Features of Functioning of the Combined Air Heating Systems and Ventilation of a Three-story Museum

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Abstract. The analysis of the air-thermal regime of a three-story experimental residential museum building with a basement floor is presented. The equations of material and energy balances of the investigated building were compiled, allowing to determine the required air temperature at the outlet of the stream from the air-heating chamber. A method for determining the maximum performance of an air heater of a combined air heating and ventilation system at given temperatures of outside air and fresh air at the outlet of the jet from the air distributor is presented. The dependence of the thermal performance of the air heater on the change in the outside air temperature is established, with the same parameters of supply air at the outlet of the air distributors. A method for determining the parameters of supply air at the outlet of the jet from the air distributor, which allows to ensure the necessary parameters of the air inside the heated premises, is proposed. A survey of the temperature and humidity of the microclimate in the premises of the building, allows us to estimate the sanitary and hygienic conditions. A method for the simultaneous application of the processes of humidification and heating of the supply air in the combined air heating and ventilation system providing the specified microclimate parameters in the premises of the building under study is proposed.

1. Introduction
The analysis was performed as part of an integrated engineering and technological survey of the combined air heating and ventilation system of a three-storey experimental residential museum building with a basement in Moscow.

Parentheses, following the example. Some components, such as multi-leveled equations, graphics, and tables are not prescribed, although the various table text styles are provided. The formatter will need to create these components, incorporating the applicable criteria that follow.

2. Determination of the air-heat balance of a three-story museum building with a basement floor
Determination of air-heat balance of the three-storey building of the Museum with the ground floor The air-heat balance of the experimental three-storey residential building for Museum purposes in Moscow allows to determine the parameters of the supply air entering the room. Full-scale studies have shown that the amount of outside air in the supply system in the cold period of the year is from 18 to 22 % of the total flow rate heated in the air heating chamber of the air entering the surveyed
residential building of the Museum purpose, to compensate for the total heat losses (transmission and infiltration).

Full-scale examination showed that the amount of incoming outdoor air exceeds the required amount of incoming sanitary standards [1]. According to the equations of material balance, the amount of outdoor air entering the room corresponds to the amount of removed air through exhaust systems from the sanitary unit, bathroom and kitchen.

![Figure 1. Schematic diagram of the air-heat balance of the building.](image)

The supply air temperature at the jet outlet from the air distributor \((t_{\text{sup}})\) in the combined air heating and ventilation system is determined from the equation of air-heat balance (material and energy) for a residential building.

The material balance for the surveyed residential building as a whole, in accordance with the scheme presented in Figure 1, has the form

\[
(G_0 + G_{\text{rec}}) - G_{\text{rec}} - G_{\text{out}} = 0. \tag{1}
\]

The energy (heat) balance for the surveyed residential building as a whole, in accordance with the scheme presented in Figure 1, and on the basis of equality (1) is determined by equality (2):

\[
(G_0 + G_{\text{rec}})c t_{\text{sup}} - c t_{\text{int}} G_{\text{rec}} - c t_{\text{int}} G_{\text{out}} - (Q_{\text{inf}} + Q_{\text{tr}}) = 0, \tag{2}
\]

\[
G_0 = G_{\text{out}} \quad c (t_{\text{pr}} - t_{\text{s}}) (G_0 + G_{\text{rec}}) = Q_{\text{inf}} + Q_{\text{tr}}. \tag{3}
\]

The required value of the air temperature at the outlet of the jet from the air distributor (air-heating chamber) is determined by the joint solution of equations (1), (2) and (3):

\[
t_{\text{sup}} = t_{\text{int}} + \frac{Q_{\text{inf}} + Q_{\text{tr}}}{c (G_0 + G_{\text{rec}})}, \tag{4}
\]

