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Rentability of Rotary Heat Regenerator Use in Ventilating Systems

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Dwelling and working environments should be ventilated in order to satisfy the need for healthy living space. In this article the mathematical model for determining the economy in the case of investment into rotary heat regenerator for ventilating systems is presented. The dynamic economic method, which considers discount degree and inflation rate, was used for economy calculations. This procedure enables relatively precise calculations of operation of rotary heat regenerator. Evaluation of heat savings was made on the basis of a curve of sum of days with average daily temperatures for the previous five years.

Rentabilnost upotrebe regeneratora topline u ventilacijskom sustavu

Izvornoznanstveni rad

Kućanski i radni prostori trebaju biti ventilirani da se zadovolji potreba za zdravom okolinom. U članku je razvijen matematički model za proračun ekonomičnosti investicije u rotacijskim regeneratorima topline. Upotrebljena je dinamička ekonomska metoda, koja uključuje diskontnu stopu i stopu inflacije. Metoda omogućava relativno točnu kalkulaciju rada regeneratora topline. Proračun toplinskih dobitaka izveden je na osnovi krivulje sume dana sa srednjom dnevnom temperaturom za poslednjih pet godina

1. Introduction

Energy is a basic factor for human welfare and social development. Power strategy of how to obtain and use energy has a great influence on the total economic development of each country. Nowadays, many efforts regarding energy savings are made due to large environmental problems and declining energy sources, which result from inconsiderate use of natural sources, wasteful use of fossil fuel and electricity in the past. The industrial revolution and the subsequent accelerated economic growth were achieved without any rational energy use, causing excessive environmental contamination. As a response to this, the developed countries have decided on stronger restrictions regarding environmental pollution, in which thermal energy will play an important role. We are more than ever interested in discovering ways to save energy and lower the costs of specific systems [1 - 7].

Aspirations of contemporary constructions strive after extremely tight closing of buildings and this prevents sufficient exchange of polluted air with fresh air. The consequence is frequent room ventilation to assure healthy living space and to prevent accumulation of moisture. As a result a large amount of energy is lost, which could otherwise be used again.

The fundamental principle of heat regeneration is heat exchange between two gases over the surface [8-9]. The installation of ventilating units provides us not only with a healthier environment, but also yields some economical benefits [5]. All types of ventilating systems

Symbols/Oznake

a_1, a_2, a_3	- constants - konstante
b_1, b_2, b_3	- constants - konstante
c_1, c_2	- constants - konstante
b	- discount factor - diskontni faktor
c_{lp}	- yearly income with selling heat, EUR/year - godišnji prihod s prodajom topline
c_t	- heat price, EUR/Wh - cijena topline
c_p	- specific heat of air, J/kg·K - specifični toplinski kapacitet zraka
c_{vz}	- maintenance costs, EUR/year - trošak izdržavanja
c_{reg}	- price of heat regenerator, EUR - cijena regeneratora topline
c_{em}	- costs of electric power for electromotor, EUR/year - cijena električne energije (za elektromotor)
c_{ev}	- costs of electric power for fan, EUR/year - cijena električne energije (za ventilator)
c_{ste}	- costs of electric power, EUR/year - cijena električne energije
c_e	- price of electric power, EUR/Wh - cijena električne energije
g	- degree of increase costs because of other expenses, % - stopa rasta cijene zbog ostalih troškova
i	- interest rate, % - kamatna stopa
L_p	- middle value of annual annuity, EUR/year - srednja vrijednost godišnjeg anuiteta
n	- regenerator lifetime, year - vijek trajanja regeneratora
P_e	- electromotor power, W - snaga elektromotora
p_y / p_{iz}	- pressure drop of fresh/waste air, Pa - pad tlaka svježeg/odpadnog zraka
r	- degree of increase of costs because of maintenance costs, % - stopa rasta cijene zbog troškov održavanja
S_1	- annual temperature number, K day/year - godišnji broj stupnja dana
S_2	- lost annual temperature number, K day/year - izgubljen godišnji broj stupnja dana
t_1	- operating time, h/day - radno vrijeme
t_2	- operating time, day/year - radno vrijeme
T_a	- average daily temperature, K - prosječna dnevna temperatura
T_{11}	- input temperature of waste air, K - ulazna temperatura otpadnog zraka
T_{12}	- output temperature of waste air, K - izlazna temperature otpadnog zraka
T_{22}	- output temperature of fresh air, K - izlazna temperature svježeg zraka
T_{21}	- input temperature of fresh air, K - izlazna temperature svježeg zraka
z	- number of days with average daily temperature - broj dana sa prosječnim dnevnim temperaturama
q_y / q_{iz}	- fresh/waste air flow rate, m^3/s - protok svježeg/odpadnog zraka
β_e	- electromotor efficiency - stupanj koristnosti elektromotora
β_y	- fan efficiency - stupanj koristnosti ventilatora
η_1	- degree of heat recovery for waste air - stupanj povrata topline odpadnog zraka
η_2	- degree of heat recovery for fresh air - stupanj povrata topline vanjskog zraka

