Assessment of the efficiency of using heat recovery units in ventilation systems in the conditions of the Southern Urals

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Abstract. The increase of energy efficiency and energy saving are the main indicators of the improvement and growth of the competitiveness of the Russian economy. One of the system approaches is saving of energy resources through heat recovery. The use of heat recovery units and assessment of the boundaries of their effective use are rather relevant for regions with a long heating period and low negative temperatures. The study proves that special climatic conditions of the Southern Urals provide certain benefits when using heat recovery units in the cold season, relative to other regions, which allows us to use them effectively in ventilation and air conditioning systems throughout the year.

1. Introduction
The increase of energy efficiency and energy saving are the main indicators of the improvement and growth of the competitiveness of the Russian economy.

One of the system approaches is saving of energy resources through heat recovery[1,2]. In a modern building, ventilation is one of the main sources of heat losses, and exhaust ventilation air is one of the most important sources of its recovery. The main element of the heat recovery unit is the heat-mass-transfer apparatus. The efficiency of the entire engineering solution of the installation depends on the thermodynamic efficiency of the heat exchanger.

2. Relevance of the research
The world experience has shown that the recovery of heat from exhaust air can significantly reduce heat loads as compared to conventional ventilation systems. It has been also established that the rationality of using a heat recovery system depends on the type of building, heat loads and characteristics of the ventilation equipment [3,4,5].

In [6] considers various heat recovery units and proposes an optimal way of their integration into the climate system of a building. We point out that such indicators as heat efficiency, pressure drop, exhaust air flow into the inlet air and leakage of the inlet air are used to assess the efficiency of heat recovery units. A comparison of the characteristics of heat recovery units is shown in Table 1.

It follows from the work results that when heat recovery units are used, it is necessary to determine carefully such parameters as the location of each unit in the system, design productivity of each unit in winter and summer conditions, and the total annual energy saving. The Association of European Engineers ASHRAE has developed a manual [7], which provides recommendations and technical data of recovery units. The efficiency of using heat recovery units is shown in the work [5].
However, the aforesaid foreign sources pay insufficient attention to the problem of freezing of heat exchangers. It is quite understandable, because in most technically advanced countries the calculated air temperature does not reach -10 °C. In Russia, on the majority of territories, climatic conditions during the cold season differ sharply from those of most foreign countries. Therefore, the problems of freezing of heat exchangers come to the fore when considering the issue of an efficient use of heat recovery units.

Table 1. Comparison of the characteristics of heat recovery units.

| Type of heat exchanger                  | Airtightness | Moving mechanical parts | Efficiency of heat recovery | The possibility of freezing |
|----------------------------------------|--------------|-------------------------|-----------------------------|-----------------------------|
| The plate heat exchanger               | flow to 1%   | no                      | 50-70%                      | high                        |
| Rotary regenerator                     | flow to 4%   | yes                     | 70-90%                      | high                        |
| Heat exchanger with intermediate heat carrier | impossible | no                      | 40-50%                      | low                         |

The authors in [8,9], as well as practitioners, determine that the threat of freezing of the heat exchanger in the course of recovery is a visible and major obstacle to the widespread introduction of heat exchangers in the climatic conditions of Russia. In [8] gives the values of the freezing temperature at various values of the exhaust air temperature and its relative humidity and the temperature efficiency at equal mass air flows at the inflow and outflow. According to these data, the heat exchanger is frozen when the removed air is cooled to -8 °C and -5 °C, respectively, for heat exchangers with the temperature efficiency coefficients of 60 and 65% at the external air temperature of -30 °C and the relative internal air humidity of 30%.

Most authors believe that the data on the efficiency of the heat exchanger presented by the manufacturers of heat recovery units, ignoring the influence of frost preventing devices, are insufficient to assess the economic efficiency or determine the required heat power at the inlet air temperatures below the freezing limit.

