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Energy Demand and Operating Costs Associated with Mechanical Ventilation of Classrooms

Potřeba energie a náklady spojené s provozem nuceného větrání učeben

The aim of the contribution is to determine the energy demand for ventilating classrooms with the inclusion of heat gains and to analyse the energy benefits of high heat recovery efficiency. On a simple model of the classroom, a calculation was performed in an ESP-r energy simulation programme and the operating costs of the mechanical ventilation were determined. Part of the contribution is also an analysis of the selected local ventilation units, which leads to the determination of specific financial costs for the operation of the mechanical ventilation. It was found that the total cost of continuous mechanical ventilation with a defined air flow rate is not a crucial element of a school budget.

Keywords: *ventilation, school, energy demand, heat gains, heat recovery*

Cílem příspěvku je stanovit potřebu energie na větrání učeben se započítáním tepelných zisků a analyzovat energetické přínosy vysokých teplotních faktorů zpětného získávání tepla. Na jednoduchém modelu učebny byl realizován výpočet v energetickém simulačním programu ESP-r a stanoveny náklady na provoz nuceného větrání. Součástí příspěvku je také analýza vybraných lokálních větracích jednotek, která vede ke stanovení konkrétních finančních nákladů na provoz nuceného větrání. Bylo zjištěno, že celkové náklady spojené s provozem trvalého nuceného větrání vybaveného zpětným získáváním tepla s definovanou dávkou vzduchu nejsou pro rozpočet školy nikterak zásadní položkou.

Klíčová slova: *větrání, učebny škol, potřeba energie, tepelné zisky, zpětné získávání tepla*

INTRODUCTION

The issue of school ventilation is often completely neglected, not only in the Czech Republic, where the vast majority of school buildings are equipped with openable windows with the possibility of natural ventilation [5], but air quality in classrooms is largely inadequate [4]. Natural ventilation is not automatic and depends on many factors (outdoor climatic conditions, outdoor air quality, classroom location, building location in the landscape, surroundings, building solution, human factor, etc.). Often the natural ventilation system does not ensure that the basic requirements for indoor air quality are met.

A number of studies have shown that the degraded quality of the indoor environment in schools has a negative impact on the attention and performance of pupils [1], [11]. Similarly, this is also the case for higher morbidity, which is associated with absence, including the impact on health problems that are manifested by allergies, asthma, etc. [7], [8], [9], [10]. It is certain that ventilation (whether natural or mechanical) entails operating costs (energy payments). Energy savings due to the reduction of the ventilation may seem to be justified in the context of lowering school running costs (little money for education), at a time when there is considerable pressure to reduce the energy consumption of buildings. However, the issue is much wider, has a societal character and interferes with other sectors (health, education, industry). These costs are hardly quantifiable and argumentation in favour of a healthy indoor environment in schools is extremely difficult.

Requirements for ventilating schools

According to Decree No. 410/2005 Coll. as amended, No. 343/2009 Coll. [13], the ventilation airflow rate of school buildings is 20 to 30 m^3/h per pupil, practically representing continuous ventilation. The German VDI [16] states that the permissible concentration of CO_2 is 1000 ppm in the classroom. Interestingly, however, the German VDI Directive lists relatively high CO_2 emissions from children (15.6 l/h.pupil for the 1^{st}-4^{th} classes, 18.9 l/h.pupil for the 5^{th}-13^{th} classes in the years of education), which results in relatively high airflow rates per pupil (Table 1). Higher concentrations of CO_2 than the German directive [16], but not more than 1500 ppm [14], can be accepted in the interior. The CO_2 concentration in the outdoor unpolluted environment is assumed to be 400 ppm.

