интенсивности закрутки потоков на коэффициент теплоотдачи, тепловую мощность и общую эффективность аппарата.*

Разработана и реализована экспериментальная установка с тангенциальным вводом газа и жидкости, обеспечивающим формирование устойчивого вихревого режима, развитой межфазной поверхности контакта и повышенного уровня турбулентности. Обработка результатов выполнена на основе критериев подобия Нуссельта и Рейнольдса, а также уравнения теплового баланса с учетом процессов испарения, конденсации и изменения влагосодержания воздуха. Эксперименты проведены в широком диапазоне чисел Рейнольдса и значений L/G, что позволило выявить устойчивые тенденции изменения теплопередачи и оценить вклад каждого параметра в общий тепловой эффект.

Установлено, что увеличение числа Рейнольдса газа от 45360 до 97253 сопровождается ростом числа Нуссельта от 2300 до 15700, что свидетельствует о существенном повышении турбулентности и интенсивности обновления межфазной поверхности. Повышение плотности орошения *дополнительно усиливает теплообмен за счет диспергирования жидкости и увеличения площади контакта фаз. Научная новизна работы состоит в экспериментальном подтверждении комплексного влияния закрутки потоков на сопряженные процессы тепломассопереноса и тепловую эффективность вихревого аппарата. Полученные результаты могут быть использованы при проектировании энергоэффективных вихревых теплообменников и аппаратов мокрой газоочистки нового поколения, а также при модернизации действующих промышленных установок.*

Ключевые слова: *контактный теплообмен; вихревой аппарат; закрутка потока; испарительное охлаждение; теплопередача; число Нуссельта; число Рейнольдса; мокрая газоочистка.*

GAZLARNI HOʻL USULDA TOZALASH SAMARADORLIGINI OSHIRISH MAQSADIDA VIXRLI APPARATDA KONTAKT ISSIQLIK ALMASHINUVINI JADALLASHTIRISH

Axmatov A.A.

Navoiy davlat konchilik va texnologiyalar universiteti, Oʻzbekiston Respublikasi

Annotatsiya. *Ushbu maqolada issiq suv va havo oqimlarining bevosita oʻzaro taʼsiri sharoitida uyurmali kontaktli apparatda issiqlik almashinuvini jadallashtirish boʻyicha kompleks eksperimental tadqiqot natijalari bayon etilgan. Tadqiqotning dolzarbligi energiya samaradorligini oshirish, ekspluatatsion xarajatlarni kamaytirish va issiqlik texnikasi hamda gaz tozalash tizimlarining ekologik xavfsizligini taʼminlashga qoʻyilayotgan talablarning ortib borishi, shuningdek sanoatning barqaror rivojlanish tamoyillariga bosqichma-bosqich oʻtishi bilan belgilanadi. Ishning asosiy maqsadi gidrodinamik parametrlar, fazalarning massaviy sarflari nisbatlari hamda oqimlarning aylanish jadalligining issiqlik berish koeffitsienti, issiqlik quvvati va apparatning umumiy issiqlik samaradorligiga taʼsirini miqdoriy jihatdan aniqlashdan iborat.*

Tadqiqot doirasida gaz va suyuqlikni tangensial yoʻnalishda kiritish orqali barqaror uyurmali rejimini va fazalararo kontakt yuzasini hamda yuqori turbulentligini taʼminlovchi eksperimental qurilma ishlab chiqildi va amaliy sinovdan oʻtkazildi. Olingan natijalar Nusselt va Reynolds mezonlari asosida, shuningdek bugʻlanish, kondensatsiya va havoning namlik miqdori oʻzgarishini hisobga oluvchi issiqlik balansi tenglamalari yordamida qayta ishlangan. Tajribalar Reynolds sonining keng diapazonida va turli L/G nisbatlarida olib borildi, bu esa issiqlik uzatish jarayonidagi barqaror qonuniyatlarni aniqlash imkonini berdi.

