Effect of phase transitions on operation of air-to-air heat exchangers with drop irrigation

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Abstract. The article presents the results of experimental studies of the thermal and humidity parameters of air flows of a regenerative air-to-air heat exchanger with drop irrigation and an intermediate heat carrier when operating in winter conditions with negative outside temperatures. The dependences of temperature and humidity efficiency of the heat exchanger on saline solution flow rate were determined, while the maximum temperature efficiency in the heating column was more than 70%. It is shown that under all investigated regimes in the heating column, moisture evaporated from the saline solution, and the air entering the room became more humid, which is a positive factor that increases the comfort of premises at negative outside temperatures.

1. Introduction

The air environment of premises, where a modern city dweller spends most of time, should provide healthy and comfortable conditions of stay. In indoor air, the content of carbon dioxide, harmful emissions from furniture, linoleum, paintwork and other sources can increase. To remove harmful components from air of rooms where people are, it is necessary to perform ventilation, that is, partially or completely replace indoor air with outdoor air. At that, it becomes necessary to condition outside fresh air in terms of cleanliness, temperature and humidity to the required parameters, taking into account medical and comfortable characteristics. Conditioning of ventilation air consumes significant energy resources, and the share of these energy costs in the total energy balance of modern buildings is increasing all the time [1].

To reduce energy consumption for conditioning the ventilation air, various air recuperation and regeneration units are being developed and actively used [2-3]. The most widespread are plate recuperators [4-5]. The disadvantage of such devices is a rather large area of heat transfer surfaces and problems associated with moisture condensation and ice formation, when operating at low ambient temperatures [6]. Cyclic regenerators have shown sufficient operation efficiency. These devices include rotating porous wheel regenerators [7] and regenerators of periodic action [8-9]. But these devices also have a significant drawback of the partial mixing of incoming and outgoing air flows, and they cannot be used in medical institutions where special air purity is required. Recently, research with membrane recuperators [10], which allow not only heat transfer between air flows through vapor-permeable membranes, but also transfer of moisture, has been actively carried out.

The existing designs of recuperators and regenerators for energy-saving ventilation of rooms have a number of disadvantages that limit application of these devices; therefore, the development of new designs of such devices is in progress [11-14]. A computational model of a new design of the air-to-air heat exchanger with drop irrigation and intermediate heat carrier is described in the recent publication
This paper presents the results of experimental studies of the thermal and humidity parameters of air flows in such a heat exchanger.

2. Test setup and experimental conditions

To study experimentally the operation of a regenerative air-to-air heat exchanger with drop irrigation and intermediate heat carrier, an experimental setup, whose schematic diagram is shown in figure 1, was assembled.

![Figure 1. Scheme of air heat regenerator with intermediate heat carrier: 1 - column body, 2 - grate, 3 - packing, 4 - sprinkler, 5 - pipeline, 6 - air ventilator, 7 - water pump.](image)

The main elements of setup are two cylindrical columns with a diameter of 600 mm and a height of 600 mm, filled with ceramic gravel with an average granule diameter of 8 mm. Air fans supply the columns with air from below; air passes through the column and exits through its upper part. Air from the outside is supplied to the heating column, and air from the room is supplied to the cooling column. From above, the gravel packing is irrigated with a 30% solution of CaCl₂ with a density of 1290 kg/m³. The solution serves as an intermediate heat carrier; it is drawn from the bottom of each column by a water pump and fed to the top of the other column for irrigation. At the inlet and outlet of each of the columns, thermocouples are installed in the solution, and thermocouples and relative humidity sensors are installed in the air. To measure temperatures, we used chromel-copel thermocouples made of a wire with a 0.2-mm diameter, and to determine the relative humidity of air flows, we used autonomous sensors Eclerk-USB-RHT. The error in temperature measurements was ± 0.2°C, and in measurements of relative humidity, it was ± 2%. Thermocouples were connected to a computer via an ADC and interrogated in 25 s; the relative humidity was measured every minute. The experiments were carried out in the winter. Air was fed to the heating column from the outside at temperature $t_{in}$ = -10 ÷ -20°C and relative humidity of 50-70%. Air entered the cooling column from a room with temperature $t_{out}$ = 24-25°C and low relative humidity of 20-25%. In the experiments, the air flow through each of the columns was kept constant, $G_a$ = 130 m³/h, the flow rate of the saline solution $G_l$ through each of the columns was the same and varied from experiment to experiment from 40 to 90 l/h.

3. Results and discussion

The results of measuring the air temperature at the outlet of the heating (figure 2a) and cooling (figure 2b) columns, as well as the indoor and outdoor air temperatures in one of the experiments at $G_l$ = 75 l/h are shown in figure 2 as an example. Each experiment lasted more than 6 hours, with stabilization of the air temperature at the column outlet in about 2 hours from the beginning of the experiment. To carry out all subsequent calculations, the measured parameters in each experiment were averaged from 4 to 6 hours from the beginning of the experiment. According to the results of figure 2a, at outdoor air
The temperature of -12.6°C, and at indoor air temperature of 24.8°C, the air entering the room was heated by 26.7°C to 14.1°C. The air removed from the room was cooled by 23.7°C to 1.1°C (figure 2b).

The processes of air heating and cooling in the columns were accompanied by a change in its humidity (figure 3).

At the same time, moisture evaporated from the saline solution in the heating column, and humidity of the outgoing air increased by 2.61 g/kg (per kg of air). The reverse process of moisture condensation from the air was observed in the cooling column, and humidity of the outgoing air decreased by 1.73 g/kg. Thus, the evaporation process in the heating column was more intensive than condensation in the cooling column. This was due to the conditions of the experiment. On the one hand, there was low relative air humidity (21%) at the heating column inlet, which limited moisture condensation. On the other hand, low absolute humidity of outside air (0.76 g/kg) supplied to the cooling column inlet intensified the process of moisture evaporation from the saline solution.

