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CONTENTS Page

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Double-skin Facade Configuration to Increase its Thermal Efficiency: Simulation Study

IBPSA-CZ

Konfigurácia dvojitej fasády pre zvýšenie jej tepelnej účinnosti: energetická simulačná štúdia

Nowadays, double-skin facades represent a distinctive architectural element in modern buildings. However, their real thermal impact on the overall building energy performance can be enhanced by the facades internal modifications. The main modifications include the dimensions of the facade cavity, the intensity of the solar radiation, the combination of the optical parameters of both the transparent and opaque parts, as well as the possibility to have a natural or forced air flow movement in the cavity. The presented paper is focused on the quantification of the different levels of the above-mentioned factors as the boundary conditions for the thermal performance of the air flow movement in the facade cavity through its overall height.
Keywords: *double-skin facade, energy performance, CFD simulation*

Dvojplášťové fasády tvoria v súčasnosti na moderných stavbách zaujímavý a výrazný architektonický prvok. Ďaleko väčší prínos ale tvorí ich reálny účinok na celkovú energetickú bilanciu budovu, ako aj vytvorenie tepelnej pohody v nej. Tento prínos do značnej miery ovplyvňuje niekoľko významných faktorov. Medzi tie najhlavnejšie patrí konštrukčná šírka tohto medzipriestoru, intenzita slnečného žiarenia, kombinácia optických parametrov oboch jej transparentných častí (vnútornej a vonkajšej), ako aj možnosť jeho prirodzeného či technikou podporeného odvetrávania. Práve posledne zmieňovaný faktor, v kombinácií so spôsobom odvetrávania a aplikáciou niekoľkých netransparentných častí, výrazne ovplyvňuje okrajovú podmienku teplovýmenného obalu budovy a tak do značnej miery ovplyvňuje aj energetickú bilanciu budovy. A práve kvantifikácia toho tvorí podstatnú časť, náplň predkladaného príspevku.
Klíčová slova: *dvojplášťová fasáda, energetická bilancia, CFD simulácia*

INTRODUCTION

The presented paper can be divided into two main parts. In the first part, the study of the influence of several boundary conditions on the performance of the double-skin facade (DSF) with a forced air movement in the upper part of the facade cavity (heat pump implementation) together with a reduced flow can be found. In the second part, the natural air flow movement in the facade cavity was investigated.

THEORY OF DOUBLE-SKIN FACADES

Double-skin facades, as a modern architectural element, still receive considerable attention in the scientific community. The generalisation of their impacts on the building energy saving potential has revealed the main advantages (with consideration to the technical design aspects) in symbiosis with the results achieved in real buildings [1]. Its thermal performance represents a significant factor influencing a facade's selection and application in real buildings. The computational methods of the DSF performance prediction are often based on different principles, one of which is the so-called "response factor" of the external boundary condition, towards this facade [2]. Many parametric studies have been carried out investigating the physical phenomena in DSFs, which took the whole set of variables that affected the results of energy savings into account [3]. A current trend is especially seen in the application of DSFs on high-rise buildings, where some of the important factors may be its height position and localisation. Moreover, existing buildings can be suitably supplemented by incorporating an innovative element of DSF in the process of their reconstruction [4]. The DSF can be realised with the support of building services technology, but also as a natural system based on the basic physical principles of air flow [5-6]. A separate chapter of research and development of DSFs is regarding the application of blinds in the facade cavity, which can also significantly affect the energy effect of the entire facade [7], as well as the direct dependence of the air flow on the cavity width [8].

SIMULATION MODEL

For the present study, a CFD 3D model of a DSF was created with a total (visible) length of 4500 mm, varied facade cavity widths (600 to 1500 mm) and a height of four floors having a construction floor height of about 3450 mm.

The outer glazing is simple (with parameters R_{E1} = 6 %, A_{E1} = 34 %, T_{E1} = 60 % a U_{g1} = 4,60 W/(m^2.K)) and the inner glazing is insulating triple glazing (with parameters R_{E2} = 33 %, A_{E2} = 20 %, T_{E2} = 47 % and U_{g2} = 0,60 W/(m^2.K)).

The remaining non-transparent structures were modelled in accordance with the current standard requirements of the thermal protection of buildings [9], the wall structure – a reinforced concrete wall (250 mm) and mineral wool (180 mm), U_{wall} = 0.205 W/(m^2.K) and a flat roof – a reinforced concrete slab (180 mm), a sloping lightweight concrete layer (100 mm) and mineral wool (220 mm) U_{roof} = 0.150 W/(m^2.K).

The inlet opening of the DSF is in the lower part, with an area identical to the floor area of the facade cavity (the effective area of the cover grille is 70%) and in the upper part is located in an opening intended for the forced and natural outlet.

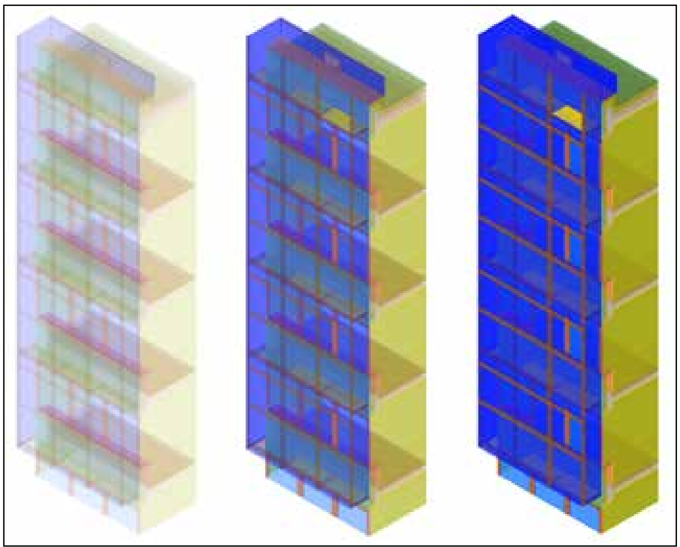

Figure 1 CFD model of the investigated DSF

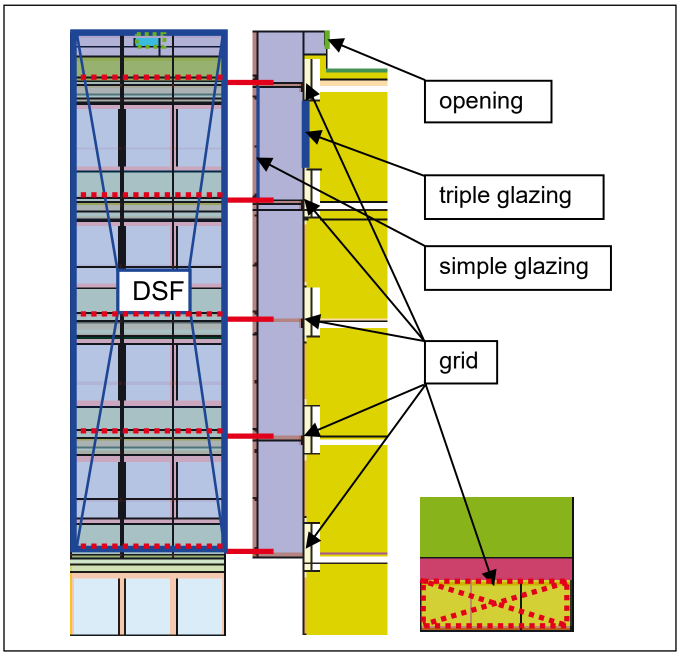

Figure 2 CFD model of the investigated DSF

At the level of each ceiling, a walkable full-area grid is modelled at the floor level, with a total effective area of 70%. The 3D simulation model itself is depicted in Fig. 1 and Fig. 2.

All the case simulations were realised in the calculation program FLOVENT [10], at the boundary condition of the outside air temperature of -11.0 °C, without considering the effect of wind.