Aniqlanishicha, gaz Reynolds soni 45360 dan 97253 gacha oshganda Nusselt soni 2300 dan 15700 gacha ortadi, bu esa turbulentligining sezilarli kuchayishi va fazalararo sirtning jadal yangilanishini koʻrsatadi. Sugʻorish zichligining ortishi suyuqlik yupqa qatlami tez yangilanishi va kontakt yuzasining kengayishi hisobiga issiqlik almashinuvini qoʻshimcha ravishda jadallashtiradi. Olingan natijalar energiya tejamkor uyurmali issiqlik almashinish apparatlari hamda nam gaz tozalash qurilmalarini loyihalash, optimallashtirish va mavjud sanoat qurilmalarini modernizatsiya qilishda qoʻllanishi mumkin.

Kalit soʻzlar: *kontakt issiqlik almashinish; uyurmali apparat; oqimning uyurmaviy harakati; bugʻlanishli sovitish; issiqlik oʻtkazish; Nyusselt soni; Reynolds soni; nam gaz tozalash.*

Introduction

The intensification of contact heat exchange processes is one of the key challenges in modern thermal power engineering, chemical technology, and environmental industries. In contemporary industrial systems, energy efficiency and environmental safety are no longer optional characteristics but mandatory design criteria. Enhancing heat transfer efficiency during the direct interaction of liquid–gas phases not only reduce energy consumption and decreases equipment dimensions but also significantly improves the efficiency of dust and gas cleaning processes based on evaporative cooling and condensation–diffusion mechanisms of impurity capture [1].

In recent decades, stricter environmental regulations and the global transition toward sustainable industrial development have stimulated research aimed at increasing the performance of gas-cleaning systems while minimizing operating costs. Contact heat exchange devices are widely applied in cooling towers, scrubbers, absorbers, and evaporative heat exchangers. Their effectiveness directly affects overall process stability, emission control efficiency, and operational reliability. Therefore, the study of intensification methods for such processes remains highly relevant.

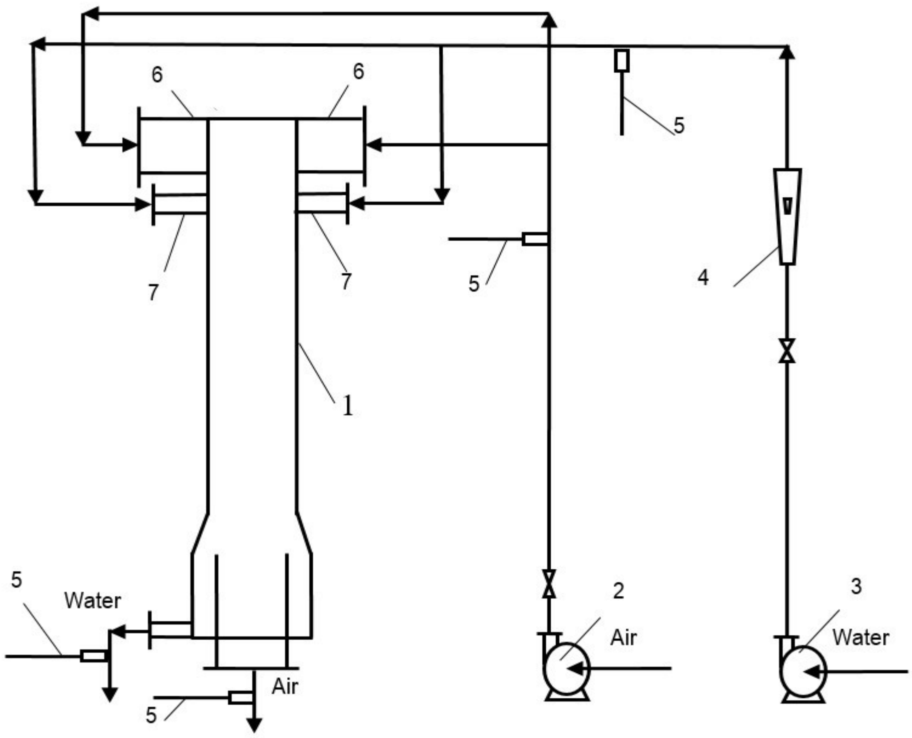
In wet gas-cleaning systems, heat and mass transfer occur simultaneously, and the intensity of these processes directly determines the degree of deposition of solid and gaseous contaminants. The mechanisms involved include convective heat transfer, phase transition due to evaporation and condensation, diffusion of vapor into the bulk gas, and inertial and diffusional deposition of particles. The higher the rate of renewal of the interfacial surface and the heat transfer coefficient, the more effective the condensation of vapors and the adsorption of particles on liquid droplets. As a result, the increase in contact surface area and turbulence level becomes a decisive factor in improving pollutant capture efficiency. Thus, the intensification of contact heat exchange is not only a thermotechnical but also an environmentally significant task that contributes to increasing the efficiency of waste gas purification [2].