In [9] the author concludes that a deep understanding of the mechanisms and processes accompanying freezing of plate heat exchangers is a necessary condition for their successful implementation in the conditions of the severe Russian climate.

However, there are very few works dealing with the study of heat recovery units in the Russian climate. One of the few [10] presents the results of introducing ventilation systems based on rotary heat exchangers in Novosibirsk. According to the authors, the estimated thermal capacity in winter decreased by 1.6 Gcal/h, the operating costs decreased by 4.7 million rubles.

We did not find any publications on such studies for the conditions of the Southern Urals.

After analyzing the existing problems, the main advantages and disadvantages, it was decided to study the effective use of heat recovery units in ventilation systems of Chelyabinsk.

This research was based on the assumption that special climatic conditions of the Southern Urals can provide certain benefits when using heat recovery units in the cold season, relative to other regions, which will allow us to expand the boundaries of their effective use, relative to the determined in [8], therefore, to increase energy saving in ventilation and air-conditioning systems.

The relevance of the research is that the use of heat recovery units and the assessment of the boundaries of their effective use are extremely important for regions with a long heating period and low negative temperatures.

The scope of the research is the boundaries of the effective use of plate heat exchangers in the cold season in the conditions of the Ural region.

The novelty of the research is the expansion of the concepts about the effective use of heat recovery in the conditions of the Southern Urals.

The practical implication of the research is to create a procedure for assessing the efficiency of using plate heat exchangers.
3. The purpose and tasks of the work

Purpose of the research: to assess economically and thermodynamically the usability of heat recovery units in the ventilation systems of public buildings in Chelyabinsk as exemplified by a particular facility.

Tasks of the research:
- Theoretical studies based on statistical processing of climatic data;
- Selection of the most rational model of a heat recovery unit and assessment of its thermodynamic performance;
- Selection of the object of research. Development of an inflow exhaust ventilation system of a building using the selected type of the heat recovery unit and determination of the main performance indicators of the system;
- Analysis of energy efficiency of the heat recovery units during the cold season in Chelyabinsk;
- Selection of a procedure for assessing the economic efficiency of using the heat recovery unit of the selected type;
- Evaluation of the expediency of using the heat recovery unit in the cold and transition seasons for the selected facility;

4. Description and results of the research

4.1. Background data for the research

The object of the research is the ventilation system of a building with a plate cross-flow heat recovery unit.

The research tool is statistical and graphoanalytical methods.

The research was conducted for the conditions of the cold season.

4.2. Theoretical research

The climatic parameters for Chelyabinsk were analyzed by the following indicators to study the effective usability of heat recovery units in ventilation systems of buildings in the Southern Urals:
- moisture content of the external air;
- external air temperatures and their duration.

A peculiar feature of the climate is that the moisture content of the external air in Chelyabinsk is low, as evidenced by a map of humidity zones, where Chelyabinsk is in the center of the dry zone (zone No. 3).

To analyze the indicator of the duration of the negative temperature action, based on the weather archive data from [11], we built a diagram of the duration of negative external air temperatures for the cold season in Chelyabinsk for 2017 - 2018 (Figure 1).

![Diagram of the duration of external air temperatures](image_url)

**Figure 1.** Diagram of the duration of external air temperatures in the period from September to May for Chelyabinsk (2017/2018).
The theoretical research has established the \textit{possible boundaries} of using heat recovery units in the cold season. The theoretical research was carried out for the conditions of an "average" room most typical for most public buildings, i.e. rooms, where people are constantly present, and the main hazards are heat and moisture release from people.

The average indicator of the process beam was determined for such room:

\[ \varepsilon = 3600 \frac{Q}{W}, \]  

where \( Q \) represents the excess of the total heat from one person, \( Q = 150 \, \text{W} \); \( W \) represents the moisture flow from one person, \( W = 75 \, \text{g/h} \), so \( \varepsilon = 7200 \, \text{kJ/kg} \).