Table 1 Requirements for ventilation of classrooms according to selected regulations

Regulation	Concentration limits CO_2 [ppm]	Airflow per pupil [m^3/h.pupil]			
		3 - 6 y.o.	6 - 10 y.o.	10 - 15 y.o.	15 - 18 y.o.
		Nursery school	Elementary school		High school
Decree No. 343/2009 Coll	-	20 – 30			
EN 15251	1 200	-	14 – 36		
ÖNORM H 6039:2008	1 200	-	15	19	24
VDI 6040-1	1 000	-	26	31	31

Where outdoor air is not significantly polluted, carbon dioxide CO_2 is used as an indicator of indoor air quality. On the basis of the CO_2 balance in the interior space, the minimum airflow per pupil can be determined, according to the pupil's age, resp. of school attendance. CO_2 production depends on the activity and physical proportions of a person (weight, height). The modified ASHRAE [1] relationship can be used for the calculation:

$$\dot{V}_{CO2} = 1.742 H^{0.725} W^{0.425} M \text{ [l/h]} \quad (1)$$

For the determination of CO_2 production, the physical proportions of children can be advantageously used by standard growth charts used by paediatricians to control the correct growth of the child. The common (expected) proportion of the child is the 50% percentile, and it was used for the calculations.

The results of the airflow calculation based on CO_2 production for different limit concentrations are shown graphically in Figure 1. Table 2 shows the limit values of the air flow rate for the different levels of the educational process. As can be seen from Tab. 1, the Austrian Standard (ÖNORM H 6039:2008) permits similar considerations [17].

Table 2 Airflow rates determined on the basis of CO_2 in the room

Air quality	Concentration limits CO_2 [ppm]	Airflow per pupil [m³/h per person]			
		3 - 6 y.o.	6 - 10 y.o.	10 - 15 y.o.	15 – 18 y.o.
		Nursery school	Elementary school		Secondary school
I.	1 000	12	17	25	27
II.	1 200	9	12	18	20
III.	1 500	7	9	13	15

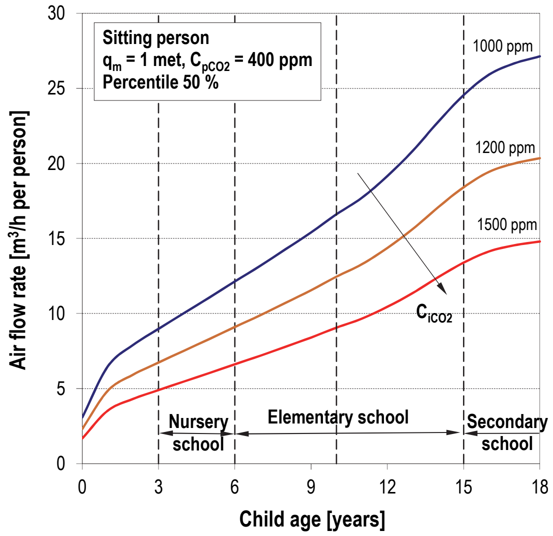


Figure 1 Airflow rate per pupil based on CO_2 balance

ENERGY REQUIREMENTS FOR VENTILATION

With today's construction requirements, heat gains significantly contribute to the overall heat balance. From the point of view of school buildings, it is mainly the internal heat gains caused by the presence of people (children) and their activities, as well as the thermal gains from the outdoor environment caused by the sun's radiation. The resulting heat flux consists of three basic items:

1) heat transmission through the wall and window,
2) heat loss by ventilation,
3) heat gains (internal and external).

Table 3 List of examined cases

A previously published analysis of the energy demand calculation for classroom ventilation [3] is based on a simplified calculation, and heat gains are practically not included (except fan gain). For a detailed analysis, it is more advantageous to use an energy simulation calculation that provides the prediction of heat loads, heat losses, indoor environment parameters, and energy demands for a given zone with the specified outdoor climate condition, usually with an hourly time step.

MODEL CASE

For the analysis, a simulation model of the classroom was constructed, the ground plan of which is shown in Fig. 2. The total floor area of the classroom is 70 m², the volume of the classroom is 245 m³.

