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Research in the Efficiency of a Vortex Apparatus for Evaporative Cooling solution of Rock

Oybek Tuyboyov Valijonovich, Khoshim Bakhranov Shayimovich

Abstract— In the present work the feasibility and effectiveness of the vortex apparatus used for evaporative cooling of foaming solution of rock is investigated by studying the results of experimentations. Today, the relationship between the vortex structure parameters and characteristics of heat and mass transfer remains very poorly understood. The objective of experimental research we carried out was to determine the capabilities and efficiency of evaporative cooling of foaming pulp of rock. It was also observed that the the method of evaporative cooling of the pulp by air can reduce the pulp temperature significantly. The effectiveness of the use of a vortex apparatus during the process of evaporative cooling can also be defined by the values of volumetric heat transfer coefficient K_v and efficiency η. It was observed that by increasing the air velocity the value of K_v increases significantly. Thus the experimental studies have confirmed that the pulp can be cooled by air using the method of evaporative cooling. The research allowed to establish that at the swirling flow when the Reynolds number is increased to a high value, the volumetric heat transfer coefficient increases about forty times as compared with the values for the untwisted flow which means a significant intensification of the processes of heat and mass transfer occurs due to its acceleration, no less turbulization of the jet, with the emergence of properly alternating vortices etc.

Index Terms— vortex apparatus, evaporative cooling, pulp of rock, effectiveness, heat transfer coefficient, thermal efficiency, reynolds number, swirling flow, intensification, heat and mass transfer, turbulization of jet, alternativng vortices, absorption, distillation etc.

1 Introduction

The present work shows the results of experimental studies on determination of feasibility and effectiveness of the vortex apparatus for evaporative cooling of foaming solution of rock. Semi-industrial pilot plant was developed to complete set tasks and experimental studies have been conducted. It has been identified that an efficiency of the use of a vortex unit at evaporative cooling of fluid through intensification of heat transfer rate, as well as heat and temperature indications. On the basis of the research, at a minimal consumption of air for evaporative fluid cooling, industrial design of the vortex apparatus and engineering methods of calculation have been created.

Production of metallurgical, chemical, oil and energy industries are in great demand, which requires an increase in productivity and quality. The main focus of technical development is the creation of new and improvement of existing facilities. An increase in performance of the standard heat and mass transfer and other devices is possible only by increasing their diameter or supply them with additional elements, which leads to a sharp increase in their weight and metal content, complicates the manufacture, transportation and installation. An increase in the flow rate of the carrier in the gas-liquid countercurrent apparatus with the value above the limit (1- 2 m / s) leads to the development of intense entrainment of liquid and apparatus repletion.

Finding ways of intensification of heat and mass transfer in gas-liquid systems led to the development and introduction of fundamentally new devices with direct-contact eddy devices, regular nozzles of increased bandwidth, etc.

Development of scientific bases of creation of new vortex technologies for intensification of heat and mass transfer processes is an important and urgent task. Organization of intense vortex motion can meet the challenges of energy efficiency and reduction of material consumption of technological installations and devices. The efficiency of technological devices with a twist flow are significantly associated with the generation of concentrated helical (spiral) vortices. However, today, the relationship between the vortex structure parameters and characteristics of heat and mass transfer remains very poorly understood. Among the particularly complex hydrodynamic objects and at the same time the most effective for heat and mass transfer are thin liquid pellicle, characterized by the presence of highly nonlinear waves and a strong local vortex formation. Currently, different application of swirling flow and vortex technology surpasses the process of their detailed research.

- *Oybek Tuyboyov Valijonovich is currently a Senior Researcher in Novai State Mining Institute, Uzbekistan, E-mail: tuybo@list.ru*
- *Khoshim Bakhranov Shayimovich is currently an advisor in Department of Chemical Technology, Novai State Mining Institute, E-mail: bahronav@mail.ru*

2 Experiments

The objective of experimental research we carried out was to determine the capabilities and efficiency of evaporative cooling of foaming pulp of rock. There were doubts that foaming occurs when rock solution contact s with the air and consequently further processing of the pulp deteriorates. Because of a possibility of foaming of being cooled liquid and its high efficiency, vortex (centrifugal) apparatus for the evaporative cooling of the pulp was selected. In the process of development of highly efficient designs of vortex devices for hydrodynamic and heat and mass transfer processes in the systems of gas-liquid, gas-liquid-solid there have been engaged employees of the Navoi State Mining Institute. Studies involving complex fluids with rheological properties, such as rock pulps, by vortex devices were not previously performed.

