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Calculation Method of Energy Efficiency Assessment of Ventilation Systems with Local Recirculation Diffusers

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Abstract
Taking into account low values of specific heat protection performances of buildings, specified by Russian regulations, and high values of internal heat generation office buildings in most of Russian regions are characterized by internal heat excess even at low ambient temperatures in cold seasons. Assimilation of internal heat excess due to supply of cold outdoor air while providing comfortable parameters of air flow at inlet to working area of attended rooms is provided by ventilation system with local recirculation diffusers developed by authors; this article presents the concept flowchart of ventilation system with local recirculation diffusers and design of the developed recirculation diffuser. In previous articles we presented feasibility study of development and application of local recirculation diffusers for energy efficient ventilation systems, as well as numerical simulation of efficiency of the developed design of local recirculation diffuser. This article discusses calculation procedure of energy efficiency of the developed system in comparison with conventional direct ventilation system, the analysis is given for an office building in Moscow. The obtained results evidence significant potentials of energy saving by means of the developed ventilation system with local recirculation diffusers upon application in buildings with internal heat excess in cold and interim seasons.

Keywords: Ventilation systems, recirculation, local recirculation diffuser, diffuser, energy efficiency, calculation, consumption, heat, electric energy.

INTRODUCTION

Nowadays the main aim of an engineer is decrease in energy consumption by buildings with simultaneous provision of comfort environment for humans in rooms. This task stipulated improvement of existing systems and development of new schematic and process designs for internal engineering systems [1, 2, 3, 4, 5, 6, 7, 8, 9].

Currently, together with low value of heat loss in building in cold and interim seasons (when the outdoor ambient temperature is lower than that of indoor air) due to high thermal protection of envelope in public buildings there exists increase in internal heat excess due to operation of numerous office machines.

We analyzed the ratio between internal heat generation and loss for office buildings in various regions of Russia; it was concluded that in most office buildings of Russia even at negative temperatures of outdoor air there are internal heat excesses (for instance, in office building with the volume of 6000 m^3 in Moscow the internal heat excess occurs at the temperature of ambient air above –9°C). In order to maintain comfort temperature the internal heat excess should be assimilated.

One of engineering solutions for assimilation of internal heat excesses is application of ventilation systems with central recirculation, which are characterized by certain disadvantages: significant increase in energy consumption by the system for transfer of recirculation air, propagation of bacteria and contaminations between attended rooms, increase in occupied space by ducts for recirculation air, impossibility to account for heat and humidity processes in each room upon operation of the system.

Aiming at the use of cooling potentials of outdoor air for rooms with internal heat excesses in cold and interim seasons, as well as at elimination of disadvantages of ventilation system with central recirculation we developed ventilation system with local recirculation diffusers (Fig. 1). The developed system makes it possible to supply underheated air into a room to recirculation diffuser which mixes outdoor and recirculation air for the room, which provides assimilation of internal heat excesses and maintains comfort temperature of supply air flow at inlet to working area.

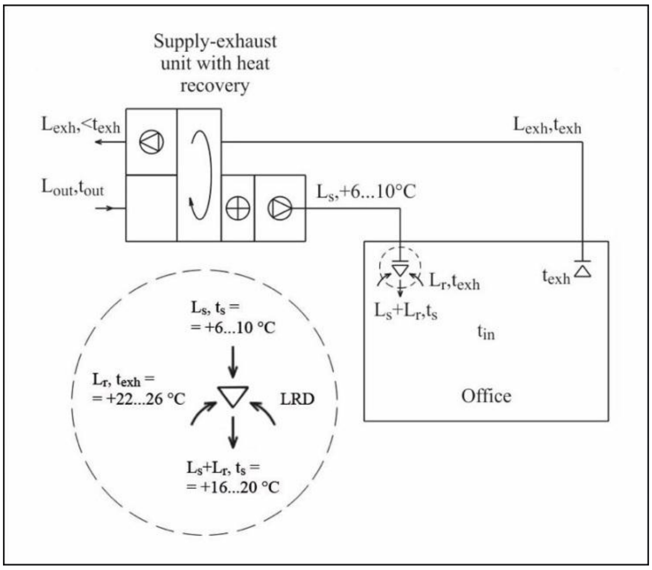

Figure 1. Schematic view of ventilation system with local recirculation diffusers.