For the purposes of this study, a classroom located in the inner building of a building with one outer wall with windows (adjacent rooms are classrooms with similar traffic and a corridor) was investigated. The orientation of the classroom was either southern or northern. The classrooms of an Elementary School, 1st level (1st to 5th years) and a Secondary School were examined. The air temperature in the classroom is considered as a constant 22 °C. The classroom is designed for 30 pupils and 1 teacher. Classroom availability for students is assumed to be 90% (27 pupils) at the time of operation, every day of the week from 8.00 to 13.00. The heat gain from the pupil was determined according to [12].

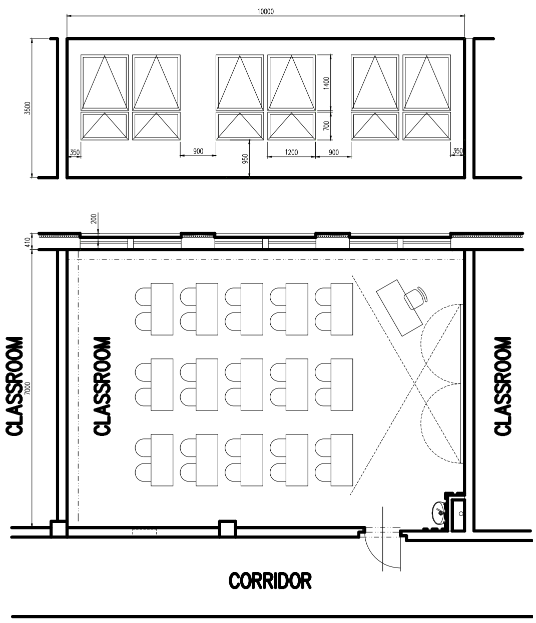


Figure 2 Floor plan of the classroom with external facade arrangement

Heat balance of the classroom

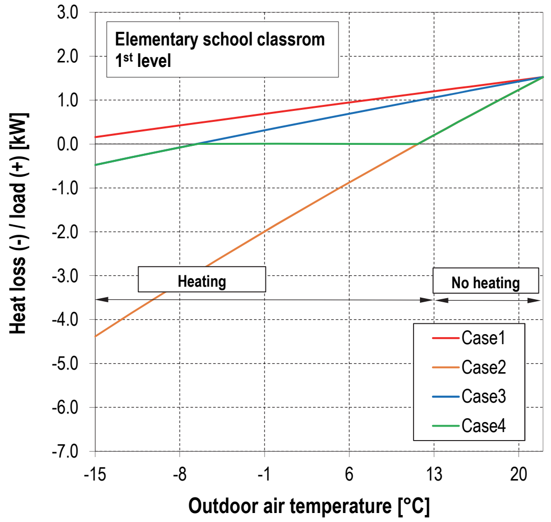
The resulting heat flux Q_t can be determined on the basis of a simplified heat equation including heat loss by walls $Q_{hl,t}$, ventilation $Q_{hl,vent}$, and internal heat gains $Q_{hg,i}$:

$$\dot{Q}_t = \dot{Q}_{hg,i} - \dot{Q}_{hl,vent} - \dot{Q}_{hl,t} \text{ [W]} \quad (2)$$

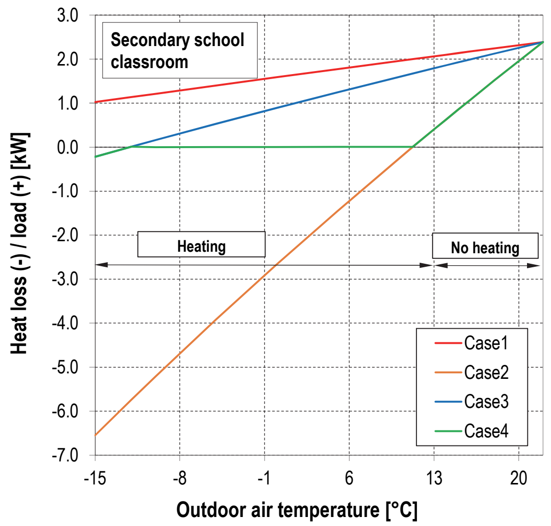
The sign "-" in the heat equation means heat loss, the sign "+" means heat gain. For simplification, we will neglect heat gains from the sun (we are considering a north-facing room where the gains from the sun in winter are negligible - see below).