with heat regeneration are constructed to induce fresh air into rooms in the first place, but they can also save some energy using the heat from waste air.

Savings due to use of heat regenerator are shown in:

- smaller required surface of heat devices,
- reduced cost of warming, cooling and drying of outside air and
- decreased thermal and chemical pollution of the environment.

Economic viability of investment depends on the price of regenerator, operation regimes and savings, which depend upon temperature difference between waste and fresh air. Because of this, it is important to know the conditions of a specific climatic area and time period.

Temperature distribution is presented with a curve of sum of days for average daily temperature, on which the calculation of economic profitability into heat regenerator is based.

2. Heat regenerator

Heat regenerators, which are actually heat exchangers, comprise two basic systems [10-13]:

- regenerative heat exchanger with rotating accumulative mass – rotary heat regenerator,
- regenerative heat exchanger with stable accumulative mass – stable heat regenerator.

Rotary heat regenerator consisting of massive honeycomb, rotating in counter-flows of the warm waste and the cold fresh air, is presented in (Figure 1).

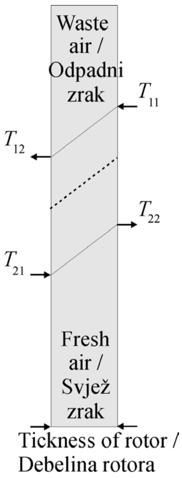

Figure1. Scheme of the temperature distribution in the rotary heat exchanger

Slika 1. Shema raspodjele temperature u rotacijskom regeneratoru topline

It operates with laminar regime of flows to prevent fouling by dry particles while the reversal of flow direction enables self – cleaning. Filtration of the effluent air is usually not required except when it contains adhesive particles and particles larger than 300 μm.

According to the way of operation we distinguish two types of regenerators, the enthalpy and the condensed ones. The enthalpy one can transmit sensual as well as bounded heat, because it has very good absorption properties. The condensed one transmits heat and also enables moistening or drying of the air by raising the temperature of waste air on the exit side below the dew point.

The efficiency of the heat exchanger is about 70 % - 80 % and depends on the type and size of regenerator, the flow rate of air and the rotation speed, which is adjusted on constant value or regulated automatically according to input temperatures. Figure 2 presents the efficiency of a rotary heat regenerator depending on the number of rotor rotation.

The selection of type and size of the heat exchanger depends on air flow capacity, quantity of waste and fresh air, allowed pressure drop, quantity of necessary heat to exchange and yearly operating time.

In Table 1, the comparison of efficiency of different heat exchangers is given for the case when temperature of waste air is T_{11} = 22 °C.