Recirculation diffuser (Fig. 2) operates as follows.

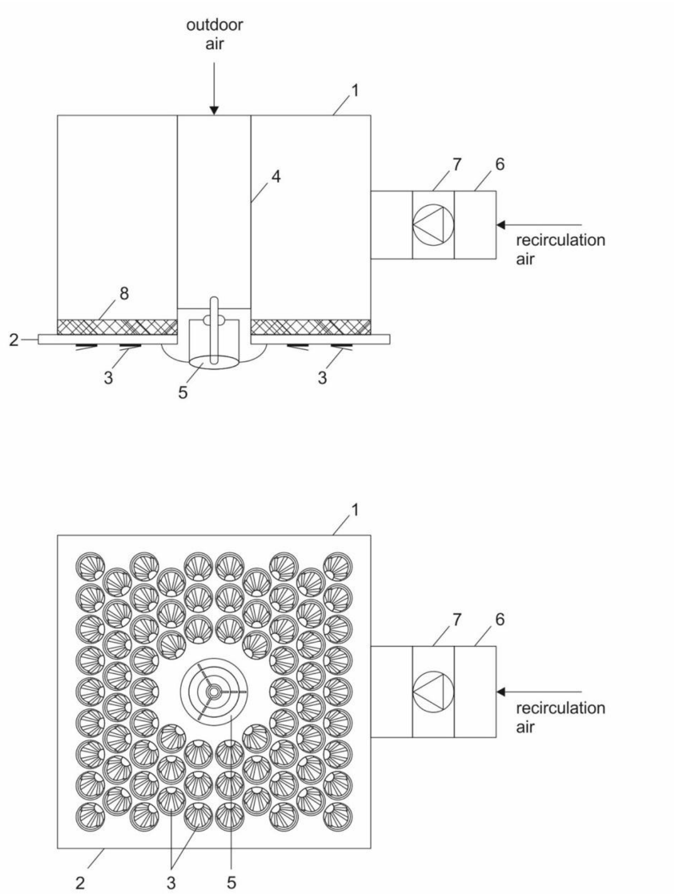

Figure 2. Schematic view of local recirculation diffuser.

Outdoor air at lower temperature (≥ +6°C) from ventilation unit (not shown) is supplied to the pipe 4 and, via the diffuser 5, into a room. The diffuser 5 generates adhering radial air jet, outdoor air consumption remains stable upon operation of the system. The fan 7 supplies recirculation air (indoor air) via the recirculation air pipe 6 into the chamber of static pressure 1, the air passing through the filter 8 is cleaned and also supplied to the room via the swirl cells 3, located on the diffuser front panel 2. The swirl cells 3 generates adhering radial jet of recirculation air, which is mixed with outdoor air supplied from the diffuser 5, thus generating the supply air jet. The preset temperature of supply air, and consumption of recirculation air are maintained by controller and variable frequency drive (not shown) by means of speed variation of the fan 7.

Feasibility study of the development and application of local recirculation diffusers for energy efficient ventilation systems is discussed elsewhere [10], numerical simulation of application efficiency of the developed design of local recirculation diffuser is described in [11]. This work analyzes energy efficiency of ventilation system with local recirculation diffusers.

Experimental

Contrary to conventional direct ventilation the system with local recirculation diffusers should provide decrease in consumption of heat energy in cold and interim seasons due to assimilation of internal heat excesses by heated supplied air. Herewith, electric energy consumption by ventilation system increases because local recirculation diffuser is equipped with fan.

While estimating energy consumptions the heat consumption was calculated both for ventilation system and heating system due to redistribution of loads on these systems at low internal heat generation in the periods of low occupancy rate (at the start and at the end of working hours).

The procedure is based on main provisions stated in [12, 13, 14, 15, 16], the procedure takes in account consumption of heating energy for heating and ventilation systems occurring only in working hours (this should be based on data of outdoor temperature of typical year published on energyplus.net for Moscow [17]).

Temperature of indoor air was assumed in the ranges of optimum and allowable norms according to Russian Standard GOST 30494-2011 [18].