where

- \(G_0\) is the outdoor air flow rate;
- \(G_{\text{rec}}\) - consumption of recirculated air;
- \(G_{\text{out}}\) - consumption of exhaust air (outgoing);
- \(t_{\text{sup}}\) is the supply air temperature after the air-heating chamber (at the outlet of the jet from the air distributors);
- \(t_{\text{int}}\) is the internal air temperature;
- \(c\) is the heat capacity of the air;
- \(Q_{\text{inf}}\) - infiltration heat loss;
- \(Q_{\text{tr}}\) - transmission heat loss.
The required supply air temperature at the jet outlet from the air-heating chamber, determined from the equation of the thermal (energy) balance of the building as a whole (equation 2), according to the circuit diagram presented in Figure 2 (equation of the heat balance of the air-heating chamber) allows determining the heat capacity of the heat exchanger (registers from smooth pipes). When the calculated outdoor temperature ($t_{\text{out}}$) for the conditions of the city of Moscow and supply air ($t_{\text{sup}}$) in the combined air heating and ventilation system is determined by the maximum performance of the heater (maximum thermal power registers of smooth pipes): $Q_{\text{heat}}$.

The material balance for the hot-air chamber is:

$$
(G_0 + G_{\text{rec}}) - (G_0 + G_{\text{rec}}) = 0.
$$

(5)

The material (heat) balance of the air-heating chamber, in accordance with the scheme presented in Figure 2, and on the basis of equality (5) has the following form:

$$
cG_0(t_{\text{out}} - t_{\text{sup}}) - cG_{\text{rec}}(t_{\text{int}} - t_{\text{sup}}) - Q_{\text{heat}} = 0.
$$

(6)

Figure 2. Schematic diagram of the air-heat balance of the building.

The maximum thermal power of the registers of smooth pipes (air heating chamber) is determined by the joint solution of equations (5) and (6)

$$
Q_{\text{heat}} = cG_0(t_{\text{sup}} - t_{\text{out}}) + cG_{\text{rec}}(t_{\text{out}} - t_{\text{int}}).
$$

(7)

Leaving a constant value of the supply air temperature ($t_{\text{sup}} = \text{const}$), from the energy balance equation of the supply air heating chamber (7), it is possible to establish the dependence of the change in performance of the heater in the direction of its decrease (or increase) depending on the change in the outside air temperature. At the same time the smallest amount of supply air should exceed the required air exchange at sanitary standards.

Figure 3. The dependence of the thermal power of the air-heating chamber on the ambient air temperature: $Q_{\text{heat}} = f(t_{\text{out}})$. 


3. Field survey of temperature and humidity conditions of the premises of a three-story museum building

Temperature and humidity are factors that can significantly affect the acceleration of the aging process of objects in a museum building. Air parameters (temperature and humidity) are interrelated and are considered in the complex.

The expediency of ensuring the integrated air-heat regime in the museum building, due to the storage of various exhibits in a single internal space. Optimal parameters of the internal air in the main rooms of the museum building should be provided with systems for ensuring the parameters of internal air [2]. The optimal parameters of the internal air when placing exhibits of various materials are presented in Table 1.

Table 1. Optimal parameters of internal air.

| Period of the year         | Exhibit                        | Optimum parameters of indoor air temperature, °C | relative humidity, % | mobility, m/sec. |
|---------------------------|--------------------------------|-----------------------------------------------|----------------------|------------------|
| Cold, transitional, and warm | Fabrics, clothes, carpets     | 18 - 22                                       | 30 - 50              | 0, 15 - 0, 20    |
|                           | Manuscripts, books, drawings  | 18 - 22                                       | 30 - 50              | 0, 15 - 0, 20    |
|                           | Furniture                      | 18 - 22                                       | 40 - 60              | 0, 15 - 0, 20    |

A survey of the temperature and humidity conditions of the premises was carried out to determine the parameters of the microclimate of the premises and to assess the sanitary and hygienic conditions, based on the requirements of building and hygiene standards for museum buildings (table 1).

Permissible air parameters in the auxiliary premises are provided by combined air heating and ventilation systems [3–5]. Permissible parameters of the internal air in the auxiliary premises are presented in table 2.