The building's simulation model has the overall dimensions of 4.5 × 4.0 × × 17.7 m. Due to the modelling of the parameters of the free air flow movement in its surrounding area, it was further widened by 2.0 m in front of the facade (also due to the variant extension of the double-skin facade) and by 1.5 m above the highest level of the attic.

The computational network is modelled using the internal tool of the network creation program, with thickening even in the surrounding area of all surfaces, as well as a sufficient number of cells in the individual modelled elements, especially the glazing. The optimal design of the network leads to the convergence of the solution in the range of 500 – 1000 computational iterations (depending on the specific variant of the model). The total number of computational cells of the model is in the range of 2.08 to 2.83 million cells, increasing in dependency to the width of the facade cavity.

The convergence of the solution itself was controlled by means of control points, which were located in the exposed part of the model and, thus, directly in the double-skin facade, evenly along its entire height.

The program-integrated turbulence model KVEL K-Epsilon was used to calculate the turbulence.

The solar radiation was modelled using an integrated solar configurator with intensities of 200 – 1000 W/ m^2, always in a position perpendicular to the facade, at a constant height angle, the impact of the sunlight on the facade is 45°.

SIMULATION STUDY – MECHANICAL VENTILATION

The primary assumption was, in addition to the positive effect of the increased air temperature of the facade cavity (as a boundary condition of the interior spaces in the winter), the use of the energy from the facade cavity as a direct input to the heat pump. The air flow in this location was considered at the levels of 2000, 4000 and 6000 m^3/h (expressed in the physical unit m^3/s in the tables and graphs, i.e., the values of 0.555, 1.111 and 1.666).

The second variable in the parametric study was the intensity of the incident solar radiation at four basic levels of 200, 400, 600 and 800 W/m^2.

The last variable in the energy simulation was the width of the facade cavity, gradually modelled with dimensions of 600, 900, 1200 and 1500 mm.

OUTPUTS – MECHANICAL VENTILATION

The results of the simulations are presented in Table 1, which presents the average air temperatures in the facade cavity of the DSF, in dependence on the different air flow, the width of the cavity and the intensity of the incident solar radiation, the graphical representation is depicted in Fig. 3.

Table 2 shows the instantaneous energy output of the DSF - calculated by the air flow movement at the exhaust level, in combination with the average air temperature at the exhaust. Fig. 4 documents this quantity graphically.

In accordance with presented results, the width of the facade cavity itself only has a minimal effect on the air temperature.

However, the intensity of the incident solar radiation has a much greater influence, which ranges from 200 to 800 W/m^2 in the simulation and increases the average air temperature in the facade cavity by up to about 8.0 K (with the smallest air flow at the outlet of 2000 m^3/h). However, this increase is considerably reduced at the highest modelled flow rate of 6000 m^3/h to about half (3.5 K).

By transforming the air flow and air temperature at the exhaust, it is then possible to subsequently identify the so-called "Energy performance of a DSF", where it is also possible to observe the minimal effect of the facade cavity's width on this quantity.

As the intensity of the solar radiation quadruples (from 200 to 800 W/m^2), this output increases almost identically as well. On the contrary, a threefold increase in the air flow at the exhaust level (from 2000 to 6000 m³/h) only brings about a 1.4 - 1.5-times increase in the energy output of the facade.

Table 1 Average air temperature in the facade cavity

variant	air flow		
	0.555 m³/s	1.111 m³/s	1.666 m³/s
600 mm + 200 W/m²	-8.14	-9.18	-9.56
600 mm + 400 W/m²	-5.69	-7.72	-8.40
600 mm + 600 W/m²	-3.18	-6.25	-7.24
600 mm + 800 W/m²	-0.66	-4.76	-6.08
900 mm + 200 W/m²	-8.08	-9.31	-9.65
900 mm + 400 W/m²	-5.51	-7.88	-8.61
900 mm + 600 W/m²	-2.87	-6.35	-7.60
900 mm + 800 W/m²	-0.17	-4.81	-6.57
1200 mm + 200 W/m²	-8.06	-9.34	-9.75
1200 mm + 400 W/m²	-5.46	-7.85	-8.83
1200 mm + 600 W/m²	-2.73	-6.32	-7.76
1200 mm + 800 W/m²	0.04	-4.77	-6.62
1500 mm + 200 W/m²	-8.11	-9.33	-9.85
1500 mm + 400 W/m²	-5.65	-7.88	-8.82
1500 mm + 600 W/m²	-3.14	-6.39	-7.72
1500 mm + 800 W/m²	-0.54	-4.88	-6.61

Table 2 Immediate facade performance (kW)

variant	air flow		
	0.555 m³/s	1.111 m³/s	1.666 m³/s
600 mm + 200 W/m²	3.88	4.94	5.68
600 mm + 400 W/m²	7.03	8.91	10.25
600 mm + 600 W/m²	10.18	12.85	14.76
600 mm + 800 W/m²	13.32	16.79	19.25
900 mm + 200 W/m²	3.99	4.90	5.55
900 mm + 400 W/m²	7.29	8.98	10.08
900 mm + 600 W/m²	10.60	13.09	14.65
900 mm + 800 W/m²	13.90	17.20	19.23
1200 mm + 200 W/m²	4.01	4.93	5.53
1200 mm + 400 W/m²	7.34	9.08	10.15
1200 mm + 600 W/m²	10.70	13.24	14.81
1200 mm + 800 W/m²	14.04	17.41	19.49
1500 mm + 200 W/m²	3.86	4.81	5.41
1500 mm + 400 W/m²	7.05	8.82	9.94
1500 mm + 600 W/m²	10.27	12.85	14.51
1500 mm + 800 W/m²	13.48	16.89	19.05

