Regenerative air heat exchanger with intermediate heat carrier

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Abstract. The results of physical and mathematical modeling of a new air heat exchanger with an intermediate heat carrier and with drip irrigation of granular layer are presented. The effects of the equivalent diameter of the granules, height of the layer and the heat transfer coefficient on the thermal effectiveness of the heat exchanger are analyzed. The results of an experimental study of the uniformity of the distribution of the heat carrier in the tower cross-section for various methods of granular layer irrigation are presented.

1. Introduction
Requirements for heating and ventilation systems are constantly raising due to improvement of thermal protection characteristics of building envelopes and increase of their impermeability [1]. Experience in the operation of multi-apartment and low-rise residential buildings shows that energy costs for heating and cooling of ventilation air can reach up to 50% of total energy consumption [2]. At present time the ventilation systems are widely used in conjunction with heat recovery systems. In such systems, heat exchangers of various types are used for this. Air-to-air heat exchangers with an intermediate heat carrier can be singled out as a separate group of apparatuses [3]. The main advantage of such devices is that they allow spatially dividing the places of input and output of ventilation air. This simplifies the use of mechanical ventilation systems. The results of physical and mathematical modeling of a new air heat exchanger with an intermediate heat carrier and with drip irrigation of granular layer are presented in the paper.

2. Results of numerical simulation
Figure 1 shows a scheme of the heat exchanger. The main elements of the construction are scrubbers (towers with a granular layer). Despite of widespread use of scrubber processes they are still insufficiently studied. A heat exchange unit for heating and cooling ventilation air can be obtained by combining two towers with a granular layer by means of an intermediate heat carrier. Advantages of this type of heat exchanger are the absence of freezing, low losses of air pressure and the possibility of spatially dividing the places of input and output of ventilation air.

Such heat regenerators are new, and therefore in the literature there is limited information on such devices. The physical and mathematical model was developed and earlier described in [4]. The base of the model is a concept about counterflow interpenetrating continua of the liquid and gaseous phases, which exchanging heat on interfacial surface and pass through each other without mixing. In this case, the interfacial surface is formed on a solid base, which is the surface of the granular layer.
Figure 1. The scheme of an air heat exchanger with an intermediate carrier:
1, 2 – towers; 3 – grates; 4 – granular layer; 5, 6 – sprinkler; 7, 8 – pipelines, 9, 10 – air fans; 11, 12 – water pumps.

Suppose that expanded clay gravel is a material for backfilling of towers, and an aqueous solution of calcium chloride is the intermediate heat carrier. The following values will be used for materials: $\rho_a = 1.27 \text{ kg/m}^3$ is the density of air, $c_a = 1005 \text{ J/(kg K)}$ is the specific heat capacity of air; $\rho_e = 400 \text{ kg/m}^3$ is the density expanded clay gravel, $c_e = 840 \text{ J/(kg K)}$ is the specific heat capacity of expanded clay gravel; $\rho_w = 1280 \text{ kg/m}^3$ is the density of the aqueous solution of calcium chloride, $c_w = 2760 \text{ J/(kg K)}$ is the specific heat capacity of the aqueous solution of the calcium chloride.

Parameters of backfilling of expanded clay gravel: $d = 0.0125 \text{ m}$ is average diameter of the granules; $\Phi = 0.9$ is the form factor; $\varepsilon = 0.42$ is the porosity of granular layer; $A = 0.04 \text{ m}^2$ is the frontal area of the tower; $H = 0.4 \text{ m}$ is the layer height, $M = 70 \text{ kg}$ is the mass of the gravel in the layers; $G_e = 0.04 \text{ m}^3/\text{h}$ is the volume flow rate of the intermediate heat carrier; $G_a = 110 \text{ m}^3/\text{h}$ is the volume flow rate of air; $h = 100 \mu\text{m}$ is the thickness of a liquid film on the interfacial surface; $\alpha = 13 \text{ W/(m}^2\text{ K)}$ is the heat transfer coefficient on the interfacial surface; $T_{\text{in}} = +25\degree\text{C}$ is the indoor temperature; $T_{\text{ex}} = -12\degree\text{C}$ is the outdoor temperature.

The efficiency of heat exchange processes in each of the heat exchange columns can be characterized by its own value of the temperature effectiveness. The temperature effectiveness of the heating and cooling columns is denoted by $\Theta_1$ and $\Theta_2$, and is determined according to the expressions:

$$\Theta_1 = \frac{T_{\text{sup}} - T_{\text{out}}}{T_{\text{in}} - T_{\text{out}}}, \quad \Theta_2 = \frac{T_{\text{in}} - T_{\text{ex}}}{T_{\text{in}} - T_{\text{out}}}.$$  

where $T_{\text{sup}}$ – the supply air temperature, $T_{\text{out}}$ – the outdoor air temperature, $T_{\text{in}}$ – the indoor air temperature, $T_{\text{ex}}$ – the exhaust air temperature.

Without taking into account evaporation processes the equilibrium values of the temperature effectiveness of the towers is equal if the towers have the same construction and if the mass flow rates of the both the liquid and the air are equal. A typical behavior of the temperature efficiency of regenerator towers with stabilization at equilibrium is shown in Figure 2. The equilibrium value is the temperature effectiveness of the regenerator $\Theta = \Theta_1 = \Theta_2$. 


Figure 2. The temperature effectiveness of the heating and cooling towers as function of time.