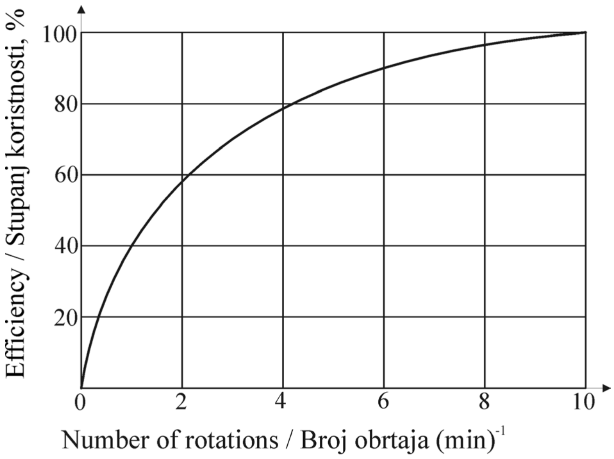

Figure 2. Efficiency of regenerator depending on number of rotor rotation

Slika 2. Efikasnost regeneratora ovisno o broju okretaja rotora

Table 1. Comparison of efficiency of different heat exchangers for recuperation at T_{11} = 22 °C

Tablica 1. Usporedba efikasnosti različitih prijenosnika topline pri rekuperaciji kod T_{11} = 22 °C

Heat exchanger / Izmenjivač topline	Heat efficiency / toplotni stupanj koristnosti	Temperature of inlet air T_{22} / Temperature ulaznog zraka
Heating pipe / Toplinska cijev	40 %	3 °C
Plane regenerator / Ploščni regenerator	50 %	6 °C
Rotary regenerator / Rotacijski regenerator	75 %	14 °C

3. Climatic parameters and effectiveness of heat recovery

Heat savings in a ventilating system with regenerator depend on the temperature of outside air and are calculated from the curve of sum of days with average daily temperature for specific climatic area [14]. If we enter values of external temperature and moisture, measured throughout the entire year, into Mollier diagram $i - x$, we get the curve of the outside air temperature or the enthalpy duration.

The average daily temperature, T_a, is calculated from three measurements a day (at 7 am, 3 pm and 9 pm) by the following formula:

$$T_a = \frac{T_7 + T_{14} + 2T_{21}}{4}. \quad (1)$$

The curve of sum of days with average daily temperatures consists of three characteristic regions. The first part of the curve comprises the region of the lowest temperatures including the interval T_a = 271 K to T_a = 275 K. The third part involves the region of the highest temperatures, T_a = 290 K to T_a = 294 K. For these regions we can use the exponential relationships:

$$z = a_1 + b_1 \cdot \exp\left[c_1 \cdot (T_a - 273\ \mathrm{K})\right], \tag{2}$$

$$z = a_3 + b_3 \cdot \exp\left[c_3 \cdot (T_a - 273\ \mathrm{K})\right]. \tag{3}$$

The second part comprises linear relationship for temperatures between T_a = 275 K and T_a = 294 K.

$$z = a_2 + b_2 \cdot (T_a - 273\ \mathrm{K}) \tag{4}$$

Constants a_1, b_1, c_1, a_2, b_2, a_3, b_3, c_3 are determined by leading equations (2), (3), (4) to $T_a^* = (T_a - 273)$. Results are:

- for the first part of the curve

$$\frac{\mathrm{d}z}{\mathrm{d}T_a^*} = b_1 \cdot c_1 \cdot \mathrm{e}^{(c_1 \cdot T_a^*)}, \tag{5}$$

- for the second part of the curve

$$\frac{\mathrm{d}z}{\mathrm{d}T_a^*} = b_2, \tag{6}$$

- for the third part of the curve

$$\frac{\mathrm{d}z}{\mathrm{d}T_a^*} = b_3 \cdot c_3 \cdot \mathrm{e}^{(c_3 \cdot T_a^*)}. \tag{7}$$

The first part of the curve is defined by equation (5), the second part by equation (6) and the third part by equation (7).

The efficiency of rotary heat regenerators depends on type and size of the rotor and the ratio between input and output of air. The degree of heat recovery for waste air, for the same rotation number, is defined as:

$$\eta_1 = \frac{T_{11} - T_{12}}{T_{11} - T_{21}} \tag{8}$$

and for fresh air as:

$$\eta_2 = \frac{T_{22} - T_{21}}{T_{11} - T_{21}}. \tag{9}$$

Figure 3 presents the distribution of average daily temperatures in the city Celje, between 1995 to 2004 [7].