For field measurements of the internal air temperature, the relative humidity of the internal air, the external air temperature and the relative humidity of the external air, in the monitoring mode, data recorders were used for long-term measurements Testo 175-H1, which allows to measure the temperature and humidity of the air over a specified time interval and to remember in the internal memory 48,000 measurements.

The results of field studies of the temperature and relative humidity of air in the three rooms of the examined museum building in the period from March 1 to March 12, 2019, are presented in table 3.
Table 2. Parameters of internal air in the auxiliary premises.

| Period of the year | Premises          | Permissible indoor air parameters | temperature, °C | relative humidity, % | mobility, m/sec. |
|--------------------|-------------------|-----------------------------------|-----------------|----------------------|-----------------|
| Cold, transitional | Entrance lobby    |                                   | 16 - 20         | not standardized     | 0, 3            |
|                    | Administrative premises |                               | 18 - 22         | 30 - 45              | 0, 3            |
|                    | Technical premises |                                   | 10 - 12         | not standardized     | not normalized  |
| Warm               | Entrance lobby    |                                   | 22 - 26         | not standardized     | 0, 25           |
|                    | Administrative premises |                               | 20 - 24         | 30 - 60              | 0, 25           |
|                    | Technical premises |                                   | less 35         | not standardized     | not standardized|

The data on the temperature and humidity of the air in the premises of the building, which were recorded with similar devices for 2 years, was also analyzed.

Analysis of the material obtained allowed us to estimate the degree of influence of various factors on the process of microclimate formation in the premises of the museum building. At the same time, the true values of temperature and humidity were established during the day; maximum and minimum values; daily fluctuations and so on.

In the cold season, the air temperature in individual rooms is unevenly distributed. During the warm period of the year, there is an uneven distribution of temperature across the floors: the air temperature on the upper floors is higher than the temperatures on the first floor. Thus, the temperature regime in the building throughout the year is unstable and for the most part does not meet the requirements presented in Tables 1 and 2.

The relative humidity of indoor air in the warm period of the year ranges from 65% to 40%, in the transition period from 45% to 30%, in the cold period of the year from 45% to 20%. In the warm and transitional periods of the year, this range of changes in indoor humidity is due to the fact that it completely depends on the humidity of the outside air. In the cold period of the year, the relative humidity values of the rooms are very low. Airing during the cold period of the year leads to an even lowering of the relative humidity of the indoor air, since the outside air during this period is characterized by low absolute humidity.
Table 3. The results of measurements of microclimate parameters.

| Date      | Room #1 | Room #2 | Room #3 | Parameters of outdoor air |
|-----------|---------|---------|---------|---------------------------|
|           | t, °C   | φ, %    | t, °C   | φ, %                      | t, °C | φ, %  |
| 12.03.19  | 19,9    | 23,2    | 20,1    | 31,5                      | 20,1  | 31,2  | -0,5  | 75,7  |
| 11.03.19  | 20,1    | 31,6    | 20,4    | 32,6                      | 20,2  | 24,3  | -1,7  | 74,7  |
| 10.03.19  | 20,0    | 28,1    | 20,2    | 33,1                      | 19,5  | 23,6  | -3,8  | 82,2  |
| 09.03.19  | 19,3    | 28,0    | 19,8    | 33,8                      | 19,8  | 24,7  | -1,3  | 67,9  |
| 08.03.19  | 21,2    | 27,3    | 19,9    | 33,4                      | 20,1  | 24,6  | -6,7  | 79,6  |
| 07.03.19  | 20,8    | 26,9    | 20,8    | 31,9                      | 20,2  | 23,5  | -4,3  | 77,6  |
| 06.03.19  | 20,1    | 29,2    | 21,1    | 28,1                      | 19,6  | 23,1  | -7,5  | 63,9  |
| 05.03.19  | 21,7    | 23,6    | 19,5    | 33,2                      | 20,8  | 25,4  | -5,8  | 76,6  |
| 04.03.19  | 20,6    | 28,5    | 20,5    | 31,4                      | 20,7  | 23,3  | -7,7  | 83,4  |
| 03.03.19  | 20,6    | 24,2    | 21,3    | 29,4                      | 21,2  | 22,1  | -8,9  | 83,2  |
| 02.03.19  | 19,8    | 26,2    | 20,4    | 29,1                      | 20,1  | 20,2  | -9,5  | 71,9  |
| 01.03.19  | 20,1    | 21,6    | 19,8    | 27,2                      | 20,4  | 19,8  | -10,7 | 64,2  |

Thus, the results of a study of the temperature and humidity conditions of the premises have shown the need for air humidification in the cold periods of the year [6–18].