Case	Description	Outside airflow		Heat recovery efficiency Φ [%]	Supply air temperature
		Elementary school	Secondary school		
1	Infiltration ventilation / micro-ventilation	0.1 h^{-1}		0 %	t_o
2	Natural ventilation	12 m^3/h.pupil	20 m^3/h.pupil	0 %	t_o
3	Mechanical ventilation	12 m^3/h.pupil	20 m^3/h.pupil	80 %	$\Phi\,(t_i - t_o) + t_o$
4	Controlled ventilation as required	12 m^3/h.pupil	20 m^3/h.pupil	max. 80 % + controlled bypass	variable

The calculations were realised for the different boundary conditions outlined in Tab. 3. Case 1 represents a classroom with insufficient ventilation, Case 2 is then with sufficient natural ventilation. Cases 3 and 4 represent mechanical ventilation with heat recovery. In Case 4, the demand controlled ventilation was used with respect to the classroom heat load removing.



a) Elementary school, 1st level



b) Secondary school

Figure 3 Heat balance of the Elementary school and Secondary school classrooms

The heat balance results are shown in Figures 3a (elementary school) and 3b (secondary school) for all the variants examined. It is clear that classroom in Case 1 is burdened by heat gains throughout the year (the resulting equation is positive - red dependence), despite the fact that we neglect the solar radiation, as a result of which the air temperature in the classroom will rise, the non-ventilated classrooms tend to overheat, which is also known from practical experience. If the permanent natural ventilation is admitted (Case 2) the effect will be the opposite - practically the whole heating period needs to be heated (orange line). In addition, commonly used heating systems cannot flexibly react to the continuous supply of outdoor air. Mechanical ventilation with high efficiency of heat recovery (Case 3) is also not an ideal solution, because the classrooms are overheated again for a significant part of the year. High requirements for the heat recovery efficiency [13] are justified, as they will only apply on the coldest days of the year (for $t_o < -5$).

These considerations lead to the need for **controlled ventilation** of the classrooms so that the resulting Equation (2) is zero as far as possible ($Q_t = 0$) – Case 4 (green dependence). This applies to the **air flow control** (based on the aiflow requirements and heat load) as well as to the **regulation of the air supply temperature**. In order to remove heat loads, it is possible to use the outside air (most of the school year $t_o < 22$ °C), without the use of mechanical cooling. It is advisable to regulate the air supply temperature by bypassing the heat recovery exchanger.