From a thermodynamic standpoint, contact heat exchange involves complex nonequilibrium processes. The driving force for heat transfer is the temperature difference between interacting phases, whereas the driving force for mass transfer is the difference in partial vapor pressures. These processes are strongly interdependent: evaporation absorbs latent heat, thereby influencing the temperature field within the apparatus, while condensation releases latent heat, affecting local thermodynamic equilibrium. Consequently, a comprehensive understanding of coupled heat and mass transfer phenomena is essential for accurate modeling and optimization of contact devices [3].

Contact heat exchange is characterized by a complex interrelation between thermodynamic and hydrodynamic factors. When hot water interacts with cold air, heat transfer occurs both due to direct phase contact and as a result of liquid evaporation into the gas flow. In addition, micro-scale processes such as droplet fragmentation, coalescence, and film formation on internal surfaces further complicate the system behavior. The intensity of the process is determined by the water temperature, gas flow velocity, degree of turbulence, ratio of mass flow rates of the phases, as well as by the geometry and organization of the flows within the working volume of the apparatus [4].

The hydrodynamic regime plays a decisive role in determining contact efficiency. Laminar flows provide limited mixing and relatively small interfacial area, whereas turbulent flows enhance convective transport and promote intensive mixing between phases. The Reynolds number of the gas flow, Weber number for droplet breakup, and Froude number characterizing inertial forces all contribute to the formation of stable or unstable hydrodynamic structures inside the apparatus. Therefore, controlling the flow regime becomes a primary tool for intensifying heat transfer [13].

One of the most effective methods for intensifying contact heat exchange is the creation of vortex motion of the flows, which increases turbulence and ensures repeated renewal of the interfacial surface. Swirling flows generate centrifugal forces that redistribute droplets radially, increasing the residence time of phases within the contact zone. This phenomenon results in the formation of a highly developed interfacial area and promotes droplet dispersion. Vortex-type apparatuses form a highly developed contact zone, promote the dispersion of the liquid, and provide intensive heat and mass transfer at relatively low energy consumption [5].



1 – vortex contact heat exchanger;
2 – fan; 3 – pump; 4 – water flowmeter;
5 – temperature sensors; 6 – gas nozzles; 7 – liquid nozzles;
Fig. 1. Diagram of the experimental setup

Compared to traditional axial-flow contact devices, vortex apparatuses demonstrate improved mixing characteristics and higher volumetric heat transfer coefficients. The swirling of flows makes it possible to significantly increase the heat transfer coefficient compared to axial contact devices, which is especially important for evaporative cooling and simultaneous purification of gases from pollutants. Additionally, vortex configurations often exhibit lower hydraulic resistance per unit heat transfer area, making them attractive for industrial applications where energy consumption must be minimized.

This study is devoted to the investigation of the regularities of contact heat exchange during the direct interaction of liquid and gas flows in a vortex contact apparatus, the determination of the influence of operating and geometric factors on heat transfer intensity, and the substantiation of the role of heat and mass transfer in improving the efficiency of wet gas cleaning. Special attention is paid to the combined influence of gas velocity, liquid temperature, and swirl intensity on the resulting thermal performance. The results obtained can be used in the development of highly efficient next-generation vortex gas-cleaning devices and compact heat exchangers for energy-saving systems.

Materials and Methods

This work focuses on the intensification of heat transfer during air heating by hot water in a vortex-type heat exchanger. The selection of the air–water system is determined by its widespread industrial application and well-established thermophysical properties, which enable reliable experimental evaluation and comparison with theoretical models. A method for enhancing the heat transfer process was developed and investigated, based on swirling the gas flow through tangential injection. The underlying concept assumes that tangential inlet flow creates a stable rotational structure inside the apparatus, thereby increasing turbulence intensity and the frequency of contact surface renewal.