In the three-story museum building under study, it is envisaged that the supply and recirculated air will be heated exclusively by means of smooth-tube registers. The ongoing process of heating the air in the chamber without changing its humidity can be represented as follows.

In the existing system, the process of air heating takes place as a result of contact with the dry heated surface of registers made of smooth pipes, in which air receives only apparent convective heat. At the same time, the moisture content of the air remains unchanged; therefore, in the I-d diagram, the heating process is traced from the bottom up along the d = const lines, that is, with a constant moisture content of air. Air with parameters that correspond to the “H” point \((t_\text{a}, \varphi_\text{a})\) (Fig. 4) is heated in the air-heating chamber, while on the I-d diagram the process is displayed as a straight line drawn vertically upwards from the “H” point along the line \(d = \text{const}\). The more heat is transferred to air, the more it heats up and the higher the “K” point corresponding to the heated air state will be located along the \(d = \text{const}\) line. (Fig. 4).

Figure 4. I - d-diagram of the process of heating air from a dry surface.
In accordance with regulatory requirements in the premises it is necessary to maintain not only a certain temperature, but also humidity. Low humidity contributes to the accumulation of static electricity on metal objects. Increased leads to a feeling of stuffiness and condensation on surfaces (the dew point temperature rises). The three-story experimental museum building under study is the building of the historical heritage of the city of Moscow, which limits the possibility of using modern technical solutions in the microclimate maintenance systems. The required level of humidity is supposed to be supported by air humidification devices operating on the principle of evaporation of water from the open surface of a tank filled with water installed in the volume of the incoming air heating chamber (Fig. 5).

![Figure 5](image)

**Figure 5.** I - d-diagram of the processes of heating and humidification.

The simultaneous application of the processes of humidification and heating of the supply air in the combined air heating and ventilation systems makes it possible to obtain the specified parameters of the microclimate in the premises of the building [1–3].

Provide for a local (autonomous) control system of the air-heat regime, thereby minimizing the dependence on the thermal regime of the urban heating networks. Develop a system for automating the existing heat supply station (connection unit of the urban heating network to the heater) and a system for humidifying the air directly in the heat chamber.

To regulate the humidity of the air leaving the heat chamber, a device is proposed consisting of a reservoir with an open surface. As a result of evaporation from the surface of the tank, water vapour enters the heated air and then into the channels of the intake systems. In this case, the valves of the float type with lateral connection will provide water to maintain the level at a given value.

### 4. Conclusions

According to the results of the measurements, it follows that the amount of air supplied to the room depends on the air temperature after the air-heating system. The amount of air depends on the outdoor temperature.

The obtained dependence of the supply air temperature on the air and air temperature on the outside air temperature makes it possible to determine the supply air temperature to ensure the energy and material balance in the room.

The amount of air entering the room, according to the equations of material balance, corresponds to the amount of exhaust air through the exhaust system. The amount of air entering the building is equivalent to sanitary norms.

Analysis of the results of measuring the temperature and humidity inside the premises, as well as data from previous long-term studies conducted by the customer, showed that the relative humidity of indoor air in the cold period of the year ranges from 45% to 20% during the transition period - from 45% to 30% and in the warm period of the year - from 65% to 40%.
The air conditioning and ventilation system does not have a certain value of relative humidity in the cold season. Therefore, it is necessary to provide additional measures for humidifying the supply air.

The simultaneous application of the processes of humidification and air conditioning in the air conditioning system and ventilation will provide an opportunity to obtain a microclimate in the premises of a building with specified parameters.

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