In terms of heat balance in cold and interim seasons a building is characterized by:

1) Heat losses via envelope, Q_{hl}, W:

$$Q_{hl} = k_{vol}^{mp} \cdot V_{hv} \cdot (t_{in} - t_{out}) \quad (1)$$

where k_{vol}^{mp} is the specific heat protection performance of building, $\frac{W}{m \cdot °C}$, determined according to Regulations SP 50.13330 [19]; V_{hv} is the heated space of building, m^3.

2) Internal heat generation, Q_{hg}, W:

$$Q_{hg} = Q_{hum} + Q_{light} + Q_{office}, \quad (2)$$

where Q_{hum} is the heat gains from humans, W:

$$Q_{hum} = q_{hum} \cdot n \cdot \eta_{pres}, \quad (3)$$

q_{hum} is the heat gains from a human, W/hum, determined by the table 6.1 [16] as a function of indoor temperature and work burden; n is the number of humans in building, persons; η_{pres} is the coefficient accounting for heterogeneity of number of personnel in building during working hours; Q_{light} is the heat gains from lighting, W:

$$Q_{light} = q_{light} \cdot \eta \cdot A \cdot \eta_{work.light}, \quad (4)$$

q_{light} is the specific preset power of lamps, W/m^2, determined by Table 6.2 [16]; η is the coefficient accounting for heat portion from lamp in room, determined by Table 6.4 [16]; A is the lighted surface area in building, m^2, assumed to be equal to overall surface area of building; $\eta_{work.light}$ is the coefficient accounting for simultaneous activation of all lamps; Q_{office} is the heat gains from office machines, W:

$$Q_{office} = q_{comp} \cdot n_{comp} \cdot \eta_{pres} + q_{l.mach.} \cdot n_{l.mach.} \cdot \eta_{work}, \quad (5)$$

q_{comp} is the heat gain from one computer, W, assumed to be equal to 150 W; n_{comp} is the number of computers, pieces, assumed to be equal to number of personnel in building; $q_{l.mach.}$ is the heat gain from one large office machine (plotter, scanner), W; $n_{l.mach.}$ is the number of large office machines, pieces; η_{work} is the coefficient of simultaneous operation of large office machines.

Direct ventilation systems

Conventional direct ventilation systems (DVS) are designed for supply of outdoor air in amount of sanitary norm, L_{out}^{DVS}, m³/h, (in Russia in office buildings: 60 m³/h per one employee, according to Regulations SP 118.13330 [20]). In cold and interim seasons outdoor air with the temperature t_{out}, °C, is heated in heater of ventilation unit and supplied to working zone with the temperature t_s, °C, which usually equals to the temperature of indoor air t_{in}, °C.

Heat energy consumption for heating of outdoor air, Q_{vent}^{DVS}, W:

$$Q_{vent}^{DVS} = \frac{c\rho L_{out}^{DVS}(t_s - t_{out})}{3.6}, \qquad (6)$$

where c is the air heat capacitance, kJ/(kg·K); ρ is the air density, kg/m³.

Consumption of heat energy for heating of outdoor air can be decreased by means of supply and exhaust ventilation units with heat recovery in ventilation system. Air temperature after heat recovery, t_{hr}, °C, is determined as follows:

$$t_{hr} = t_{out} + \eta_{hr} \cdot (t_{exh} - t_{out}), \qquad (7)$$

where η_{hr} is the efficiency of heat recovery; t_{exh} is the temperature of exhaust air, °C.

With installed heat recovery in ventilation unit outdoor air is heated from the temperature after heat recovery t_{hr}, °C, to the temperature t_s, °C.

Herewith, heat energy consumption for heating of outdoor air, Q_{vent}^{DVS}, W, is determined as follows:

$$Q_{vent}^{DVS} = c\rho L_{out}^{DVS}(t_s - t_{hr})/3.6 \qquad (8)$$

In conventional direct ventilation system, when heat generation is higher than heat loss, heating is not required. Herewith, the indoor temperature, t_{in}, °C, will increase and, hence, the heat recovery temperature t_{hr}, °C will also increase.