To study contact heat exchange in a vortex apparatus with a swirling gas flow, an experimental setup was designed and assembled (Fig. 1). The installation includes a vortex contact chamber, gas supply system, liquid circulation system, heating unit, measurement instruments, and control elements. The design ensures reproducibility of operating conditions and accurate measurement of thermal parameters.

Air is supplied by a high-pressure fan (model CZ 1500; capacity – 1530 m³/h, power – 1.5 kW, pressure – 2400 Pa) into the upper part of the contact heat exchanger through two tangential nozzles and then enters the working zone of the apparatus. The tangential orientation of the nozzles ensures the formation of a rotating gas flow inside the cylindrical chamber. The symmetrical arrangement of the nozzles contributes to the formation of a stable vortex core along the axis of the apparatus.

A frequency converter (ANDELI, 1.5 kW) was connected to the fan to regulate the air flow rate. This allowed smooth adjustment of gas velocity and ensured precise control over the hydrodynamic regime. By varying the rotational speed of the fan, different Reynolds numbers were achieved, enabling the investigation of both transitional and fully turbulent flow conditions.

The air velocity inside the apparatus was measured using a thermo-anemometer CEM DT-619 with a measurement period of 0.6 s and an accuracy of ±0.2 m/s. Measurements were carried out at several cross-sections along the height of the apparatus to assess velocity distribution and confirm vortex formation. Averaged values were calculated to reduce the influence of local fluctuations.

Cold water was pumped by a centrifugal pump (Q_{max} = 2.1 m³/h, P_{max} = 10 bar) from a storage tank into a heater, where it was heated to 61–63 °C. The selected temperature range ensured sufficient temperature difference between phases while preventing excessive evaporation losses. The heated water was then supplied to the upper part of the vortex apparatus through two tangential liquid swirlers. The co-directional injection of liquid and gas stabilized the rotational motion and minimized hydrodynamic disturbances.

The liquid flow rate was measured using a rotameter calibrated by the volumetric method. Calibration was performed prior to the experimental campaign to reduce systematic errors. The uncertainty in liquid flow measurement did not exceed ±3%.

Temperatures of air and water at the inlet and outlet were measured using resistance thermometers W1209 (range: −50 °C to 110 °C; accuracy: 0.1 °C). Sensors were installed in thermally insulated sleeves to minimize external heat influence. The relative humidity of air was measured with a humidity meter ADA-ZHT-100 (range: 0–99.9%; accuracy: ±3%). Monitoring humidity allowed indirect evaluation of evaporation intensity and mass transfer rate.

To ensure hydrodynamic stability, both gas and liquid were introduced tangentially in the same rotational direction. Counter-rotation was avoided because preliminary tests showed unstable vortex formation and reduced heat transfer efficiency under such conditions.

Each experimental condition was repeated at least five times. Statistical processing of results included calculation of mean values and standard deviations. The reproducibility of data confirmed reliability of the obtained results. Initial operating parameters corresponded to data presented in source [2], ensuring methodological continuity with previous studies.

Overall, the developed experimental methodology made it possible to systematically evaluate the influence of flow velocity, temperature difference, and swirl intensity on the heat transfer coefficient. The approach provides a reliable foundation for further scaling of vortex contact apparatuses to industrial applications.

1. The procedure for processing the experimental data to study the intensity of contact heat and mass transfer in the vortex apparatus is presented below.

$$\mathrm{Nu}=\frac{K_T D}{\lambda} \quad (1)$$

where K_T - coefficient of heat transfer from liquid to gas, W/(m²·K);

D - diameter of the vortex apparatus, m;

λ -thermal conductivity coefficient gas, W/(m·K).

2. The obtained experimental data results in the contact vortex apparatus are generalized in the form of empirical equations:

- by heat exchange [4]

$$\mathrm{Nu}=A\mathrm{Re}_Г^n \mathrm{Re}_Ж^m (L/G)^z \mathrm{Pr}_Г^c \quad (2)$$

3. Reynolds criterion for air [5]:

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

where w_0 is the average axial velocity of gas in the working chamber of the vortex apparatus, m/s;

D - diameter of the vortex apparatus, m;

$\rho_Г$ - air density, kg/m³;

μ -viscosity environment, Pa·s or kg/(m·s).