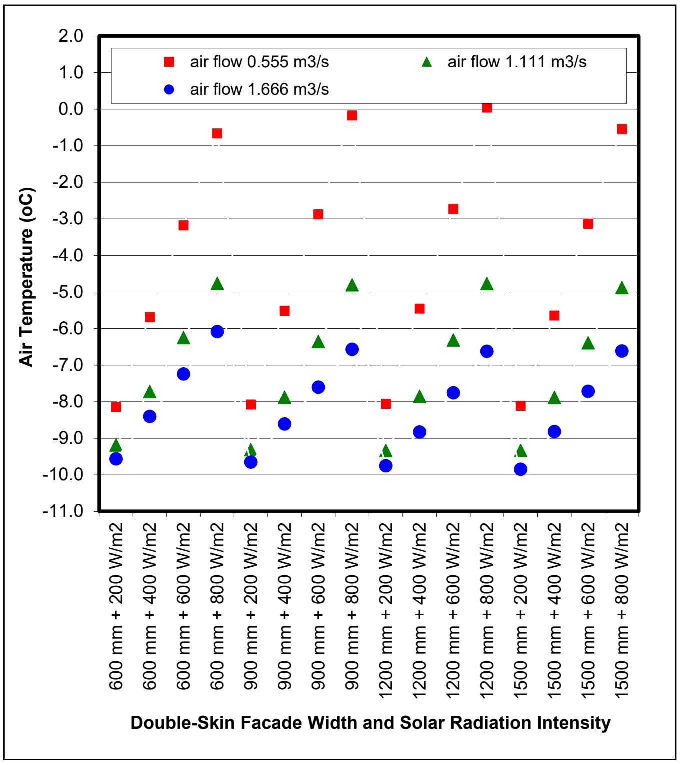

Figure 3 Average air temperature in the facade cavity

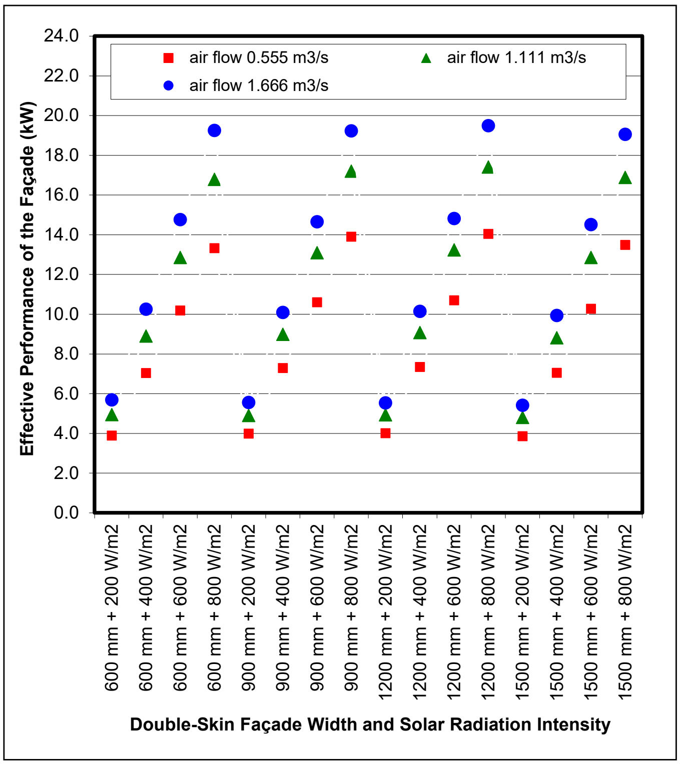

Figure 4 Immediate facade performance

SIMULATION STUDY – NATURAL VENTILATION

In this part, the forced ventilation of the air extraction was replaced by an effective area of the opening, which will work naturally, based on the physical principles of buoyancy-driven air flow, depending on the temperature. In the subsequent study, four variants were considered - the area of this opening was set up to 0.125, 0.250, 0.375 and 0.500 m². The intensity of the solar radiation was, in contrast to the previous part, alternatively extended by the highest intensity of the solar radiation – 1000 W/m². As the width of the facade cavity in the previous part of the analysis did not show any significant effect, it was reduced to only two values - 600 and 1200 mm.

OUTPUTS – NATURAL VENTILATION

The results of the simulations are presented in Table 3, which presents the air temperatures at the outlet level from the cavity of the DSF, depending on the area of the opening (outlet), the width of the cavity as well as the intensity of the incident solar radiation for the cavity width of 600 mm (Fig. 5), and for a width of 1200 mm (Fig. 6).

Table 3 The air temperature at the exhaust

No.	variant	0600 mm	1200 mm
01	200 W/m² + 0.125 m²	-10.80	-10.83
02	400 W/m² + 0.125 m²	11.27	14.62
03	600 W/m² + 0.125 m²	16.28	19.28
04	800 W/m² + 0.125 m²	21.63	22.71
05	1000 W/m² + 0.125 m²	23.61	26.66
06	200 W/m² + 0.250 m²	-10.90	-10.91
07	400 W/m² + 0.250 m²	10.74	-10.83
08	600 W/m² + 0.250 m²	15.68	17.94
09	800 W/m² + 0.250 m²	18.75	20.19
10	1000 W/m² + 0.250 m²	19.59	22.66
11	200 W/m² + 0.375 m²	-10.93	-10.94
12	400 W/m² + 0.375 m²	-10.83	-10.87
13	600 W/m² + 0.375 m²	15.24	17.80
14	800 W/m² + 0.375 m²	21.29	21.18
15	1000 W/m² + 0.375 m²	17.06	21.27
16	200 W/m² + 0.500 m²	-10.95	-10.95
17	400 W/m² + 0.500 m²	-10.88	-10.89
18	600 W/m² + 0.500 m²	14.16	-10.85
19	800 W/m² + 0.500 m²	15.06	20.52
20	1000 W/m² + 0.500 m²	16.21	20.84

As shown in the first part of the study, again, the cavity width of the facade cavity had a minimal effect on the achieved air temperatures in the cavity or at the outlet.

When combining the lowest solar radiation intensity of 200 W/m² with the largest exhaust area of 0.500 m², the average temperature of the exhaust air is almost identical to the outside air temperature of -10.8 °C. On the contrary, with a solar radiation intensity of 1000 W/m² and a smallest exhaust area of 0.125 m², this temperature is up to almost 32-36 K higher and reaches +20.8 °C in the case of the cavity width of 1200 mm, and +16.2 °C in the case of the cavity width of 600 mm, which is almost 5.5 K less.

A deeper analysis of the results revealed that the air temperature rises in the facade cavity, due to solar radiation, accompanied by the classic

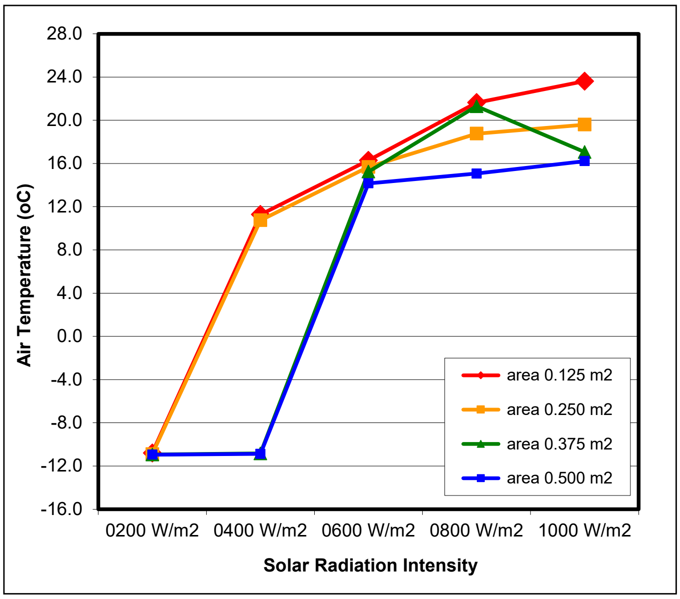

Figure 5 The air temperature at the outlet from the facade cavity, width 600 mm.

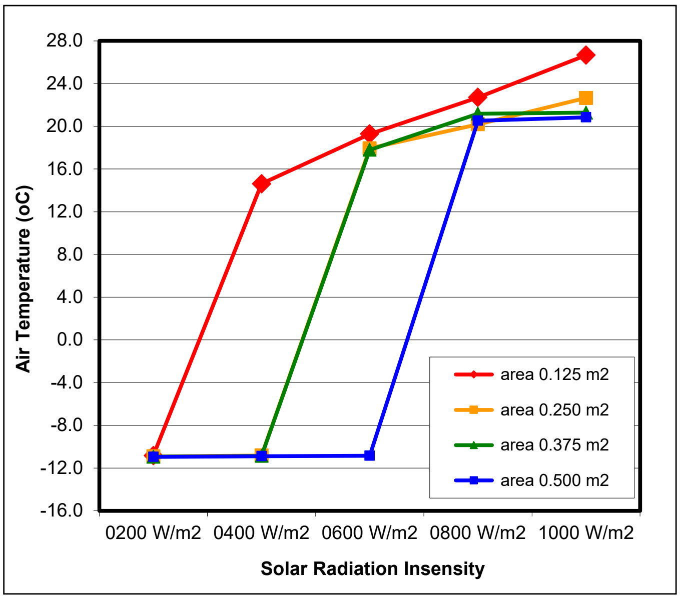

Figure 6 The air temperature at the outlet from the facade cavity, width 1200 mm

chimney effect – causing the hot air in the cavity to rise, which occurs only under certain boundary and geometric conditions. It can also be clearly seen in Fig. 5 and 6.

With a facade cavity width of 600 mm and a minimum solar radiation intensity of 200 W/m², the cold exterior air at all four exhaust surfaces pushes out any chimney effect, preventing the air from flowing outwards, and this cold air falls to the bottom of the entire cavity. At a solar radiation intensity of 400 W/m², this phenomenon is repeated, but smaller openings of 0.125 and 0.250 m² can already initiate the chimney effect and, thus, there is good air flow. At an intensity of 600 W/m² and more, but without any difference in the area, the DSF ensures the air flow in the cavity rises, and it also considerably overheats. It works almost identically, even with a facade cavity width of 1200 mm, with the only difference that the air enters the exhaust and falls in the cavity even with a radiation of 600 W/m² in combination with the largest opening of 0.500 m².