The efficiency of heat and cold regeneration in various recuperative and regenerative apparatuses is usually characterized by temperature efficiency $\varepsilon_t$ [9]. For the considered regenerative air-to-air heat exchanger with drop irrigation and intermediate heat carrier, the temperature efficiency for each of the columns can be written as:
\[ \varepsilon_{ij} = \frac{t_{\text{out}i} - t_{\text{in}i}}{t_{\text{out}i} - t_{\text{in}i}}, \]  

where \( i = h \) for the heating column and \( i = c \) for the cooling column; 
\( t_{\text{in}i} \) and \( t_{\text{out}i} \) are air temperatures at the inlet and outlet of the \( i^{th} \) column, 
\( t_{\text{in}} \) and \( t_{\text{out}} \) are indoor and outdoor air temperatures.

Experimental dependences of the temperature efficiency for each of the columns on the saline solution flow rate \( G_l \) (lower horizontal axis) are shown in figure 4.

![Figure 4](image)

Figure 4. Dependence of the column temperature efficiency on the saline solution flow rate.

The maximum temperature efficiency in the heating column exceeded 70\%. With an increase in \( G_l \) to 75-80 l/h, the temperature efficiencies in both columns increased, and with a further increase in \( G_l \), a slight decrease in \( \varepsilon_t \), especially pronounced for the cooling column, was observed. The upper horizontal axis corresponds to a change in water equivalent \( W \) with a change in \( G_l \). The water equivalent was determined as:

\[ W = \frac{\rho_a G_l c_a}{\rho_l G_l c_l}, \]  

where \( \rho_a \) and \( \rho_l \) are the densities of air and saline solution, \( c_a \) and \( c_l \) are heat capacities of air and saline solution. The maxima of temperature efficiency for both columns were observed at \( W > 1 \) (\( W = 1.2 - 1.4 \)), this confirms the earlier conclusion of [15] that the temperature efficiency of this type of recuperators with a limited column height shifts towards \( W > 1 \).

According to the results of experiments, the air flows passing through the regenerator columns changed their humidity. A change in the humidity of air flows \( \Delta m \) between the inlet and outlet of the heating and cooling columns of the regenerator at different flow rates of the saline solution is shown in figure 5.

\[ \Delta m = m_{\text{out}i} - m_{\text{in}i}, \]  

where \( m_{\text{in}i} \) is the mass flow rate of air at the inlet of the \( i^{th} \) column, and \( m_{\text{out}i} \) is the mass flow rate of air at the outlet of the \( i^{th} \) column.
where \( i = h \) for the heating column and \( i = c \) for the cooling column; 
\( m_{\text{in},i} \) and \( m_{\text{out},i} \) represent air humidity at the inlet and outlet of the \( i \)th column, g/kg.

According to the results obtained, when regenerative heat exchanger operated at negative outside air temperatures in winter, for all saline solution flow rates in the heating column, moisture evaporated from the solution and the air flow became more humid. Humidification of air entering the living rooms in winter at low absolute humidity is a positive factor that increases the comfort of premises. On the contrary, moisture condensation took place in the cooling column and humidity of the air flow leaving the column decreased. Moisture condensation in the cooling column is also a positive factor. Condensation generates heat, which increases the temperature of the saline solution, which then enters the heating column. In addition, condensation of moisture in the cooling column reduces water consumption during operation of the heat exchanger. In the experiments, the amount of moisture evaporated from the saline solution in the heating column was 1.5–2 times higher than the amount of its condensate in the cooling column, which was associated with low relative humidity in the room (20–25%). With an increase in humidity of the indoor air, the observed imbalance between evaporation and condensation of moisture during regenerator operation will decrease. According to the data presented in Fig. 5, with an increase in the saline solution flow rate from 40 to 90 l/h, an increase in air humidity in the heating column and a decrease in air humidity in the cooling column were observed.

To characterize quantitatively the process of changing humidity of the air flows, passing through the columns of a regenerative heat exchanger, by analogy with the temperature efficiency, it is convenient to use humidity efficiency \( \varepsilon_{\text{m}} \).

\[
\varepsilon_{\text{m}} = \frac{m_{\text{out}} - m_{\text{in}}}{m_{\text{out}} - m_{\text{in}}},
\]

where \( i = h \) for the heating column and \( i = c \) for the cooling column; 
\( m_{\text{in},i} \) and \( m_{\text{out},i} \) represent indoor and outdoor air humidity.

Figure 6 shows the results of determining \( \varepsilon_{\text{m}} \) at different flow rates of the saline solution.
According to the experiments, the humidity efficiency of the heating column was higher than that of the cooling one and it was about 75% at the saline solution flow rate from 60 to 90 l/h.

4. Conclusions
Operation of the air-to-air regenerative heat exchanger with drop irrigation and intermediate heat carrier in winter at negative outside air temperatures has been experimentally studied. The maximum temperature efficiency for the heating column of the heat exchanger was more than 70%, while the maximum temperature efficiency for the heating and cooling columns was achieved at a water equivalent of 1.2-1.4. Under all investigated regimes, moisture evaporated from the saline solution and the air entering the room became more humid in the heating column, while in the cooling column, on the contrary, the process of moisture condensation and a decrease in humidity of the leaving air were observed. The moisture efficiency of the heating column was about 75% at the saline solution flow rate from 60 to 90 l/h.

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