4. Reynolds criteria for liquid film [5]:

$$\mathrm{Re}=\frac{4Г}{\mu} \quad (4)$$

where $Г$ is the irrigation density, kg/(m·s);

μ - dynamic viscosity water, Pa·s .

5. Moisture content of air kg moisture/kg at the inlet and $x_н x_к$ at the output of the device [11]:

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

where $\varphi_н$ and - accordingly, the relative humidity of the air at the input and output of the apparatus, %; $P_{н.н}$ and $P_{н.к}$ - respectively, the pressure of saturated water vapor at the input and output of the apparatus, Pa; $P_б$ - barometric pressure, $P_б$ =101300 Pa.

6. Saturated water vapor pressure at the entrance and exit of the apparatus in the air were determined by the equation [6]:

$$P_{Н.Н}=1000e^{\frac{16{,}57t_{ГН}-155{,}72}{233{,}77+0{,}997t_{ГН}}},\quad P_{Н.К}=1000e^{\frac{16{,}57t_{ГК}-155{,}72}{233{,}77+0{,}997t_{ГК}}} \quad (6)$$

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

7. The heat balance equation for a vortex contact apparatus has the form [7]:

$$GI_н+L_нH_н=GI_к+L_кH_к+Q_п \quad (7)$$

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

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

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

$GI_к$ - 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.

8. 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 [7]:

$$I_Н=(1007+1970\cdot x_Н)\cdot t_{ГН}+r_Н x_Н \quad I_К=(1007+1970\cdot x_К)\cdot t_{ГК}+r_К x_К \quad (8)$$

where $r_н$ and $r_к$ - 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, ⁰C .

9. The specific heat of vaporization was $r_н$ and $r_к$ determined using the equation [8]:

$$r_Н=1000\cdot(2501-2{,}36\cdot t_{ГН}) \quad r_К=1000\cdot(2501-2{,}36\cdot t_{ГК}) \quad (9)$$

10. The enthalpy of water at the inlet and outlet of the apparatus was determined using the equation *H*, J/kg [9]:

$$H_Н=T_{ЖН}\cdot c_Н \qquad H_К=T_{ЖК}\cdot c_К \quad (10)$$

where $c_н$, $c_к$, $T_{жн}$ *and* $T_{жк}$ - is the heat capacity of water at temperatures, J/(kgK);

$T_{жн}$ *and* $T_{жк}$ - water temperature at the input and output of the apparatus, ⁰C;

11. The heat transferred from water to air was determined from equation (4.9) [9]:

$$Q=G(I_К-I_Н) \quad (11)$$

$$Q=L_Н H_Н-L_К H_К \quad (12)$$

12. The total amount of heat transferred from hot water to air is determined by the formula [9]:

$$Q=Q_{ис}+Q_{con}+Q_{п} \qquad (13)$$

Where $Q_{ис}$=Mr - heat transferred by evaporation of water into the air, W; Q_{con} - heat of contact of water with air, W; $Q_{п}$ - heat loss to the environment, W.

13. The intensity of heat exchange is estimated by surface heat transfer coefficients [9]:

$$K_т=\frac{Q}{F_{an}\cdot\Delta t_{cp}} \qquad (14)$$

where Q is the amount of heat, W; F_{an} =πDH – area of the internal surface of the apparatus, m²; Δt_{cp} - average temperature difference in the apparatus, °C.

14. The average driving force Δtcp was calculated using the equation [9]:

$$\Delta t_{cp}=\frac{(T_{жн}-t_{гн})-(T_{жк}-t_{гк})}{\ln(T_{жн}-t_{гн})/(T_{жк}-t_{гк})} \qquad (15)$$

$T_{жн}$ and $T_{жк}$ are the temperatures of the water at the inlet and outlet of the apparatus, °C; $t_{гн}$ and $t_{гк}$ - air temperatures at the inlet and outlet of the apparatus, °C.