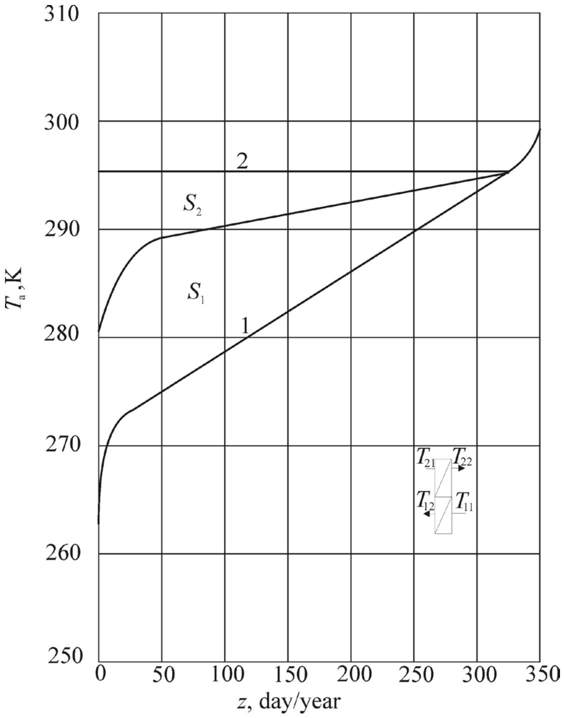

Figure 3. The curve of sum of days with average daily temperatures, T_a

Slika 3. Krivulja sume dana s prosečnom dnevnom temperaturom, T_a

The surface (Figure 3) between the curve of average daily temperature - 1 and temperature of inside air - 2 presents the energy needed for heating. Surface S_1 is called annual temperature number and presents the heat, which is saved by using rotary heat regenerator. Its largeness depends on the efficiency of the heat regenerator. Surface S_2 is a heat portion, which must be ensured from another source in order to achieve the inside temperature of the air.

The computer programme for making curves on fig. 3 and determining surfaces S_1 and S_2 with the help of integration was developed at the Faculty of Chemistry and Chemical Engineering, University of Maribor. The surfaces which were mentioned are a major source of data for carrying out the economic analysis of the operation of rotary heat regenerator.

4. Dynamic economic method

Investment decisions are the most important business decisions for a company. They determine the terms and management in the future and they also have a long-term effect on the business and the development of the company. Economic viability of investment into heat regenerator can be done with the static or dynamic economic method [15].

With the static method expenses and incomes are determined for a certain period of time and are considered as unchangeable throughout the whole investment, which is therefore suitable only for short - term projects.

Long - term projects, which depend on time, require consideration of the interest rate, inflation rate and energy prices. These parameters are considered in the dynamic method to estimate the economic efficiency, which is based on the fact that payment made in the future is worth less than the same payment paid at once. By determining the minimum of cost function with the dynamic method it is necessary to consider the rise of energy prices which go up, even though the heat losses in air conditioning systems are constant, which is taken into account in the investment into the heat regenerator.

The whole investment costs are costs for buying a rotary heat regenerator c_{reg}, which are given in EUR. The present worth of yearly annuity for investment into heat regenerator is given with equation:

$$L_p = b \cdot c_{reg}. \tag{10}$$

Discount factor – b considers regenerators lifetime n, interest i, degree of increasing maintenance costs r and degree of increasing because of other costs g.