The indoor air temperature with account for heat excess, $t_{in}^{`}$, °C, is determined as follows:

$$t_{in}^{`} = t_{in} + \frac{Q_{h/exc}}{(Q_{hl}/(t_{in} - t_{out}) + c\rho L_{out}^{DVS}/3.6)}, \qquad (9)$$

where $Q_{h/exc}$ is the amount of heat excess, W, determined as follows:

$$Q_{h/exc} = Q_{hg} - Q_{hl} \qquad (10)$$

In the calculations the indoor air temperature was set to 20°C according to Russian Standard GOST 30494-2011 [18], it is assumed that at higher temperature employees will aerate the room.

Heat recovery temperature with accounting for heat excess, $t_{hr}^{`}$, °C, is determined as follows:

$$t_{hr}^{`} = t_{out} + \eta_{hr} \cdot (t_{in}^{`} - t_{out}) \qquad (11)$$

Then, heat energy consumption for heating of outdoor air with accounting for heat excess, $Q^{`DVS}_{vent}$, W, is determined as follows:

$$Q^{`DVS}_{vent} = c\rho L_{out}^{DVS}(t_s - t_{hr}^{`})/3.6 \qquad (12)$$

Heat energy consumption for heating system, Q_{hs}^{DVS}, W, is determined as follows:

$$Q_{heat}^{DVS} = Q_{hl} - Q_{hg} \qquad (13)$$

Annual consumption of heat energy for heating of outdoor air in the case of conventional mixing ventilation, $Q_{vent.ann}^{DVS}$, kW·h, is determined as follows:

$$Q_{vent.ann}^{DVS} = \sum_{i=1}^{i=m} Q_{vent,i}^{DVS} n/1000, \qquad (14)$$

where n is the number of working hours per day, set to 10 (from 9:00 to 19:00); m is the number of working days per year when heating of outdoor air is required.

Annual consumption of heat energy in working hours in the case of conventional ventilation systems, $Q_{hs.ann}^{DVS}$, kW·h, is determined as follows:

$$Q_{hs.ann}^{DVS} = \sum_{i=1}^{i=k} Q_{heat,i}^{DVS} n/1000, \qquad (15)$$

where k is the number of working days per year when heating is required.

Annual consumption of electricity for transfer of ventilating air in DVS, $W_{vent.ann}^{DVS}$, kW·h, is determined as follows:

$$W_{vent.ann}^{DVS} = L_{out}^{DVS}(w_{spec}^{exh} + w_{spec}^{s})zn, \qquad (16)$$

where w_{spec}^{exh} is the specific consumption of electricity for transfer of 1 m³/h of exhaust air, W/(m³/h), set to 0.3 W/(m³/h); w_{spec}^{s} is the specific consumption of electricity for transfer of 1 m³/h of supply air, W/(m³/h), set to 0.45 W/(m³/h); z is the number of working days in the considered period.

VENTILATION SYSTEM WITH RECIRCULATION DIFFUSER

In the case of ventilation systems with recirculation diffusers (RDVS) outdoor air is supplied according to sanitary norms, heated by the heater of ventilation unit from the temperature t_{out}, °C, to $t_{lrd} = +6 \ldots 8$°C (lower temperature of +6°C is aimed at prevention of condensate formation of air ducts; however, heating to +6°C is possible only in electric heater, when hot water heater is used air is heated to +8°C, thus providing correct operation of automatic system of prevention of heater freezing), herewith, consumption of outdoor air, L_{out}^{RD}, m³/h, equals to consumption of supply L_s^{RD} , m³/h, and exhaust air L_{exh}^{RD}, m³/h.

Consumption of heat energy for heating of outdoor air, Q_{vent}^{RD}, W:

$$Q_{vent}^{RD} = c\rho L_{out}^{RD}(t_{lrd} - t_{out})/3.6 \qquad (17)$$

RDVS assumes mixing of supply air with the temperature of t_{lrd}, °C, of sanitary amounts with recirculation air with the temperature of t_{exh}, °C, herewith, the mixture temperature, t_{mix}, °C, after recirculation diffuser will equal to:

$$t_{mix} = \frac{L_{out}^{RD} t_{lrd} + L_r^{RD} t_{exh}}{L_{out}^{RD} + L_r^{RD}} \quad (18)$$

where L_r^{RD} is the amount of added recirculation air, m^3/h, at the ratio of $\frac{L_r^{RD}}{L_{out}^{RD}} \leq 4$.