In order to check the hazard of freezing of the heat recovery unit, we built processes of changing the air state on the I-d diagram for Chelyabinsk in an average room, using two types of plate heat exchangers with different efficiency coefficients:

- cross-flow heat exchanger at the accepted value \( \varepsilon_t = 0.6 \)
- counter-flow heat exchanger at the accepted value \( \varepsilon_t = 0.7 \)

The efficiency coefficients were adopted by the manufacturers' average data.

The amount of inlet and exhaust air was assumed to be equal.

The processes are built at the following parameters:

- temperature of the inlet air to the room \( t_{in} = +18^\circ\text{C} \),
- temperature of the outlet air from the room \( t_{out} = +22^\circ\text{C} \),
- angular process coefficient \( \varepsilon = 7000 \).

The schemes are presented in Figure 2.

The results of the theoretical research and building of the processes on the I-d diagram have shown the following:

1. The air is not moistened in most public and administrative buildings, therefore, the moisture content of the removed air during the cold season for a given process beam is low - 1.2 g/kg. Since the removed air is supplied very dry to the heat recovery unit, this significantly reduces the hazard of freezing when using any heat recovery units.

2. The use of a cross-flow plate heat recovery unit does not lead to condensation and freezing for the design conditions of the external air during the cold season in Chelyabinsk, and when a more effective count-flow heat recovery unit is used, the heat exchanger freezes. Therefore, it is more rational to adopt a heat recovery unit with the process efficiency not exceeding \( \varepsilon_t = 0.6 \), since the use of this heat exchanger makes it possible to avoid its freezing during the entire cold season.

Based on the results of the theoretical research, we proposed recommendations on the use of heat recovery units in ventilation systems:

1. The using heat exchangers in ventilation systems of Chelyabinsk buildings where people stay in the cold season (at the process beam coefficient less than \( \varepsilon = 7500 \)) is advisable, since it represents a large reserve for energy saving;

2. It is recommended to use cross-flow heat recovery units with the termal efficiency \( \varepsilon_t \) of no more than 0.6, since their use makes it possible to avoid its freezing during the entire cold season;

3. It is proposed to heat additionally the inlet air leaving the heat exchanger, to the design temperature \( t_{in} \) in a water heater. The use of a heat recovery unit significantly reduces the threat of freezing the water heater and, therefore, does not require expensive automatic protection for the heater assembly;

4. Since the amount of recovered heat depends on the external air temperature, it is necessary to determine the annual (seasonal) amount of recovered heat in order to assess the efficiency of using the heat recovery unit. Since external air temperatures during the cold period (season) will change in...
Chelyabinsk in a wide range (Fig. 2), it is proposed to assess the efficiency of using heat recovery units with the help of annual (seasonal) timetables of the duration of external air temperatures.

4.3. Practical research

The theoretical results were verified on a specific example.

To verify the theoretical assumptions, the study was conducted on a specific example of Gostiny Dvor shopping center in Chelyabinsk located at: Yelkina st. 25-a. The shopping center is a five-story building. Shops are located on the 2nd, 3rd and 4th floors, the 5th floor is occupied by administrative premises.

The object of research was a ventilation system serving the commercial premises (boutiques) of the second floor of the complex equipped with a plate cross-flow heat exchanger manufactured by VEZA, Russia.

In order to check the probability of the formation and freezing of condensate on the walls of the plates, we built processes of changing the air state for the salesroom using a steel plate heat exchanger with the heat efficiency coefficient \( E_t = 0.58 \) (determined according to the data of the unit’s manufacturer). The value of the angular process beam coefficient is determined by calculating the heat and moisture excess in the room \( \varepsilon = 7200 \text{ kJ/kg} \). The processes of changing the state of the air currents are built on the I-D diagram at the calculated external air temperature \( t_{\text{ext}} = -34^\circ\text{C} \). The results are shown in Table 1.