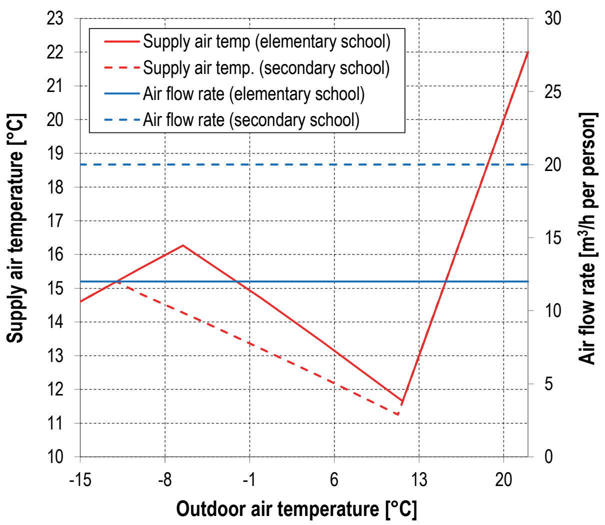


Figure 4 The supply air temperature for case no. 4

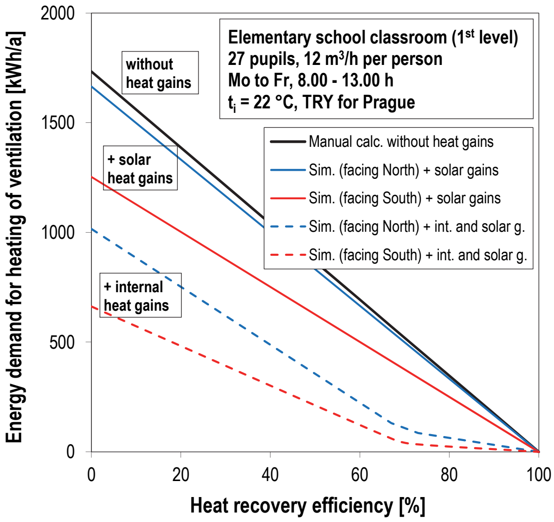
It can be seen in Fig. 4 that the air supply temperature for the thermal load discharge is relatively low (for the secondary school $t_{s,min}$ = 11.5

°C) and the difference in temperature of the inlet and supplied air is Δt_s = 10.5 °C. An integral part of the ventilation system must be, in addition to a controlled bypass, a suitable air distribution system (diffusers ensuring the diffusion of the supplied air into the space without any negative effects on the people). The heat load discharge can, of course, also be solved by increasing the air flow if the device allows it.

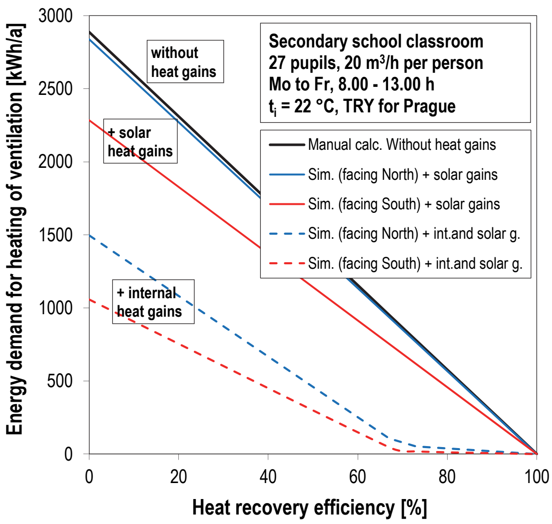
For temperatures t_o > 13 °C, natural ventilation with higher airflows can be applied to a maximum extent. From an energy point of view, this does not pose any problem as the heating system is no longer in operation.

SIMULATION

The energy demand for air heating is normally included in the need for heating. In most cases, it is difficult to separate these two values from each other, especially when heat gains enter the equation.



a) Elementary school, 1st level



b) Secondary school

Figure 5 Energy demand for outdoor air heating - results

Figure 5 shows the heat demand for ventilation depending on the efficiency of the heat recovery exchanger. The heat recovery efficiency is equal to 0% when the ventilation system is not equipped with a heat recovery, e.g., natural ventilation or under pressure mechanical ventilation. The heat recovery efficiency represent the yearly average value at the time the device is operating. The black curve represents the results of the manual calculation published in the article [3] (without considering the heat gains). The remaining dependencies were obtained based on the simulation. The red curve applies to the south-facing room, blue to the north. Dashed curves represent the realistic simulation results with consideration of both internal and external heat gains.