If required, the supply air will be additionally heated from the temperature of mixture, t_{mix}, °C, to the normal temperature of indoor air, t_{in}, °C, directly in the building by heating system.

Energy consumption by heating system for heating of supply air, $Q_{hs.vent}^{RD}$, W, is determined as follows:

$$Q_{hs.vent}^{RD} = c\rho(L_{out}^{RD} + L_r^{RD})(t_{in} - t_{mix})/3.6 \quad (19)$$

Consumption of heat energy for heating of outdoor air can be decreased by means of supply and exhaust ventilation units with heat recovery (similar to direct ventilation system). Air temperature after heat recovery, t_{hr}, °C, is determined by Eq. (7). Then, air with the temperature of $t_{hr} < 6$°C will be heated to t_{lrd} =+8°C in hot water heater, in other cases the supply air will be supplied at the temperature of $t_{hr} > 6$°C. Then, Eq. (18) will be as follows:

$$t_{mix} = \frac{L_{out}^{RD} t_{hr} + L_r^{RD} t_{exh}}{L_{out}^{RD} + L_r^{RD}} \quad (20)$$

As in the case of conventional direct ventilation system, when in RDVS the heat generation is higher than heat loss, heating is not required. Herewith, the indoor temperature, t_{in}, °C, will increase and, hence, the temperature of heat recovery t_{hr}, °C will also increase.

The indoor temperature with accounting for hear excess, $t\grave{}_{in}$, °C, is determined by Eq. (9), and the amount of heat excess, $Q_{h/exc}$, W, is determined as follows:

$$Q_{h/exc} = Q_{hg} - Q_{hs.vent}^{RD} \quad (21)$$

Consumption of heat energy for heating and ventilation system, Q_h^{RD}, W, is determined as follows:

$$Q_h^{RD} = Q_{hl} - Q_{h/exc} + Q_{vent}^{RD} \quad (22)$$

At $Q_h^{RD} < 0$ there is heat excess consumed for heating of indoor air.

In the calculations the indoor air temperature was set to 20°C according to Russian Standard GOST 30494-2011 [18], it is assumed that at higher temperature employees will aerate the room.

The temperature of heat recovery with accounting for heat excess, $t\grave{}_{hr}$, °C, is determined by Eq. (11).

The temperature of air mixture with accounting for heat excess, $t\grave{}_{mix}$, °C, is determined as follows:

$$t\grave{}_{mix} = \frac{L_{out}^{RD} t\grave{}_{hr} + L_r^{RD} t_{exh}}{L_{out}^{RD} + L_r^{RD}} \quad (23)$$

The consumption of recirculation air, $L\grave{}_r^{RD}$, m^3/h, required for maintaining of optimum temperature of supply air with accounting for heat excess is determined as follows:

$$L\grave{}_r^{RD} = \frac{L_{out}^{RD}(t_s - t\grave{}_{hr})}{t_s - t_{exh}} \quad (24)$$

Then, Eq. (19) will be as follows:

$$Q\grave{}_{hs.vent}^{RD} = c\rho\left(L_{out}^{RD} + L\grave{}_r^{RD}\right)(t_{in} - t\grave{}_{mix})/3.6 \quad (25)$$

Consumption of heat energy for heating and ventilation system, Q_h^{RD}, W, is determined as follows:

$$Q\grave{}_h^{RD} = Q_{hl} - Q_{h/exc} + Q\grave{}_{hs.vent}^{RD} \quad (26)$$

Annual consumption of heat energy for heating and ventilation system, $Q_{h,ann}^{RD}$, kW·h, is determined as follows:

$$Q_{h.ann}^{RD} = \sum_{i=1}^{i=m} Q_{h,i}^{RD}\, n/1000, \quad (27)$$

where n is the number of working hours per day, set to 10 (from 9:00 to 19:00); m is the number of working days per year when heating of outdoor air is required.