Based on the results of building I-D diagrams, we have shown that the removed air has the moisture content of \( 1.2 \text{ g/kg} \) and is cooled from the temperature \( t_1 = 20,4^\circ\text{C} \) to \( t_2 = -12,2^\circ\text{C} \), at the dewpoint temperature for a given moisture content \( t_{\text{drop}} = -14,5^\circ\text{C} \). The scheme confirms the conclusions of the theoretical research. There is no condensation in the heat recovery unit, so there is no threat of its freezing even at the design temperature according to parameters B in the cold season.

Further, we built processes in the system with intermediate values of external temperatures for several days of observations during the heating period of 2017-2018. The data on the external air temperature and the relative humidity are taken from [11] for Chelyabinsk. The results of the building the processes are shown in Table 2.

| date     | \( t_{\text{ext}}, ^\circ\text{C} \) | \( \varphi_{\text{ext}}, \% \) | \( t_{\text{drop}}, ^\circ\text{C} \) | \( t_{\text{cool}}, ^\circ\text{C} \) |
|----------|----------------------------------|-------------------------------|----------------------------------|----------------------------------|
| basic    | -34                              | 78                            | -14,5                            | -12,2                            |
| 15.12.17 | -11,4                            | 67                            | -7                               | +1,2                             |
| 20.01.18 | -16,8                            | 65                            | -10,5                            | -1,5                             |
| 01.03.18 | -10,6                            | 54                            | -8,2                             | +2                               |

The following designations are adopted in the table: date - date of observations; \( t_{\text{ext}}, ^\circ\text{C} \); \( \varphi_{\text{ext}}, \% \) - temperature and relative humidity of the external air; \( t_{\text{drop}}, ^\circ\text{C} \) – dewpoint temperature for the removed air; \( t_{\text{cool}}, ^\circ\text{C} \) – actual cooling temperature of the removed air.

Conclusion: According to the data given in Table 1, there is no condensation at any intermediate parameters during the observation period.

Thus, we confirmed the theoretical conclusion that for the conditions of Chelyabinsk the boundaries of using recuperative cross-flow heat recovery units in ventilation systems during the cold season are widening as compared to the previously established values in [12], and it is possible to use them efficiently throughout the year.

4.4. Assessment of the efficiency of using a cross-flow heat recovery unit

To assess the efficiency, we used our own methodology to determine the annual performance indicators of the system based on the graphoanalytical method. For this purpose, we built seasonal (for
the cold season) integrated diagrams of calculated, consumed and recovered heat in the ventilation system.

We used diagrams of the dependences of the heat load in ventilation systems on the values of the external air temperature $t_{ext}$, for the basic and proposed versions to build a seasonal diagram of consuming ventilation loads. The basic version is represented by a unit without air recovery, the proposed version is represented by a version of a cross-flow recuperative heat recovery unit. All the diagrams are straight lines, which are built by two points: at the design external air temperature and an arbitrarily set temperature within the temperature range of the heating period ($t_{ext} = -10^\circ C$ is selected).

The calculated heat amount was determined for the basic version by the required heat power of the air heater in the system $Q_{1(-34)}$, and amount of the consumed heat was determined for the proposed version by the required heat power of the air heater $Q_{2(-34)}$, at the calculated external air temperature:

The recovered heat was determined as a difference between the calculated and consumed heat power.

$$Q_{rec(-34)} = Q_{1(-34)} - Q_{2(-34)} \quad (2)$$

$$Q_{rec(-34)} = 49406 - 17193 = 32213 \text{ W}$$

Analogous calculations were made for the intermediate value of the external temperature $t_{ext} = -10^\circ C$.

$$Q_{rec(-10)} = 27447.7 - 9551.6 = 17896.1 \text{ W}$$

To build the main part of the annual diagram, we determined the duration of different temperature ranges with the step of 5 °C, from the value of $c_{t_{ext}} = -34$, for Chelyabinsk according to the data over 2017-2018.

The results are shown in Figure 2.