Results

The results of experiments on the intensity of heat transfer in a vortex apparatus during water cooling with air are shown in Fig. 2 in the form of a dependence of the Nusselt criterion on the Reynolds criterion for a gas flow at different ratios of the mass flow rates of liquid and gas L/G.

Experimental results showed that the higher the gas flow velocity and spray density, the higher the heat transfer intensity. This pattern of change in heat transfer intensity is explained by increased flow turbulence and the emergence of relative velocities between the liquid and gas, which facilitates rapid renewal of the water film surface, leading to an increase in the driving force of the heat transfer process and, consequently, the efficiency of water cooling.

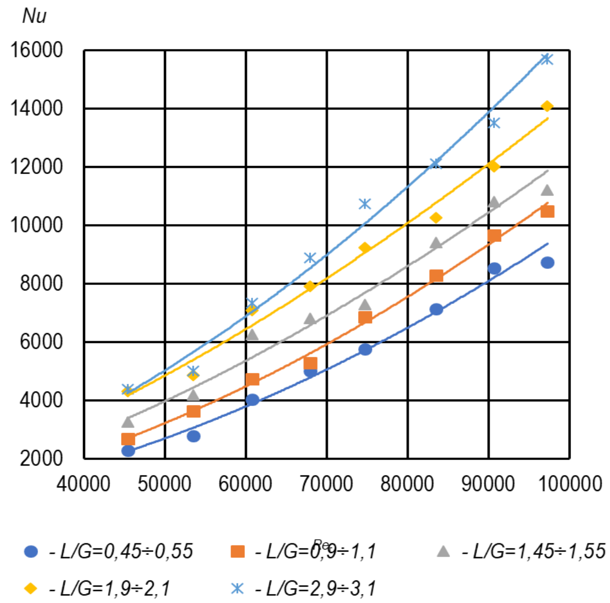


Fig. 2. Dependence of the Nusselt criterion Nu on the Reynolds criterion of gas Rer for different ratios of liquid and gas mass flow rates *L/G*

From Figure 2 it can be seen that with increasing Reynolds number of gas from 45360 to 97253 the Nusselt number increases from 2300 to 15700.

Processing of experimental data in the form of a dependence of the heat transfer coefficient on the ratio of the mass flow rates of liquid and gas showed an increase in the intensity of heat transfer with an increase in the irrigation density (Fig. 3).

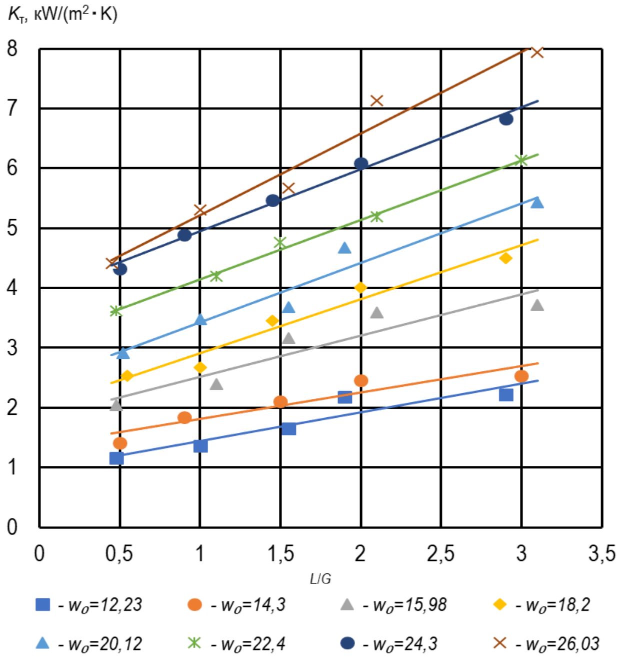


Fig. 3. Dependence of the heat transfer coefficient K_T on the ratio of mass flow rates of liquid and gas L/G at different gas velocities w0

From the experimental material examined it follows that the swirling of gas and liquid flows leads to a significant intensification of heat exchange during evaporative cooling of the liquid.