Annual consumption of electric energy for transfer of ventilating air for RDVS, $W_{vent.ann}^{RD}$, kW·h, is determined as follows:

$$W_{vent.ann}^{RD} = \left[L_{out}^{RD}\left(w_{spec}^{exh} + w_{spec}^{s}\right) + L_r^{RD} w_{spec}^{r}\right] zn, \quad (28)$$

where w_{spec}^{exh} is the specific consumption of electric energy for transfer of 1 m^3/h of exhaust air, W/(m^3/h), set to 0.3 W/(m^3/h); w_{spec}^{s} is the specific consumption of electric energy for transfer of 1 m^3/h of supply air, W/(m^3/h), set to 0.45 W/(м^3/h); w_{spec}^{rec} is the specific consumption of electric energy for transfer of 1 m^3/h of recirculation air, W/(m^3/h), set to 0.08 W/(m^3/h); z is the number of working days in the considered period.

EFFICIENCY ESTIMATION OF VENTILATION AND AIR CONDITIONING SYSTEMS

Decrease in annual heat energy consumption for ventilation system:

$$\Delta Q = \frac{Q_{vent.ann}^{DVS} + Q_{hs.ann}^{DVS} - Q_{h,ann}^{RD}}{Q_{vent.ann}^{DVS}} \cdot 100\% \quad (29)$$

Decrease in annual total energy consumption:

$$\Delta E = \frac{(Q_{vent.ann}^{DVS} + W_{vent.ann}^{DVS} \cdot x) - ((Q_{h,ann}^{RD} - Q_{hs.ann}^{DVS}) + W_{vent.ann}^{RD} \cdot x)}{Q_{vent.ann}^{DVS} + W_{vent.ann}^{DVS} \cdot x} \cdot 100\% \quad (30)$$

where x is the equivalent for normalization of electric energy with regard to heat energy, in calculations for Moscow it was set to 0.44, and calculated as the ratio of tariffs for heat to electric energy (1.59 RUB/kW·h to 3.61 RUB/kW·h).

RESULTS OF CALCULATION

An office building in Moscow (Russia) was considered. The climate in Moscow is moderately continental with expressed seasonality.

MAJOR PROPERTIES OF THE CONSIDERED OBJECT

Useful volume of the office was set to 6000 m^3 with the ceiling height of 3 m, calculated surface area per one person is 10 m^2. The heat loss of the building were determined on the basis of normalized value of heat protection performance of the building, $k_{vol}^{mp}, \frac{W}{m^3 \cdot {}^oC}$, according to Regulations SP 50.13330 [19], equaling to $k_{vol}^{mp} = 0.252 \frac{W}{m^3 \cdot {}^oC}$.

Allowable indoor temperature in winter, t_{int} =18 ºC, was set according to Russian Standard GOST 30494-2011 [18], outdoor air is supplied in amount of sanitary norm, 60 m^3/h per one employee, this air with the temperature of t_{lrd} = +6…+8°C is supplied to recirculation diffuser where it is mixed with recirculation air of the building at the ratio of $\frac{L_r}{L_{out}} \leq 4$.

The heat balance of the building considered internal heat gains from lighting units, office machines and humans at the coefficient of simultaneous attending by employees equaling to 0.6. The calculations were carried out for working hours when employees are in the office, from Monday to Friday, from 9:00 to 19:00, Saturday and Sunday as well as public holiday were not taken into account. Average daily heat gains were set to 27.54 W/m^2, including those from humans: 6.54 W/m^2, lighting units: 12 W/m^2 and office machines: 9 W/m^2.

Two variants were considered in calculations for each type of ventilation system: without and with heat recovery in supply and exhaust ventilation units (average efficiency of heat recovery unit in cold and interim seasons was set to 0.6).

RESULTS

The following results were obtained by calculations for this example (Table 1):

Table 1. Calculated energy consumption by ventilation system

Ventilation system	DVS		RDVS	
Heat recovery	No	Yes	No	Yes
Annual heat energy consumption by heating system in working hours, kW·h	34.6	34.6	34.6	34.6
Annual heat energy consumption by ventilation system in working hours, kW·h	117446.5	38511.5	72590.4	16968.9
Annual electric energy consumption in working hours, kW·h	18115.2	18115.2	24019.2	21808.1

Figure 3 illustrates specific energy consumption of the considered types of ventilation systems.