The change in the direction of air flow, thus, represents a significant change in the air temperatures in the order of 20-25 K at the exhaust

Table 4 Average air temperature in the facade cavity

No.	variant	0600 mm	1200 mm
01	200 W/m² + 0.125 m²	-5.34	-5.97
02	400 W/m² + 0.125 m²	3.07	5.30
03	600 W/m² + 0.125 m²	4.84	7.12
04	800 W/m² + 0.125 m²	6.12	8.56
05	1000 W/m² + 0.125 m²	8.50	10.50
06	200 W/m² + 0.250 m²	-8.34	-7.93
07	400 W/m² + 0.250 m²	2.57	-4.15
08	600 W/m² + 0.250 m²	4.42	6.09
09	800 W/m² + 0.250 m²	5.86	6.85
10	1000 W/m² + 0.250 m²	6.05	7.86
11	200 W/m² + 0.375 m²	-9.33	-8.28
12	400 W/m² + 0.375 m²	-4.15	-6.21
13	600 W/m² + 0.375 m²	4.00	5.91
14	800 W/m² + 0.375 m²	5.83	6.87
15	1000 W/m² + 0.375 m²	4.25	7.02
16	200 W/m² + 0.500 m²	-8.98	-9.25
17	400 W/m² + 0.500 m²	-7.34	-8.05
18	600 W/m² + 0.500 m²	3.59	-4.50
19	800 W/m² + 0.500 m²	3.45	6.48
20	1000 W/m² + 0.500 m²	3.76	6.67

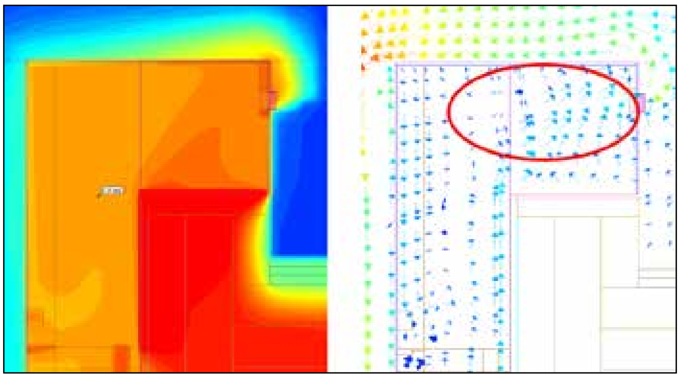

Figure 7 Air temperature and flow vectors for the variant: cavity width 600 mm + solar radiation 400 W/m² + area 0.125 m²

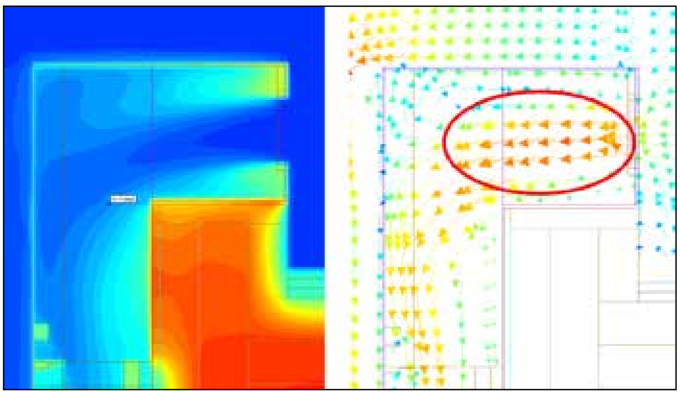

Figure 8 Air temperature and flow vectors for the variant: cavity width 600 mm + solar radiation 400 W/m² + area 0.500 m²

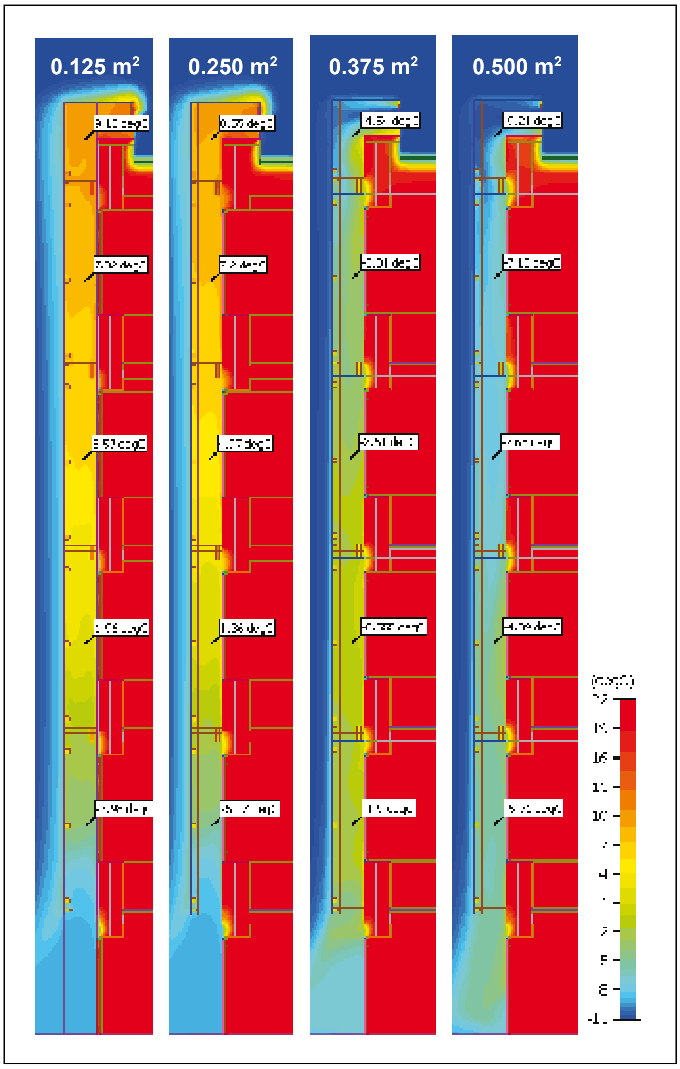

Figure 9 Air temperature in the facade cavity – cavity width 600 mm, radiation 400 W/m², exhaust opening 0.125, 0.250, 0.375 and 0.500 m² (cross section)

and 8-12 K at the level of the average temperature in the facade cavity and only with a change in the intensity of solar radiation by 200 W/m².

The phenomenon described above is depicted even more in Fig. 7 and 8, which documents the limit variants of the solar radiation intensity of 400 W/m² at the area of 0.125 m² and 0.500 m², with a facade cavity width of 600 mm. The classic chimney effect (Fig. 7) and the vice versa, so-called reverse effect, occurred (Fig. 8), i.e., the cold air inlet and its suction through the outlet (expressed through the air temperature and flow vectors). These phenomena can also be observed in Fig. 9, where the ambient air temperatures are expressed for the specific boundary condition of 400 W/m².

For a simple comparison with the first part of the analysis - realised in the form of forced ventilation (Tab. 4), which presents the average air temperatures in the facade cavity, the results are significantly higher in this case, i.e., the air flows achieved by the free opening are significantly lower than expected in the version with forced ventilation - using a heat pump.

CONCLUSION

The presented energy simulation study with 48 variants of the DSF configurations with forced ventilation and 40 variants of the DSF configurations with natural ventilation proved:

- The minimal effect of the width of the facade cavity on the air temperature conditions within the cavity,
- with a total visual area of approximately 63.0 m^2, it is possible to achieve a gross instantaneous energy output of approximately 19.5 kW,
- a significant increase in the average temperatures of the facade cavity up to 0 °C in forced ventilation and +10.5 °C in natural ventilation, with an increasing solar radiation intensity at the lowest flow,
- the phenomenon called the return effect, where the cold air falls back into the facade cavity (and results in its significant cooling) through the upper opening, approximately to the level of solar radiation intensity 400 W/m^2.