The heat demand for the ventilation of a model elementary school equipped with mechanical ventilation with a temperature factor of 67% (minimum requirement in accordance with [13]) is 131 kWh/year (for a north-facing classroom). In the case of a south-facing classroom, it is 61 kWh/year. At the average heat price of 500 CZK/GJ (€ 19.2/GJ) (it can actually range from 300 to 700 CZK/GJ, i.e., € 11.5 to € 30/GJ), this represents a cost of max. 236 CZK/year (€ 9/year) for a north-facing classroom and 163 CZK/year (€ 6.3/year) for a south-facing classroom, **i.e., a max. 6 CZK/year per pupil (€ 0.34 or € 0.23 respectively per year per pupil)!** In fact, this amount is even lower, as the heat gain from the intake fan (see below) will be reflected in the final equation. Similar results were also obtained in the secondary school room calculations. The heat demand for mechanical ventilation with heat recovery (HR) should not be an obstacle to its operation.

Note: Exchange rate for calculation 1 € = 26 CZK

Heated air from the fan

All the power of the fan, which is placed in the air stream together with the electric motor is converted to heat and contributes to the heating of the air. We assume that the supply fan takes one half of the total power consumption of the unit. The total heat demand for outside air heating reduced by the input fan for one of the examined variants is shown in Fig. 6 (*SFP* is the specific fan power).

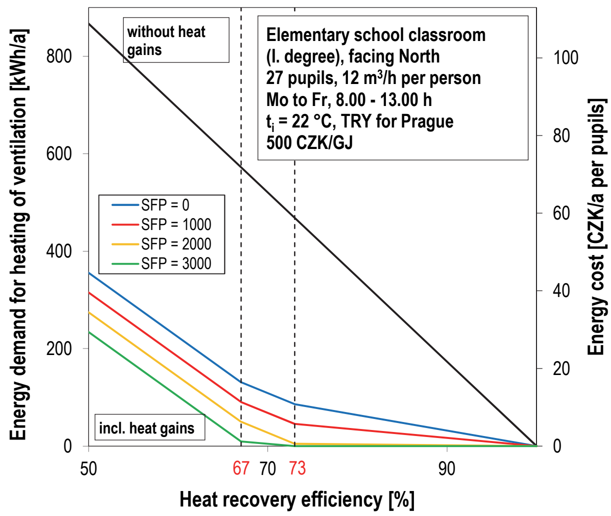


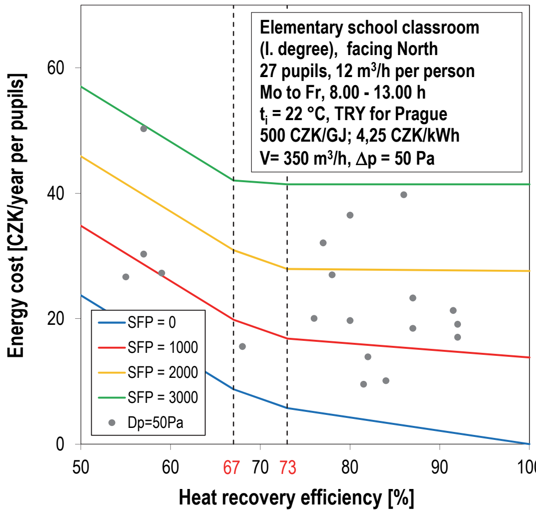
Figure 6 Energy demand for outdoor air heating when considering the heating of the air from the supply fan

The results are displayed for different *SFP* (coloured curves) values. The black line shows the heat demand without considering the heat gains. From the analyses of the ventilation units on the Czech market (see below) it was found that most units reach *SFP* values up to 3000 W.s/m³. For units with *SFP* > 3000 W.s/m³ and heat recovery Φ > 67%, it is not practically necessary to heat the air. This, of course, does not mean that the use of high-power units (high *SFP*) is energy efficient. The price for electricity is often higher than the price for thermal energy.