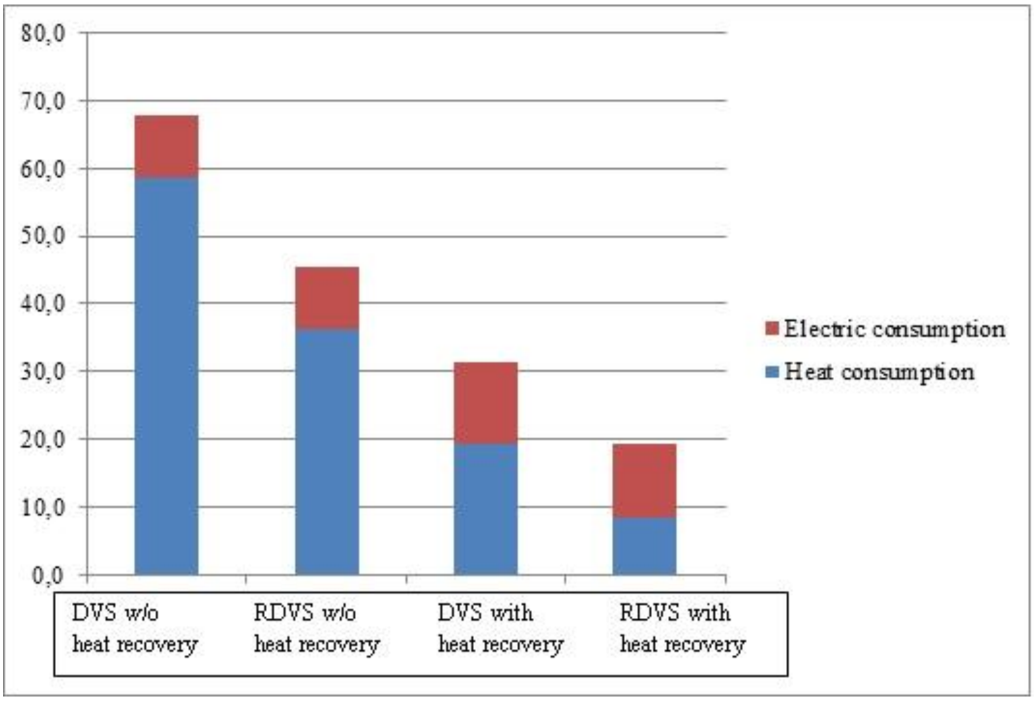

Figure 3. Specific annual energy consumption of ventilation systems, kW·h/m^2.

DISCUSSION

TABLE 2. Ventilation system efficiency with local recirculation diffusers in comparison with conventional direct ventilation systems

Heat recovery	Decrease in annual heat energy consumption per ventilation system	Decrease in annual total energy consumption
No	38.20%	19.90%
Yes	55.94%	16.50%

Table 2 summarizes estimations of energy efficiency of ventilation systems with local recirculation diffusers in comparison with conventional direct ventilation systems.

The obtained results demonstrate that the ventilation systems with local recirculation diffusers are significantly more efficient in comparison with conventional direct ventilation systems:

Without heat recovery in ventilation units the heat consumption decreased by 38.2%, and total energy consumption by 19.9%;

With heat recovery in ventilation units the heat consumption decreased by 55.94%, and total energy consumption by 16.5%.

It should be mentioned that the presented results are valid for the considered building variant; energy efficiency of ventilation systems with local recirculation diffusers installed at another site should be calculated according to the aforementioned procedure, it will depends mainly on the following factors:

- climatic features of building site;
- building geometrical configuration;
- actual value of specific heat protection performance of building;
- building operation mode including average daily heat supply;
- tariffs for electric and heat energy in the area of building site.

CONCLUSIONS

The developed procedure facilitates assessment of energy efficiency of ventilation system with local recirculation diffusers in comparison with conventional direct ventilation system.

Ventilation system with local recirculation diffusers is characterized by significant potentials of energy saving in buildings with internal heat excess in cold and interim seasons.

The subject of the considered research is promising, it requires for further analysis including field studies of performances of the developed ventilation system.

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