It is necessary to design a DSF with regard to its various specifics, the above-mentioned dependencies and real efficiencies in various boundary conditions, such as solar radiation, air flow - forced or natural, so that, in addition to the architectural aspect, the energy part also plays a significant role.

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Symbols

W cavity width [mm]
R_E solar reflectance [-]
A_E solar absorptance [-]
T_E solar transmittance [-]
U_g thermal transmittance of Glazing [$W \cdot m^{-2} \cdot K^{-1}$]
I_{sol} solar radiation intensity [$W \cdot m^{-2}$]
θ air temperature [°C]
Q immediate façade performance [kW]
V air flow [$m^3 \cdot h^{-1}$]
A area [m^2]

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Impact of Plants to Improve the Quality of Indoor Environment in Buildings

Vliv rostlin na zlepšení kvality vnitřního prostředí v budovách

The paper presents the potential of using vegetation for improving the indoor air quality. The influence of plants is investigated on an experimental element with greenery, which was designed as a dividing element in large offices with the condition of the minimum necessary maintenance. The article presents the proposed element and the results of measuring the basic parameters of the indoor environment (temperature, relative humidity, concentration of carbon dioxide, light intensity and air velocity) inside the element. At the end of the article, other possibilities are also summarised for its application.
Keywords: *plants, carbon dioxide, air quality, indoor environment*

Článek představuje potenciál využití vegetace pro zlepšení kvality vnitřního prostředí. Vliv rostlin je zkoumán na experimentálním prvku se zelení, který byl navrhnut jako dělící prvek do velkoprostorových kanceláří s podmínkou minimální nutné údržby. Článek představuje navržený prvek a výsledky měření základních parametrů vnitřního prostředí (teplota a relativní vlhkost vzduchu, koncentrace oxidu uhličitého, intenzita osvětlení, rychlost proudění vzduchu) uvnitř prvku. V závěru článku jsou shrnuty další možnosti pro jeho uplatnění.
Klíčová slova: *rostliny, oxid uhličitý, kvalita vzduchu, vnitřní prostředí*

INTRODUCTION

With the development of industry and civil engineering over the last two centuries, there has been a reduction in the vegetation in the cities. Green spaces were replaced with parking slots and new constructions, which has led to the present problem of an urban heat island effect. The necessity of replanting vegetation back into the city environment has, thus, become an often-addressed issue for urban planners, architects and civil engineers. In recent years, green roofs have become a nearly standard solution for roofs. Furthermore, the first constructions of green facades, i.e., vertical analogy of green roofs, are being implemented in urban environments.

The integration of plants into the construction of buildings has not only changed the aesthetic function, but the vegetation can also help decrease the thermal fluctuation, protect the roofing from UV radiation and actively consume rainfall. The vegetation integrated into building envelopes have some impact on the indoor environment, as they increase the thermal insulation of the building [1], [2] and help cool the buildings during the summer [3].

Vegetation is also important for the indoor environment, given the fact that modern humans spend approximately 80 to 90 % of their time indoors [4]. The indoor environment quality (IEQ) has a direct impact on the people's comfort, health and productivity [5], [6]. Various scientific research has confirmed the positive influence of the vegetation on the quality of the indoor environment and the human psyche.

The basic positives that plants have in the indoor environment include:
- oxygen production and carbon dioxide consumption [7], [8], [9];
- ability to clean the air from dust particles and bioaerosols [10], [11], [12];
- ability to reduce the chemical contaminants, such as formaldehyde, toluene, benzene and others volatile organic compounds (VOCs) [13], [14], [15];
- decrease the air temperature and increase the air humidity [16], [17];
- have a positive effect in reducing the risk of a sick building syndrome effect [18];
- increase a person's mental health [19], [20];
- increase the work efficiency [21], [22].

The influence of built-in vegetation cannot realistically replace modern methods of indoor air treatment. However, plants and their influence on the quality of the indoor environment and humans themselves should not be neglected. For these reasons, this article brings an experimental study offering an idea of what influence could be expected from plants on the indoor environment.

PLANTS IN THE INDOOR ENVIRONMENT

The basic type of plant placement in the indoor environment, which does not need to be introduced in more detail, is a plant grown in a pot. Newly, there has been the development of green walls for the indoor environment, just like the green walls on an exterior's facade. They are used as botanical biofilters – bioreactors, where the contaminated air or water passes through the biological active area, in which the pollutants are neutralised by a biological process.

In principle, biofiltration can be divided into two groups, active and passive. As can be expected, pot-based plants are typical examples of a passive biofilter. Several studies [14], [23], [24] have confirmed that even freestanding pots with plants can remove significant amounts of VOCs.

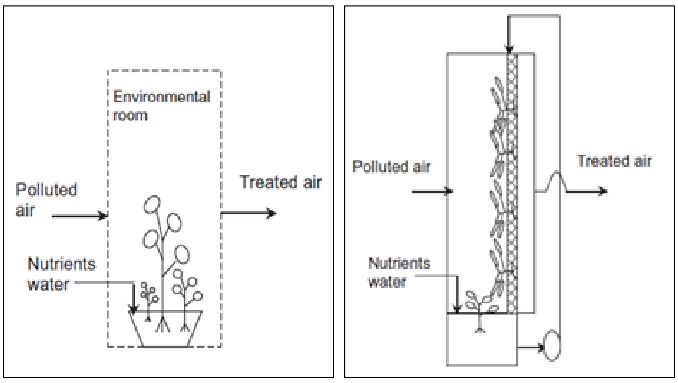

Figure 1 Representation of a passive (left) and active (right) botanical air biofiltration [7]

Active biofiltration can be defined as the use of biological processes to remove pollutants from the air or water flows that are actively conducted through the element. The processed air or water is then further used, for example, the air cleaned from pollutants is distributed throughout the room by a mechanical ventilation system. The principle of both passive and active biofiltration is shown in Figure 1.

Among the first prototype active botanical biofilters were CLER [25], which was used in a conference room ventilation system in a Toronto building, and a Darlington biofilter, which was further patented and commercialised [26]. Another example is the research conducted by Davis and Hirmer [17], which examined ways to supply air to a room through an active green wall. The most efficient way turned out to be supplying the air between the substrate and the wall. There are several large-scale installations in the world, which, in addition to the aesthetic aspect, also fulfil the function of active air biofiltrations.

In addition to the positive benefits of indoor vegetation, it is also necessary to mention its ability to reduce the CO_2 concentration. The consumption of carbon dioxide is a key aspect of photosynthesis, which depends, above all, on the light conditions of the environment. In fact, in low light conditions, a plant can be a CO_2 producer. Some research has shown that plants (with typical C3 photosynthesis – e.g., *Chlorophytum comosum*) can efficiently use CO_2 with sufficient light gain, but cannot do so in low light, where they can generate high concentrations of CO_2 [27]. It follows from the above that not all plants are suitable for such an installation and their choice should be carefully considered.

CONCEPT OF THE EXPERIMENTAL GREEN PARTITION

The goal of the presented research was to create a maintenance-free element with vegetation, which is designed to be used as a dividing partition between workplaces, for example in large open space offices. The partition should be able to create suitable conditions for the plants' growth, with the essential condition of a minimum necessary maintenance. Maintenance, i.e., irrigation and plant waste disposal, is a typical issue for free-standing vegetation. The element, should only be dependent on supply of electricity. The necessary irrigation water should be supplied at multiple intervals.

Beside the space division function, the element provides a positive influence of the inner vegetation to the indoor environment of a room. For control reasons, it is equipped with a monitoring system gathering data of the air conditions inside the partition and in the environment of the surrounding room.