Discount factor is given with:

$$b = \frac{\text{yearly costs for operating}}{\text{investment into regenerator}}. \tag{11}$$

Very often we use:

- fundamental discount factor

$$b_1 = \frac{1}{n} + \frac{i+r+g}{100}, \tag{12}$$

- fundamental discount factor taking amortisation during lifetime into account

$$b_2 = \frac{1}{n} + \frac{1}{100}\left(\frac{i+1}{2} + r + g\right), \tag{13}$$

- dynamic discount factor

$$b_3 = \frac{i/100}{1-\left(\frac{1}{1+i/100}\right)^n} + \frac{r+g}{100}. \tag{14}$$

Interest rate must be planned for a long time and based on stable economic factors. Yearly income of selling heat which is produced by operating with a heat regenerator is given by the static method with the following equation:

$$L_p = c_{lp} - c_{vzd} - c_{ste}, \tag{15}$$

$$c_{lp} = \frac{q_v \cdot \rho \cdot c_p \cdot S_1 \cdot c_t \cdot t_1 \cdot t_2}{365}, \tag{16}$$

$$c_{vzd} = 0.02 \cdot c_{reg}, \tag{17}$$

$$c_{ste} = c_{em} + c_{ev}, \tag{18}$$

$$c_{ste} = t_1 \cdot t_2 \cdot c_e \cdot \left(\frac{P_e}{\beta_e} + \frac{q_v \cdot p_v + q_{iz} \cdot p_{iz}}{\beta_v}\right). \tag{19}$$

Yearly incomes of selling heat energy with the use of dynamic methods are given with the equation:

$$L_p = c_{lp} - \left(c_{vzd} + c_{ste}\right) \cdot f. \tag{20}$$

Where factor f is given with the following relation:

$$f = \frac{P_1}{P_2}, \tag{21}$$

$$P_1 = \frac{1-\left(\frac{1+P/100}{1+i/100}\right)^n}{1-\frac{1+P/100}{1+i^z/100}}, \tag{22}$$

$$P_2 = \frac{1-\left(\frac{1}{1+i/100}\right)^n}{1-\frac{1}{1+i/100}}. \tag{23}$$

The price of acquired heat in EUR/Wh can be calculated with the static method, considering the present value of a yearly annuity for regenerator, discount factor and yearly income by equation:

$$c_t = \frac{365 \cdot \left(c_{reg} \cdot b + c_{vz} + c_{ste}\right)}{q_v \cdot \rho \cdot c_p \cdot S_1 \cdot t_1 \cdot t_2}. \tag{24}$$

Or with the use of dynamic method with the equation:

$$c_t = \frac{365 \cdot \left(c_{vtz} + c_{reg}\frac{b}{f} + c_{ste}\right)}{q_v \cdot \rho \cdot c_p \cdot S_1 \cdot t_1 \cdot t_2}. \tag{25}$$

5. Economic evaluation of rotary heat regenerator

The dynamic method is used for economic evaluation of condensed heat regenerator in air conditioning systems.

Based on the climatic data, a curve of distribution of average daily temperature during the last five years was calculated. With the help of data which are given in table 1 the economic calculation was made and their results are presented in Figures 4, 5 and 6.

Table 2. Data used for economic evaluations

Tablica 2. Podaci za ekonomsku procjenu

air flow rate / volumenski protok $q_v = q_{iz}$	2.5 m^3/s
pressure drop / pad tlaka $p_v = p_{iz}$	150 Pa
air density / gustina zraka, ρ	1.2 kg/m3
specific heat of air / specifična toplina zraka, c_p	1 kJ/kgK
electromotor power / snaga elektromotora, P_e	0.4 kW
fan and electromotor efficiency / stupanj koristnosti ventilatora i elektromotora, $\beta_v = \beta_{el}$	80 %
price of electric power / cijena električne energije, c_e	0.13 EUR/kWh
operating time / radno vrijeme, t_1	8, 12, 24 h/day
interest rate / kamatna stopa, i	8 %
inflation rate / stopa inflacije, p	1.2 %
degree of increase of costs of maintenance / stupanj porasta troškova održavanja, r	1.2 %
degree of increase of other costs / stupanj porasta drugih troškova, g	1.2 %

From these figures, according to the working time of the regenerator, it is possible to calculate the price of returned heat for the demanded payback time and investment.