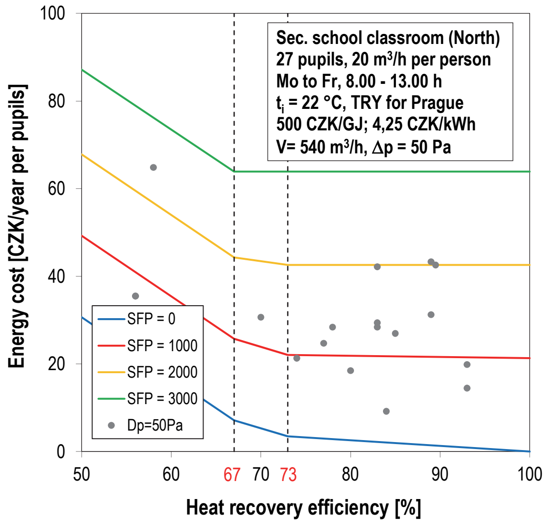
Figure 6 also sums up the indicative cost of heating the ventilating air for the examined classroom per pupil. The results take the heat load and heated air in the intake fan into account. As already mentioned, the cost of heating the ventilation air using mechanical ventilation is very low. The price for thermal energy may vary according to the heat source used or by region (district heating is used in about 1/3 of the schools) [5].

VENTILATION OPERATING COST

Figure 7 summarises the total ventilation cost per one pupil of the elementary school room considered, taking the need for electric power to drive the unit into account. The points in the graph represent the specific parameters of the ventilation units. For the purposes of this article, 19 local heat recovery ventilation units available on the Czech market (without specification) were analysed with a nominal flow of 350 resp. 540 m³/h, the transport pressure of the units was considered to be 50 Pa (the price for electric energy was considered to be 4.25 CZK/kWh).



a) Elementary school, 1st level



b) Secondary school

Figure 7 Operation cost of mechanical ventilation for different types of local ventilation units

The technical data, i.e., the power input and the efficiency of the HR, was taken from the technical documentation of the HVAC manufacturers. It is clear from Fig. 7 that most units achieve *SFP* values up to 3000 W.s/m³.

The cost of ventilation operation, depending on the type of local ventilation unit used, with heat recovery efficiency $\Phi \geq 67\%$, ranges **from 10 to 52 CZK / year per pupil (€ 0.38 to € 2 per year per pupil)**, for the classroom located in the internal tract buildings facing north). As you can see, the cost of the ventilation operation depends on the unit type, its specific fan power *SFP* and the efficiency of the HR. It is evident from Fig. 7 that a higher efficiency of the HR does not mean lower operating costs. The power input of the unit and, of course, the energy prices are essential. The actual consumption differs from the presented energy demand results - for mechanical ventilation with HR, this difference is not very significant.

CONCLUSIONS

In addition to maintaining indoor air quality, ventilation helps to reduce heat load and prevents the room overheating, even during the winter months. Due to the possible discomfort, it is not possible to continuously supply outside air without heating. On the other hand, it appears that it is necessary to bring air into the classroom at a lower temperature than the air temperature in the room for most of the year, which leads to the consideration of the need to use exchangers with high heat recovery efficiency and their benefits. Devices with a lower heat recovery efficiency will probably have less pressure loss, resulting in lower fan power consumption.

From these analyses it is clear that the operation costs of mechanical ventilation with heat recovery are minimal. In fact, it will also be necessary to consider the cost of filter replacement (usually once every 3 months), maintenance and service. The calculation is subject to some inaccuracies because it works with the energy demand rather than the energy consumption. The real heat consumption will be affected by the efficiency of the individual building HVAC systems i.e., heat sources, heating systems, power distribution, etc. These analyses were beyond the scope of the presented study.

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NOMENCLATURE

H	height of the body [m]
M	metabolic heat [met]
Q	heat flux [W]
SFP	specific fan power [W.s/m^3]
t_i	indoor air temperature [°C]
t_o	outdoor air temperature [°C]
V_o	ventilation air flow rate [m^3/h]
V_{CO2}	production of CO_2 [l/h]
W	weight of the body [kg]
Φ	heat recovery efficiency [%]

Abbreviations

CZK	Czech crowns
HR	heat recovery
HVAC	heating, ventilation and air-conditioning
SFP	specific fan power