The construction of one green partition consists of two parts. The lower part ensures the maintenance-free operation of the entire system. Besides the water tank, this part contains a distribution system for the irrigation and a system to regulate conditions inside partition and to measure the outside boundary conditions. The system controls these subsystems:

1) irrigation subsystem that processes data from the sensors in the soil,
2) subsystem of artificial lighting, necessary in the case of insufficient solar radiation,
3) air exchange system supplying filtered air into room, the exchange interval depends on the measured values of the air in the upper chamber.

The upper transparent part of the partition is intended for the vegetation. It is made of glued plexiglass and defines the outer dimensions of the element, i.e., the plants will not overgrow the predefined space.

The choice of plants is largely influenced by their demands for irrigation, the amount of plant waste and ability to fill the space evenly over a certain height. The potential suitable plants were discussed with experts from the Department of Botany and Plant Physiology at the Czech University of Life Sciences in Prague. The plant used in the experimental partition is *Rhapis excelsa* (Lady Palm). These resilient plants use C3 photosynthesis, thus, in appropriate conditions, they should increase the quality of the surrounding air during the daytime.

An experimental light is located at the highest plane of the partition, which is designed to simulate natural sunlight with the possibility of the dynamic adjustment of the power and light spectrum (very similar to a solar spectrum).

EXPERIMENTAL SETUP

The partition was monitored by two systems, its own air measuring system and Lumasense Innova analyser instruments (1412i and 1303) for

Table 1 Main sensors important for the vegetation impact analysis

Sensor name	Range	Accuracy
Moisture Guard HT01485	−40 to +125 °C, 0 to 100 % RH	±0.3 °C, ±2 % RH
Lumasense Innova 1412 gas monitor and 1303 multipoint sampler	Dynamic, 4 orders of magnitude	temperature dependence: 0.3 % /°C pressure dependence: 0.01 % /mbar reference conditions: 20 °C, 1013 mbar, RH 60 %.

Figure 2 Visualisation of a dividing green partition with vegetation in an office environment

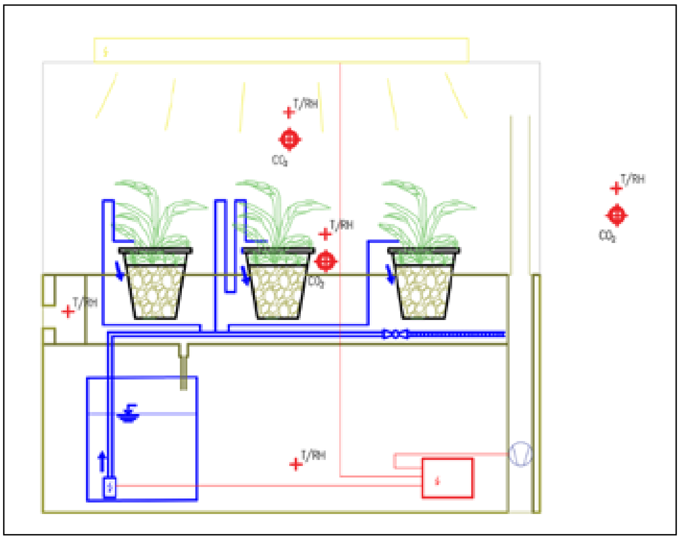

Figure 3 Location of the main sensors for the measurement and control of the green partition

Figure 4 Experimental green partition in a meeting room with an extra Lumasense Innova measuring device for the air analysis

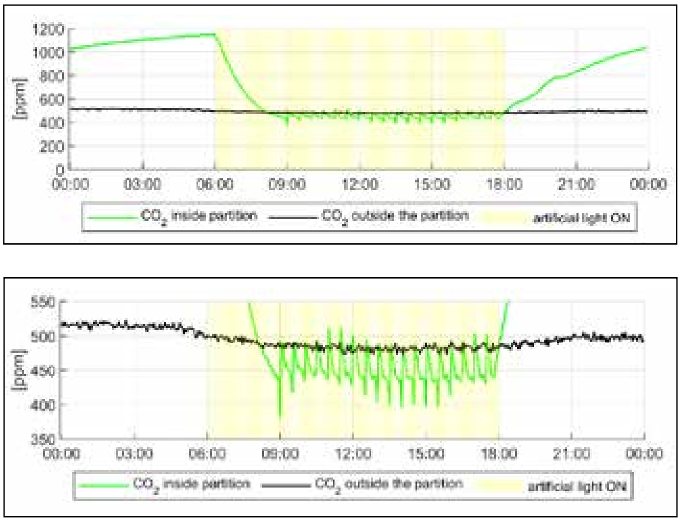

Figure 6 Example of the daily course of the CO_2 concentration in a partition placed in a dark unoccupied room. The bottom graph is the detailed CO_2 consumption with periodical ventilation during the day.

monitoring the air quality. Their specifications are summarised in Table 1. The usage of this precise device, which analyses the air with a photoacoustic method, turned out to be the key for validating the experiment. Typical CO_2 concentration measuring devices do not provide sufficiently accurate data. For a closer idea of the location of the sensors in the device, their positions are shown in Figure 3.

Over the course of several weeks, a series of measurements were performed, which gradually improved the design and performance of the partition at different boundary conditions. This development was necessary to achieve the expected properties of the element. The first measurements were held in the CVUT UCEEB facility meeting room. This larger room (approx. 5 × 10 m) has a fully glazed northeast wall. First, the partition was placed approximately 4 meters from the glazed wall. After the performance was measured, another measurement was held with the partition moved as close as possible to the glazed wall. In the end, the partition was moved to a dark room, which has no solar radiation or occupancy, thus, it offered stable boundary conditions and it was, therefore, ideal for measuring the effect of the element on its surroundings.

RESULTS AND DISCUSSION

Carbon dioxide consumption – Photosynthesis performance

The main aim of the experiment was to design a device that will provide the conditions for the plants to thrive in a deep open space. These rooms are often dark and insufficiently lightened. To evaluate this condition, the measurable photosynthesis ability was used, in which the plant processes carbon dioxide and produces oxygen. It was found that plants located 4 meters from the glazed northeast wall do not use photosynthesis, but rather photorespiration. This phenomenon is (except for the CO_2/O_2 ratio) directly dependent on the amount of radiation reaching the plant's surface. The photorespiration was suppressed by placing the element closer to the glazed wall.

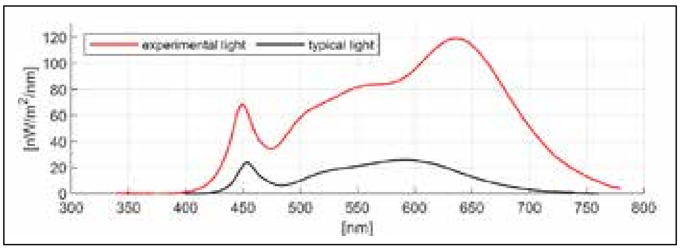

Figure 5 Comparison of the light spectrum of a typical light and the used experimental light

However, this solution is unsustainable in practice. Therefore, several types of lighting were tested on the experimental sample, while the currently used experimental light (a comparison of the light parameters is shown in Figure 5) produces light with a spectrum closer to natural light and is capable of producing an environment suitable for photosynthesis even in a room without daylight.

As can be seen in Figure 6, the experimental green partition creates ideal conditions for growth in any conventional steadily heated environment. When the artificial light is turned on, the plants located in the element begin to absorb CO_2, i.e., the C3 photosynthesis cycle starts. At the same time, the graphs show the interval after which the upper part of the partition was ventilated. This interval was 30 minutes. On the graphs, the consequence of this ventilation is the return of the CO_2 concentration inside the partition to the values of the surrounding environment. From the presented measurements in the dark unoccupied room, it can be deduced that due to the ability of the device to create sufficient conditions for photosynthesis to take place in such extreme conditions, it can be safely expected that it will be able to create suitable conditions in normal office conditions.