![Figure 2. Comparative diagram of seasonal heat consumption in the ventilation system for the proposed version: using a cross-flow recuperative heat recovery unit with $E_t = 0.58$, during the cold season of 2017-18.](image)

Annual indicators were determined by building the diagrams. The annual amount of recovered heat is:

$$Q_{rec \text{ year}} = 29 \text{ Gcal/year}$$

which, as compared to the basic version $Q_{1 \text{ year}}$ is 65%.

So, the building of processes on the integrated diagram has shown that a significant portion of the expenditures for heating the inlet air is saved due to the recovery of the heat from the exhaust air, in annual terms the saving is 65%, which can be considered as a significant reserve for energy saving.
To assess the investment attractiveness of the proposed measure, we made an economic calculation of capital and operating costs, based on the results of which we determined the payback period of the measure. The payback period of installing the chosen type of the heat recovery unit was 3.7 years, which is a high indicator as compared to the experience that has developed in practice.

5. Conclusion
As a result of the practical research, we confirmed the theoretical conclusions that in the premises with a low moisture content in the cold season, the boundaries of the effective use of cross-flow recuperative heat recovery units are widened in the climate of the Southern Urals, as compared to common practice in the central and western regions of Russia, and it is possible to use them efficiently throughout the year. Therefore, the use of these units is an important reserve for saving heat resources.

References
[1] Nemirovsky V and Kuzovlev A 2015 Energy saving with the use of waste heat Scientific journal ITMO. Series "Refrigeration and air conditioning" 2 pp 14–21
[2] Starkova L 2018 Utilization of heat in ventilation and air conditioning systems: studies. manual (Magntogorsk. State. Tech. UN-TA im. G. I. Nosova) p 58
[3] Youness E I Fouch and Pascal Stabat 2012 Adequacy of air-to-air heat recovery ventilation system applied in low energy buildings Energy and Buildings pp 29–39
[4] Roulet S Heidt F D, Foradini F, Pibiri M C 2001 Real heat recovery with air handling units Energy and Buildings pp 495–502
[5] Livchak I and Naumov A 2005 Ventilation of multi-storey residential buildings (Moscow: AVOK-PRESS)
[6] Besant R and Simonson C 2005 Air-to-air heat exchanger Journal ASHRAE
[7] ASHRAE handbook 2008 Heating, Ventilating, and Air-Conditioning Systems and Equipment American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc
[8] Diskin M 2006 The efficiency of heat recovery in ventilation systems at outdoor temperatures below the freezing hazard temperature 4
[9] Vishnevsky E 2015 Features of ensuring effective operation of plate heat exchangers of recuperative type in severe climatic conditions Journal of "JUICE" 1
[10] Rubtsov A 2013 Energy-efficient ventilation of the shopping center in Siberia 2
[11] https://www.gismeteo.ru/weather-chelyabinsk-4565/
[12] Sang-Min Kim and Ji-Hyun Lee 2012 Determining operation schedules of heat recovery ventilators for optimum energy savings in high-rise residential buildings Energy and Buildings pp 3–13
[13] Wisniewski E 2014 The Recovery of heat in ventilation systems and air conditioning Journal of "JUICE" 11
[14] Doodoa A, Gustavsson L and Sathre R 2011 Primary energy implications of ventilation heat recovery in residential buildings EnergyanBuildings 43 (7) pp 1566–72
[15] Adamski M 2008 Longitudinal flow spiral recuperators in building ventilation systems Energy and Buildings pp 1883–88
[16] Adamski M 2010 Ventilation system with spiral recuperator Energy and Buildings pp 674–77
[17] Biryukov P and Tabunshikov Y 2014 Energy Saving Magazine special issue
[18] Rymkevich A 2003 System analysis of optimization of General ventilation and air conditioning (St. Petersburg) p 272
[19] StandartVDI 2071 1996 Heat recovery in heating, ventilation and air-conditioning plants
[20] Eurovent 10/1 Heat recovery Devices – Specifications, Terminology, Classification And Functional Characteristics 1987