The experimental setup created in the metallurgical manufacture is shown in Fig. 1. Its main component was an ordinary steel pipe with a diameter of D = 0.2 m with two tangential ports of a rectangular section welded on the top of it. The pipelines pulp and air are taken to the installing. The unit was equipped with modern instrumentation. The temperature of heat carriers at the inlet to the working unit and the output from it were measured by resistance thermometers of the brand TR 10, with a measuring range of 0 ... 100º C. In order to measure the air flow a vortex flowmeter of the brand Prowirl 200, with a measuring range of 0 ... 12,000 m3 / h was used. All measuring sensors were connected to a computer. Consumption of the pulp was determined volumetrically. Humidity is measured by an aspiration psychrometer.

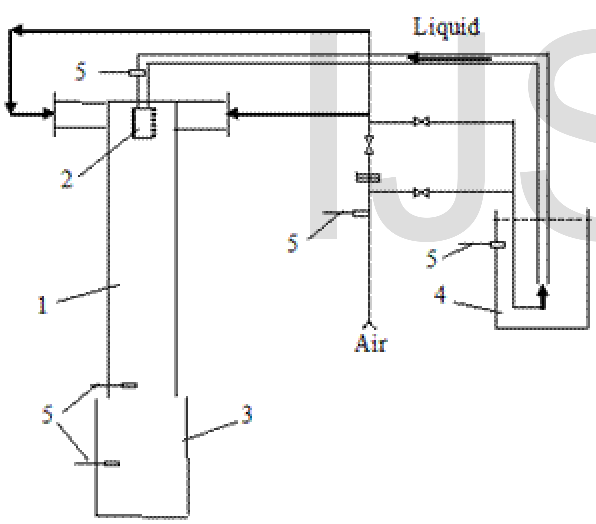

Fig. 1. The experimental setup scheme:
1-pole heat exchanger; 2-spray-swirl device; 3-dimensional receptacle; 4-fluid container; 5-sensor; 6 air-flow meter;

Measuring the temperature of the inner wall of the pipe was carried out in four sections arranged at equal intervals along the height of the tube and at three points in each section. Hot junctions of the thermocouples were made in the form of small beads which tightly pressed against its inner wall inside the tube by the means of small springs. The ends of the thermocouples were taken outside along center of the pipe. Errors in temperature measurement due to heat removal from the wires extending from the hot junction thermometer as well as local flow disturbances by the last ones, were evaluated by comparison with the indications of a special thermocouple staked into the wall and isothermal sections of wire extending from it. Last ones are placed and secured with a special refractory insulating composition in the grooves is flush with the inner wall of the pipe. The difference in the indications of these types of thermocouples in conditions which occurred in the experiments a relatively small difference between the wall temperature and flowing around it air flow, as well as through the adoption of special measures was insignificant. In this regard, in most cases, this difference was not considered. The thermocouples were made of thin wires with a diameter of 0.2 mm and a heat-insulating feature was provided by thin asbestos wires, what is more, a special attention was paid to ensuring sustainable size of balls of thermocouples and their tight fit to the wall.

To study the heat and mass transfer to the inner surface of the vortex tube a thin liquid pellicle was created. For this purpose from the nozzle, placed at the center of the swirler the liquid was spread. Its drops, reaching a rotating stream by centrifugal force were discarded to the pipe wall, forming there a liquid layer. This layer was later caught by the flow of air along a helical path with a definite step in the direction of the outlet section. The best conditions for continuous pellicles at a minimum waste of liquid are created in the case where the total height of the gap is equal to or even slightly exceeds the step of the swirling jet.

It should be noted that to obtain a continuous thin pellicle on the entire inner surface of the tube, as well as the ability to conduct visual observation through the window sufficiently clean processing of the internal surfaces of the swirler parts were required. Otherwise, the local flow disturbances caused by poorly streamlined irregularities violated the uniformity of the pellicle, throwing liquid at the inspection window, making it difficult to observe.