At the same time, however, it should be added that the mass of CO_2 consumed is negligible in terms of improving the air quality in the room. The plants can reduce the CO_2 level in the element by approximately 180 ppm in 30 minutes, which is 144 mg of CO_2 in 0.62 m^3 of air (the volume of the upper part of the partition). This means, with 18 air exchanges per day, one partition (with three medium-sized plants) consumes approximately 2 grams of carbon dioxide daily. For a comparison, a person produces approximately 1 kg of CO_2 daily by breathing.

Humidity production

The second observed phenomenon was the specific humidity of the ventilated air. The evapotranspiration of the moisture from the soil and plants should, especially in the winter months, positively affect the indoor environment of the buildings. It was found that the air in the upper chamber has a significantly higher humidity, the difference between the supply and exhaust air is approximately 5 g of water vapour per kilogram of dry air. Therefore, with 18 air changes per day, one partition is able to increase the humidity in a room with a volume of 48 m^3 by approximately 1 gram per kilogram of dry air.

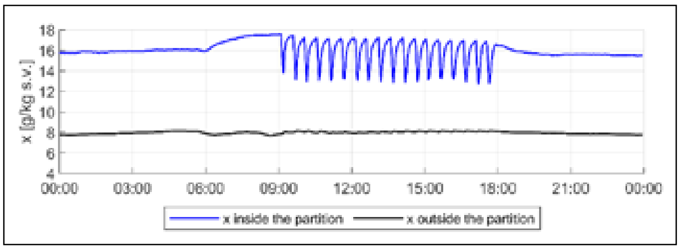

Figure 7 Daily course of the specific humidity in the partition placed in a dark unoccupied room

CONCLUSION

Plants are an important part of an outdoor and indoor environment. The article outlined the possibilities of using their potential to increase the quality of the indoor environment which may promise, at the same time, a reduction in a building's energy consumption. Thanks to their capabilities, such as lowering the ambient temperature and humidity production, they can help increase the air humidity in the buildings in the winter and reduce the need for energy for cooling in the summer. From a district's perspective, they can reduce formation of heat islands in cities and improve the air quality.

The experiment introduced an element with the function of a dividing green partition, which also contributes to improving the quality of the indoor environment. It has been proven that the system is able to create ideal conditions for vegetation growth, with minimal maintenance. In terms of the quality of the indoor environment, the element with plants primarily has an effect on the indoor humidity, its increase is desirable in the winter in our climatic conditions. On the other hand, the reduction in CO_2 was not as significant as initially assumed. Therefore, the expectation of a decrease in the ventilation rate proved to be false.

At the same time, the testing has shown that if we supplement the system with suitable lighting, it is possible to place the partition in rooms with no natural sunlight. The possibilities of using the element have, therefore, spread to shady spaces, for example, in the environment of an underground station. The variability and mobility of the developed element has the potential to be used in many other cases. The whole concept offers a wide range of variants from a solitary element, through a separating element to a partition between rooms. After the necessary adjustment (filters at the inlet and outlet of the air from the element), it should be possible to use it in areas requiring a higher degree of cleanliness, for example, in hospital buildings. Another possible use is a school environment, where it could also have, apart from the discussed benefits in this paper, an educational function.

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Hygrothermal Interaction in Romanesque Rotunda in Znojmo

IBPSA-CZ

Tepelně-vlhkostní interakce v románské rotundě ve Znojmě

The contribution is aimed at the hygrothermal interaction of an indoor climate with an original mural painting in the Romanesque Rotunda in Znojmo. This hygrothermal interaction has been analysed through impact of the heating, ventilation, and number of visitors on the indoor climate with the subsequent impact on the mural painting. This triple parametrical numerical simulation was performed in the WUFI®Plus 3.0 software and independently in the BSim 2000 software and CalA 4.0 software. The numerical simulation of the indoor climate is validated with real long-term measurements from 2011 – 2015 in hourly time steps. A correlation of 99 % was obtained for the WUFI®Plus 3.0 software with the BSim 2000 software for the indoor climate and a correlation of 97 % was obtained for the hygrothermal diffusion in the peripheral wall with the CalA 4.0 software. The obtained results show that a thermal stress up to 2.6 K and a dryness effect up to 18.3 kg/m^3 caused by the intensive heating act on the mural painting. A thermal stress up to 1.4 K and a dryness effect up to 26.8 kg/m^3 was also obtained by the intensive ventilation on the mural painting. This obtained knowledge shows that a natural indoor climate in combination with conservation heating should be preferred over a controlled indoor climate in the Romanesque Rotunda in Znojmo.
Keywords: *numerical simulation; hygrothermal diffusion; preventive conservation*

Příspěvek je zaměřen na tepelně-vlhkostní interakci vnitřního prostředí s původní nástěnnou malbou v románské rotundě ve Znojmě. Zmíněná tepelně-vlhkostní interakce je analyzována vlivem vytápění, větrání a počtem návštěvníků na vnitřní prostředí s následným dopadem na nástěnnou malbu. Uvedená triple parametrická numerická simulace je provedena v softwaru WUFI®Plus 3.0 a nezávisle v softwaru BSim 2000 a softwaru CalA 4.0. Provedená numerická simulace vnitřního prostředí je validována se skutečným dlouhodobým měřením v období 2011 – 2015 v hodinovém kroku. Korelace softwaru WUFI®Plus 3.0 se softwarem BSim 2000 je dosažena na 99 % pro vnitřní prostředí a tepelně-vlhkostní difúze v obvodové stěně koreluje se softwarem CalA 4.0 na 97 %. Získaný výsledek ukazuje teplotní napětí v nástěnné malbě až 2.6 K a efekt vysušování až 18.3 kg/m^3 způsobený intenzivním vytápěním. Teplotní napětí v nástěnné malbě až 1.4 K a efekt vysušování až 26.8 kg/m^3 je způsoben také intenzivním větráním. Získané poznání upřednostňuje přirozené vnitřní prostředí v kombinaci s konzervačním vytápěním před řízeným vnitřním prostředím v románské rotundě ve Znojmě.
Klíčová slova: *numerická simulace; tepelně-vlhkostní difuse; preventivní konzervace*

INTRODUCTION

The Romanesque Rotunda in Znojmo was built in the 11th century as a part of the Znojmo Castle in the Czech Republic. This rotunda, with an outer diameter of 9.2 m and a total height of 12.6 m, includes an original layer of lime plaster with a fresco-secco mural painting. The upper part of the mural painting presents personages of the Premyslid genealogical cycle and combines secular iconography with a religious theme. The lower religious part is composed of typical scenes from the life of Jesus Christ and the Virgin Mary. This unique combination of secular iconography with a religious theme legitimates the sovereignty of the Premyslid dynasty.

The peripheral wall with the mural painting is built from granite stones and lime mortar in a thickness of about 1.10 m. This masonry is composed from two faces of quarry stone and is filled by a lime mortar with granite stone residue in an *opus implectum* type in between. The internal surface of the masonry is covered by lime plaster in two layers. The bottom layer of the lime plaster covers the unevenness of the stones in a thickness of up to 8 cm and the fine surface layer of the lime plaster includes an *intonaco*. This *intonaco* includes the fresco-secco technique. The fresco type is applied on the fresh surface and painting's colours are dissolved in the plaster, but the secco type is applied on the dry plaster surface, see also [1].

Research Aim

The main research aim is the analysis of the hygrothermal impact of the heating, ventilation, and number of visitors on the indoor climate with the subsequent impact on the mural painting. This hygrothermal interaction was studied through numerical simulations in WUFI®Plus 3.0 and also independently in the BSim 2000 software and the CalA 4.0 software. The numerical simulation of the indoor climate was validated with real long-term measurements provided in hourly time step over the period of 2011 – 2015. The result of numerical simulation is assessed by preventive conservation method of Target range, Historical climate method [2], and according to mandatory Decision [3]. The unacceptable indoor climate, known as the "Frost risk", the "Dryness effect" and "Microbiology risk", has been evaluated according to the ASHRAE Handbook [4].