Conclusion

Experimental studies have demonstrated that an increase in gas flow velocity together with a higher spray density results in a pronounced intensification of heat transfer in a vortex device. In particular, it was established that as the Reynolds number increases from 45,360 to 97,253, the corresponding Nusselt number rises sharply from 2,300 to 15,700. This substantial growth reflects the development of a highly turbulent flow regime and the effective continuous renewal of the phase contact surface, which enhances convective heat exchange.

In addition, an increase in the liquid-to-gas mass flow ratio has a positive effect on the heat transfer coefficient. This effect is associated with improved dispersion of the liquid phase into fine droplets and a significant expansion of the interfacial surface area available for heat and mass transfer. More uniform distribution of the liquid within the gas stream further promotes efficient thermal interaction between the phases.

The swirling of both gas and liquid flows plays a crucial role in establishing and maintaining a stable vortex regime. Such a flow structure intensifies mixing, suppresses flow stratification, and ensures sustained turbulence throughout the working volume of the device. As a result, heat transfer is significantly intensified, while the efficiency of dust and gas cleaning processes is markedly improved due to enhanced contact between the dispersed liquid phase and contaminant particles.

References:

1.Bakhronov, H. Sh., Levdansky, A. E., & Akhmatov, A. A. (2023). Efficiency of using vortex devices for carrying out hydrodynamic, heat and mass transfer processes [Monograph, 210 pp.]. Navoi: Science Algorithm Publishing House. ISBN 978-9910-774-52-2.

2.Akhmatov, A. A. (2021). Intensification of mass transfer in the gas–liquid medium of a vortex apparatus. Development of Science, 1, 409 –417.

3.Bezrodny, M. K., Goliyad, N. N., Barabash, P. A., & Kostyuk, A. P. (2012). Interphase heat-and-mass transfer in a flowing bubbling layer. Thermal Engineering, 59(6), 479–484.

4.Barabash, P., Solomakha, A., & Sereda, V. (2020). Experimental investigation of heat and mass transfer characteristics in direct contact exchanger. International Journal of Heat and Mass Transfer, 162, Article 120359. 1-8.

5.Shilyaev, M. I., & Tolstykh, A. V. (2013). Simulation of heat and mass exchange in foam apparatus at high moisture content in vapor–gas mixture. Theoretical Foundations of Chemical Engineering, 47(2), 165–174.

6.Lapteva, E. A., & Laptev, A. G. (2016). Models and calculations of the effectiveness of gas and liquid cooling in foam and filter apparatuses. Theoretical Foundations of Chemical Engineering, 50(4), 430–438.

7.Akhmatov, A. A. (2025). Efficiency of using a hollow apparatus for cooling gases. Journal of Advances in Engineering Technology, 6(18), 10–13.

8.Alekseev, V. V., Lukin, V. O., & Ponikarov, I. I. (2013). Study of hydraulic resistance of a vortex-type apparatus for complex gas purification. Bulletin of the Kazan Technological University, (7), 529–537.

9.Kharkov, V. V. (2020). Hydrodynamics and heat and mass transfer in a vortex chamber for concentrating thermolabile solutions. Theoretical Foundations of Chemical Engineering, 53(6), 972-983.

10.Anufriev, I. S., Kuznetsov, G. V., Shadrin, E. Y., Sharypov, O. V., Anikin, Y. A., Dvoynishnikov, S. V., Kulikov, D. V., & Rakhmanov, V. V. (2013). Study of vortex flow structure in a new type of combustion chamber using digital tracer visualization. Izvestiya Tomsk Polytechnic University [Izvestiya TPU], 322(4), 31–35.

11.Skorodumov, A. P., & Shershnev, B. B. (2006). Heat transfer in a smooth pipe with a ribbon swirler. ANSYS Advantage RUS, (2). 41-49.

12.Sarantsev, V. F. (2020). Vortex-sieve contact device of a heat and mass transfer apparatus (Electronic patent RU200612U1).

13.Karimov, K. (2023). Improvement of heat exchangers and refrigeration machines (Catalog of Abstracts, 1(1), pp. 1–85).

14.Zhu, S., Li, L., Hu, Z., et al. (2024). Investigations of thermohydraulic performance in heat exchanger tube with rectangular vortex generators. Thermal Science, 28(4), 2917–2928.