All specifications required for the value of the heat exchange process were measured upon reaching steady state, which was installed in 10-15 minutes after changing the heat carriers flow rate.

The pulp is fed to the installation via airlift. The installation scheme allowed a selection of the air for airlift, from the air tubes as when to the flowmeter, and after it.

Before turning to a discussion of the results it makes sense to focus on the physical nature of the process of evaporative cooling.

When the temperature of the liquid (here is the water) is over the temperature (the usual case), the heat transfer through evaporation and contact (conduction and convection) is directed in one direction - from water to air. The amount of heat given off by liquid, in this case would be

$$Q = Q\alpha + Q\beta$$

where Q - the resulting amount of heat; Qα - the amount of heat transferred by convection (resistance of liquid and gas); Qβ - the amount of heat transferred through evaporation.

When the air temperature exceeds the temperature of the fluid, the heat flow Qα is directed from the air to the liquid. While heat Qβ, fluid lost due to its surface evaporation is greater than the heat provision to Qα the resulting heat flow is directed from the water to air, i.e. E. Q = Qβ-Qα, and the fluid temperature will drop.

This occurs as long as the flow Qα directed from the air to water does not become equal to losses of water heat occurred due to an evaporation Qβ. The equality Qα = Qβ is achieved when the water temperature T becomes equal to the temperature of free air at a wet bulb Tm. The balance has a dynamic nature, since no evaporation of water or the supply of heat to it from the air at Qα = Qβ and T = Tm can be suspended [1].

The quantitative relationship between heat transfer by contact and heat transfer evaporation at different temperatures of water can be represented by the curve in the graph Q = f (T) at given clear atmospheric conditions.

It should be noted that most of the heat is extracted from the fluid by evaporation, especially at its temperature T which is substantially greater than $t_м$ [1]. Thus, with an increase in fluid temperature the overall heat losses rises and heat transfer by evaporation increases much faster than the heat transfer by contact. As a result, in the overall heat losses, heat transfer by evaporation predominates.

3 Methods

The analysis of the experimental data is characterized by the following parameters.

1. The mass flow rate of the pulp, kg/s:

$$G_п=V_п \cdot \varrho_п \qquad (1)$$

2. Thermal pressure of the apparatus, W:

$$Q_п=G_п c_п(T_1-T_2) \text{ or } Q_п=G_п c_п(T_{cp}-T_2) \qquad (2)$$

3. The volumetric coefficient of heat transfer, W/(m³·K):

$$K_v=Q/(V_{ап} \cdot \Delta t_{cp}) \qquad (3)$$

4. The efficiency ratio of evaporative cooling apparatus [2]:

$$\eta= (T_1-T_2)/ (T_1-t_м) \qquad (4)$$

In these equations $V_п$ - volumetric flow of the pulp in m3 / s; $\varrho_п$ - density of the pulp, kg / $м^3$; $c_п$ - specific heat capacity of the pulp, J / (kg • K); T1, T2 and T_{cp} - pulp temperatures at the inlet to the airlift, at the outlet of the vortex device and the temperature of the pulp between the airlift device and vortex respectively; $V_{ап}$ = 0.06 $м^3$ - volume of the device; Δt_{cp} - average temperature difference in the device, ° C; $t_м$ - air temperature by the wet bulb, w - air speed, m / s.

The partial pressure at the surface of the pellicle was assumed as equal to the pressure of saturated steam at the average liquid temperature of the pellicle thickness shown by the placed there the hot junctions of thermocouples. Temperature variation across the pellicle sparked by a heat flow in the axial direction of the pipe wall, as well as indication errors used in the experimental surfaces of thermocouples caused by a thermal resistance of the contact zone and the heat removal by electrodes conduction was neglected due to the insignificance of the studied conditions (so, the pellicle had a initial thickness of no more than 0.3-0.4 mm and under the action of centrifugal forces and large shear stresses on the free surface intensively moved in the radial direction; due to a high intensity of the heat and mass transfer process the pellicle temperature differed slightly from the flow temperature, etc.)