In case that the regenerator works 150 day/year for 8h/day, costs refund after eight years if the heat price is equal to the current sale price (62 EUR/MWh). Payback time is shorter if the price of heat is higher. Economy of heat regenerator directly depends on climatic data of the area where the regenerator works.

For example, if the regenerator works for 12 h/day for 150 days/year it refunds after 6 years (Figure 5) and if it operates 24 h/day for 150 days/year it refunds in less than 2 years (Figure 6).

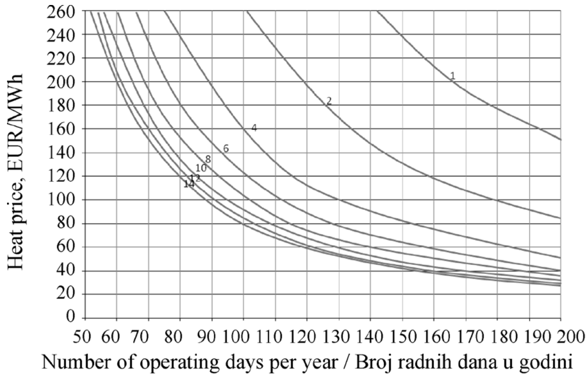

Figure 4. Heat prices and payback time depending on number of operating days if regenerator operates 8 h/day

Slika 4. Cijena topline i rok povraćaja ovisno o broju radnih dana, ako regenerator radi 8 h/dan

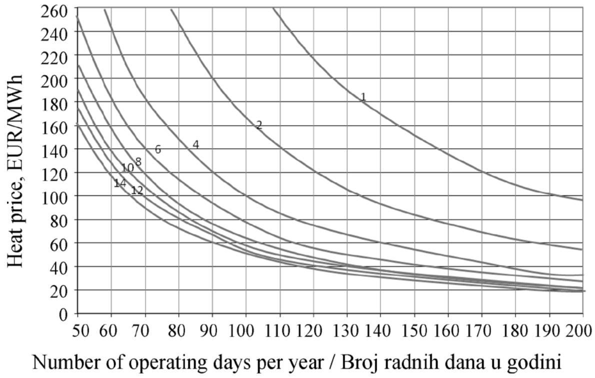

Figure 5. Heat prices and payback time depending on number of operating days if regenerator operates 12 h/day

Slika 5. Cijena topline i rok povraćaja ovisno o broju radnih dana, ako regenerator radi 12 h/dan

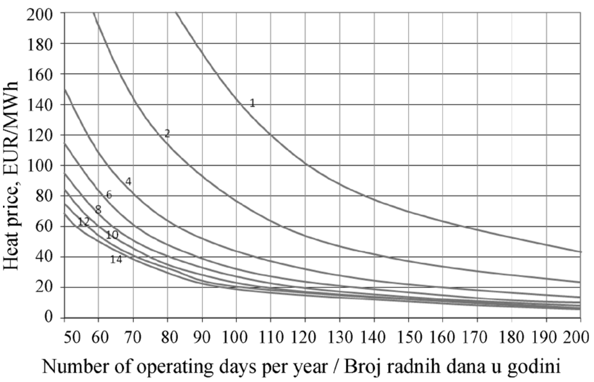

Figure 6. Heat prices and payback time depending on number of operating days if regenerator operates 24 h/day

Slika 6. Cijena topline i rok povraćaja ovisno o broju radnih dana, ako regenerator radi 24 h/dan

6. Conclusion

Heat savings depend on temperature difference between waste and fresh air. Temperature distribution of fresh air depends on season as well as climatic area. Consequently, the curve of sum of days with average daily temperatures was taken as a basis for evaluation of the investment profitability, payback time, maintenance and operating costs for the heat regenerator.

In the paper, the calculated economic efficiency of operation of rotary heat regenerator has shown that refund time is the shortest if the regenerator operates 24 h/day and much longer if it operates 8 h/day.

If we assume that energy prices in the future will be much higher and if we want to lower the heating costs, it is certainly a very good idea to build the rotary heat regenerator into the air conditioning systems.

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