Figure 3. Temperature effectiveness as function of the height of the layer of the expanded clay gravel.

According to computations, an increase in the height of the backfill $H$ resulted in an increase in effectiveness (figure 3). This is due to the increase in the heat transfer area which depends on the height of the granular layer as $S = \alpha \sigma H$, where $\sigma$ is the specific surface of the filling. The value of $\sigma$ is related to the coefficient of the grain shape, its diameter $d$ and the porosity $\varepsilon$ by the following relationship:

$$\sigma = \frac{6 \cdot (1 - \varepsilon)}{\Phi \cdot d}.$$

It is obvious that the dimensions of the towers limit the height of the layers.

The smaller the diameter of the granules of gravel, the greater the temperature effectiveness at the condition when all other parameters are retained (figure 4). The rate of its growth increases with decreasing the diameter. The dependence of temperature effectiveness is due to an increase in the specific surface area of the backfill with a decrease in the grain diameter.

At increasing height of the layer or reducing the diameter of the granules, the increase in hydraulic losses should be taken into account. Calculations have shown that it is possible to increase the temperature effectiveness of the regenerator by intensifying the heat exchange processes between the liquid and air. Figure 5 shows the calculated temperature dependence of the effectiveness on the heat transfer coefficient.

Figure 6 shows the effect of liquid flow rate on effectiveness at a constant air flow through the columns of 110 m$^3$/h and a column height of 0.4 m. At the same time, in the investigated range of the
liquid flow rates, the temperature effectiveness first increased to the maximum value, and with a further increase of the flow rate, it decreased slightly. It is clearly seen in Figure 6 that the maximum temperature effectiveness value was observed at a liquid flow rate $G_w \approx 40 \text{l/h}$, which corresponds to the equality of heat capacity rate: $\rho_w G_w c_w = \rho_a G_a c_a$.

Figure 7 shows the calculated dependences of the effectiveness of the regenerator on the air volume flow through the towers for a flow rate of 40 liters/hour at different filling heights in the towers. The dependence of the effectiveness at each filling height had a maximum, and with increasing height the value of maximum efficiency increased, and the position of the maximum approached its value at the air flow, obtained from the equality of the water equivalents of air and water. With a decrease in the height of the backfill, the heat exchange surface was reduced, the maximum value decreased and its position shifted toward lower airflow through the towers.

To carry out experiments on optimization of the irrigation system, a stand was assembled. The scheme of the stand is shown in figure 8. In experiments, water was fed through a sprinkler at a flow rate of 20-60 l/hr to the surface of a gravel layer with a fractional composition of 5-7 mm. Water flowed down through the layer into the receiving chamber, which was divided into rectangular cells 80 $\times$ 80 mm and 50 mm high. The experiments were stopped when one of the cells was completely filled,
after which the height of the water level in each cell was measured. Four variants of sprinkler installation were investigated: an uniform channel (figure 9a), radial-ray (figure 9b), uniform-channel and peripheral (figure 9c), radial-ray and peripheral. With the use of a cellular receiving chamber, an unbiased estimation of the sampling variance [5] of the irrigation uniformity was determined for different flow rates and for different irrigation systems (figure 10).

As demonstrated by the experimental studies, the uniformity of the distribution of the heat carrier over the surface of the gravel is an important parameter of the heat exchanger operation. Model experiments have been carried out to determine the uniformity of the distribution of the heat carrier under "radial-beam" and "uniformly-channel" irrigation systems, and also with additional "peripheral" irrigation. An unbiased sample variance [5] of the uniformity of irrigation at different liquid flow rates for different irrigation systems was determined using a cellular mesh receiver (figure 8):

\[ D^2 = \frac{1}{N-1} \sum_{i=1}^{N} (x_i - \bar{x})^2, \]

Figure 9. Irrigation system: a - uniform channel, b - radial-ray, c – peripheral.

Figure 10. Experimental dependence of the unbiased sample variance of the irrigation uniformity on the heat carrier flow rate: 1 - "evenly channel", 2 - radial-beam, 3 - radial-beam and "peripheral", 4 - "evenly channel" and "peripheral"
where $\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i$ is the sample mean, $x_i$ is height of the liquid level in the cellular mesh receiver, $N$ is number of the cellular mesh receiver.

According to the results of the experiments, the unbiased sample variance decreased with an increase in the heat carrier flow rate for all the investigated irrigation systems. This indicated an increase in the uniformity of the distribution of the heat carrier. The best uniformity was obtained for a "uniformly-channel" irrigation system in conjunction with "peripheral" irrigation.

3. Conclusions
The physical and mathematical model of the new air-to-air regenerative heat exchanger with an intermediate heat carrier for the premise ventilation has been tested. The possibility of a significant increase in efficiency with a reduction of the diameter of the granules is shown by analyzing the influence of various factors. As a result of the calculations it was found that when the height of the backfill was reduced, the maximum of the effectiveness shifted towards a decrease in the air flow rate from its value determined from the equality of the water equivalents of the liquid and air. Model experiments were conducted to determine the uniformity of the distribution of the heat carrier for various methods of nozzle irrigation. An increase in the uniformity of the distribution of the intermediate heat carrier with an increase in its flow rate is revealed. The best uniformity was obtained for a "uniformly-channel" irrigation system in conjunction with "peripheral" irrigation. This irrigation system is planned to be used in a regenerative heat exchanger to increase its efficiency.

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