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4 RESULTS

The completed work permitted to evaluate the possibility of air-cooling of the pulp and the effectiveness of the investigated vortex apparatus. The intensity of the process of evaporative cooling of the pulp can be estimated using the measured temperature of heat carriers. It should be noted that at the certain loses of environments the method of evaporative cooling of the pulp by air can reduce the pulp temperature from 74,4ºC to 26,6ºC.

The effectiveness of the use of a vortex apparatus during the process of evaporative cooling can also be defined

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by the values of volumetric heat transfer coefficient K_V and efficiency η . As it is seen in Figure 2 values of K_V increased with the rise of air velocity up to 130,000 W / ($м^3$· K). Note that the value of this coefficient for conventional vehicles with an axial air flow does not exceed 5000 W / (м3· K).Thus, our experimental studies have confirmed that the pulp can be cooled by air using the method of evaporative cooling

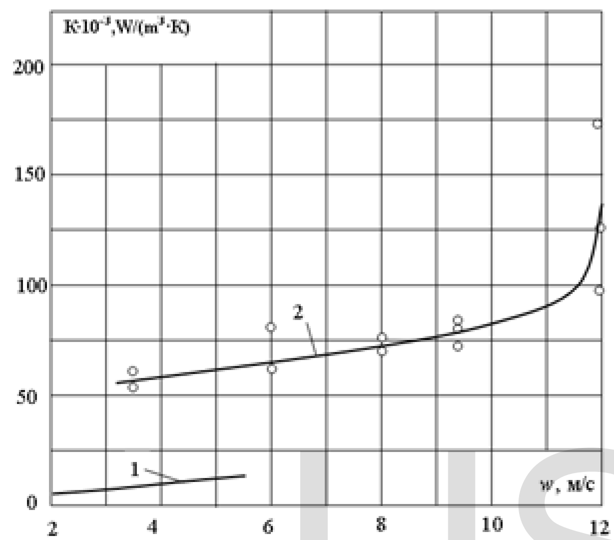

Fig. 2. Dependence of the resulting volumetric heat transfer coefficient on the air velocity:
1 - in the apparatus with the axial flow gas; 2 - in the device with the swirling gas flow.

An important parameter of evaporative cooling of liquids operation is a relative airflow $\lambda = G_{вз}/G_{п}$, where $G_{вз}$ - mass flow rate of the pulp, kg / s. For most evaporative coolers it is in the range from 0.5 to 2. Fig. 3 demonstrates the dependence of the efficiency ratio of vortex and axial devices of evaporative cooling on the relative airflow. The graph shows a rapid growth of the heat efficiency by liquid for the vortex apparatus up to the values of the relative airflow equal to 0.88 and for axial apparatus at λ <0,5.

It should be noted that the temperature difference between the hot and the cooled liquid (a decrease in the liquid temperature), which is called the width of the cooling zone (in some literature it is a cooling depth) for the vortex apparatus is equal to 47, 8ºS and for the axial apparatus 20 ° C.

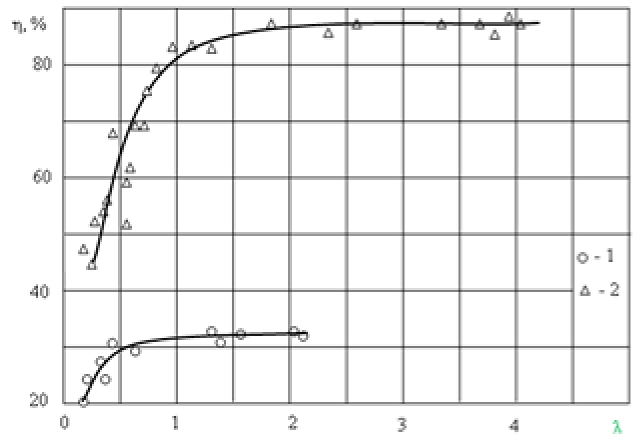

Fig. 3. The dependence of the heat efficiency ratio on the relative airflow:
1-axis apparatus; 2 - vortex apparatus.

Thus, the studied uniflow vortex devices superior apparatus with the axial flow of heat carriers by 2.5-2.8 times on thermal efficiency and up to seven times in performance. The degree of heat and mass transfer intensification by means of spin flow most conveniently can be expressed as a dependence of the volumetric heat transfer coefficient for swirling $K_з$ and the axial flow K_o on the ratio of a cross-sectional area of the pipe and inlet slits (Fig. 4). It can be seen that the intensity of heat and mass transfer with the twist of flow with a increased ratio of $F_т/F_щ$ first increases and then remains constant. The reason for this is the increasing influence of the factor of the damping twist: the narrow twisted jets that correspond to large values of the ratio of $F_т/F_щ$, more strongly intensifying heat and mass lose at the initial section of the tube, due to the relatively greater exposure to friction decay quicker and simultaneously.

The data given in figure 4 show that using twist flow can provide a significant intensification of heat and mass transfer when the liquid evaporates. For the investigated pipe in the range of changes of relationships of the pipe and swirlers cross-sections from 4 to 18, the intensity of heat and mass transfer, when twisted, increases by eleven times with a tendency to a further growth providing an increase in the ratio of $F_т/F_щ$.

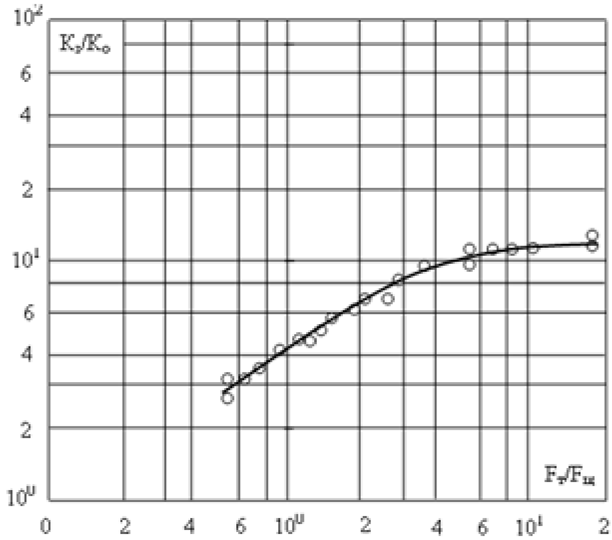

Fig. 4. The dependence of the efficiency degree of a twist $K_э/K_o$ on the ratio of cross-sectional areas of the pipe and the input slits.

5 Discussion

In the presence of both continuous and stable pellicle on the entire inner surface of each being studied vortex tube with the given geometrical characteristics and relative lengths and for each mode, characterized by definite values of the heat flux through the wall, the liquid and gas flow, their initial parameters, on the basis of this experimental data curves of the temperature of the being evaporated liquid pellicle along the tube has been constructed.

The known experimental data relates to cooling via liquid pellicles of a considerable thickness, obtained by supplying fluid through the slits. With this method of cooling a large part of the liquid is entrained by gases as a result of a mechanical pluck (erosion) from the surface of the pellicle. Therefore, the actual flow rate is considerably higher than required for cooling the wall only by evaporation.

6 Conclusion

The research allowed to establish that at the swirling flow when the Reynolds number is changed in the range from 19600 to 157000 a volumetric heat transfer coefficient increases to forty times as compared with the values for the untwisted flow which indicates a significant intensification of the processes of heat and mass transfer. A significant intensification of mass transfer when the flow is twisted is notable not only due to its acceleration, but also no less turbulization of the jet under the influence of centrifugal forces, accompanied by the emergence of properly alternating vortices.

The studied process can have a varied number of technical applications and it can in particular be very effective in the use of gas cooling, mass transfer (absorption, distillation, etc.) and chemical processes.

7 Adoption

The carried out investigations have confirmed that the intensity of the heat and mass transfer with the twist of the flow increases enormously. The studied uniflow vortex devices surpass the machines with axial flow of heat carriers by 2.5-2.8 times at the thermal efficiency and up to seven times at the performance.

Thus, the pellicle heat and mass transfer devices that use the most economically advantageous degree of twist flow, under identical conditions of the process allow more intensive heat and mass transfer per volume unit than the most currently known advanced - tray columns.

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