METHODS

The hygrothermal impact of the heating, ventilation and number of visitors on the indoor climate with the subsequent impact on the surface of the mural painting has been analysed in two different independent calculation ways, see Fig. 1. The first calculation is coupled in WUFI®Plus 3.0. The second calculation is composed from BSim 2000 designed for the numerical simulation of indoor climates and CalA 4.0 designed for the hygrothermal diffusion. The hygrothermal diffusion in the peripheral

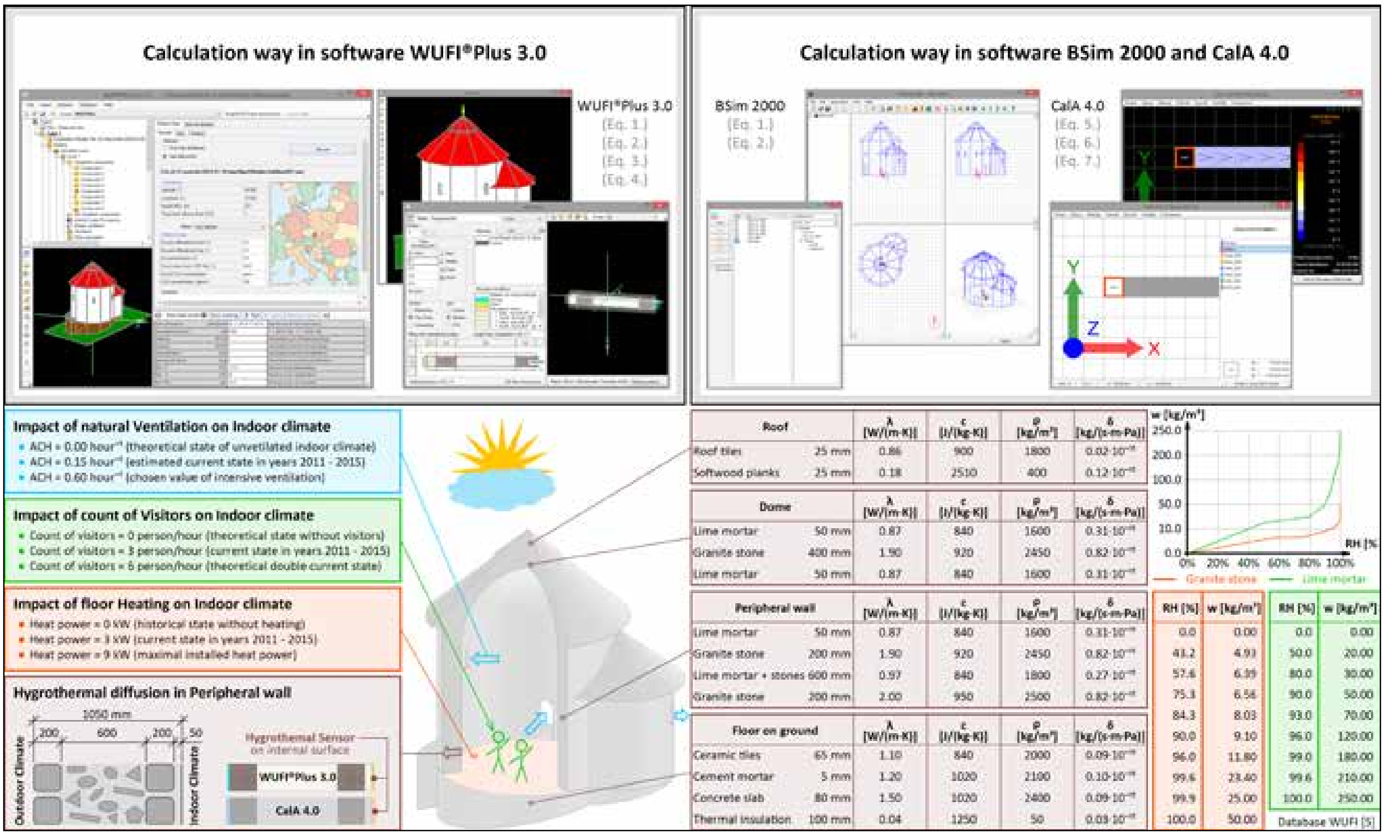

Figure 1 Hygrothermal numerical simulation in WUFI®Plus 3.0 and BSim 2000 with CalA 4.0.

wall is run with nonlinear material characteristics for the water content of the granite stone and lime mortar. The numerical simulation of the indoor climate has been validated with real long-term measurements in the Romanesque Rotunda in Znojmo, see Fig. 2.

WUFI®Plus 3.0 Software

The software WUFI®Plus 3.0 was developed at the Fraunhofer IBP for unsteady hygrothermal numerical simulations of a whole building, as well as the building components, see [5]. The hygrothermal balance of an indoor climate is calculated in each thermal zone by Equations (1) and (2), see [6] for more information. The heat and moisture transport in a multilayer building component is solved by Differential Equations (3) and (4), see [7] for more information. The right side of Equations (3) and (4) contain the storage term and the left side includes the heat flux and moisture transfer. The heat and moisture transfer are solved by a fully implicit scheme in a variable grid.

$$\dot{Q}_{\text{cond}} + \dot{Q}_{\text{vent}} + \dot{Q}_{\text{solar}} + \dot{Q}_{\text{source}} = V\rho_{\text{air}} c_{\text{air}} \frac{\partial T_{\text{int}}}{\partial \tau} \quad (1)$$

$$\dot{G}_{\text{diff}} + \dot{G}_{\text{vent}} + \dot{G}_{\text{source}} = V \frac{\partial x_{\text{int}}}{\partial \tau} \quad (2)$$

$$\nabla(\lambda \nabla T) + l_{\text{wv}} \nabla\left(\delta \nabla(\phi p_{\text{sat}})\right) = \frac{\partial T}{\partial \tau}\left(\frac{\partial H}{\partial T} + \rho c\right) \quad (3)$$

$$\nabla\left(D \nabla \phi + \delta \nabla(\phi p_{\text{sat}})\right) = \frac{\partial \phi}{\partial \tau} \frac{\partial w}{\partial \phi} \quad (4)$$

BSim 2000 Software

The software BSim 2000 from the Danish University at Aalborg is designed for unsteady hygrothermal numerical simulations of indoor climates with variable internal loads defined in the thermal zone. The numerical simulation of the indoor climate is based on a weighted average of the heat and moisture balance according to Equations (1) and (2) in each thermal zone, see [8] for more information.

CalA 4.0 Software

The software CalA 4.0 is developed at the Brno University of Technology for unsteady hygrothermal diffusion in inorganic porous materials. The heat and moisture transport are driven by three differential equations solved by the finite volume method with respect to the nonlinear material characteristics in aa regular orthogonal grid. The thermal diffusion in the material is based on a temperature gradient, see (5). The moisture diffusion is solved on the pressure gradient for water vapour (6) and separately for liquid water (7), similar in [9]. This software is designed for the numerical simulation of building components, see [10].

$$\nabla(\lambda \nabla T) + \dot{f} l_{\text{wv}} + \dot{Q}_{\text{source}} = \frac{\partial T}{\partial \tau} \rho c \quad (5)$$

$$\nabla(\delta \nabla p_{\text{v}}) - \dot{f} + \dot{G}_{\text{source}} = \frac{\partial w_{\text{v}}}{\partial \tau} \quad (6)$$

$$\nabla(\kappa \nabla p_{\text{w}}) + \dot{f} + \dot{L}_{\text{source}} = \frac{\partial w_{\text{w}}}{\partial \tau} \quad (7)$$

RESULTS

The hygrothermal impact of the heating, intensity of the ventilation, and number of visitors on the indoor climate was analysed in 43,824 hourly time steps by a numerical simulation with nonlinear material characteristics. The numerical simulation correlated with the real long-term measurements by 98 % for the air temperature and by 89 % for the

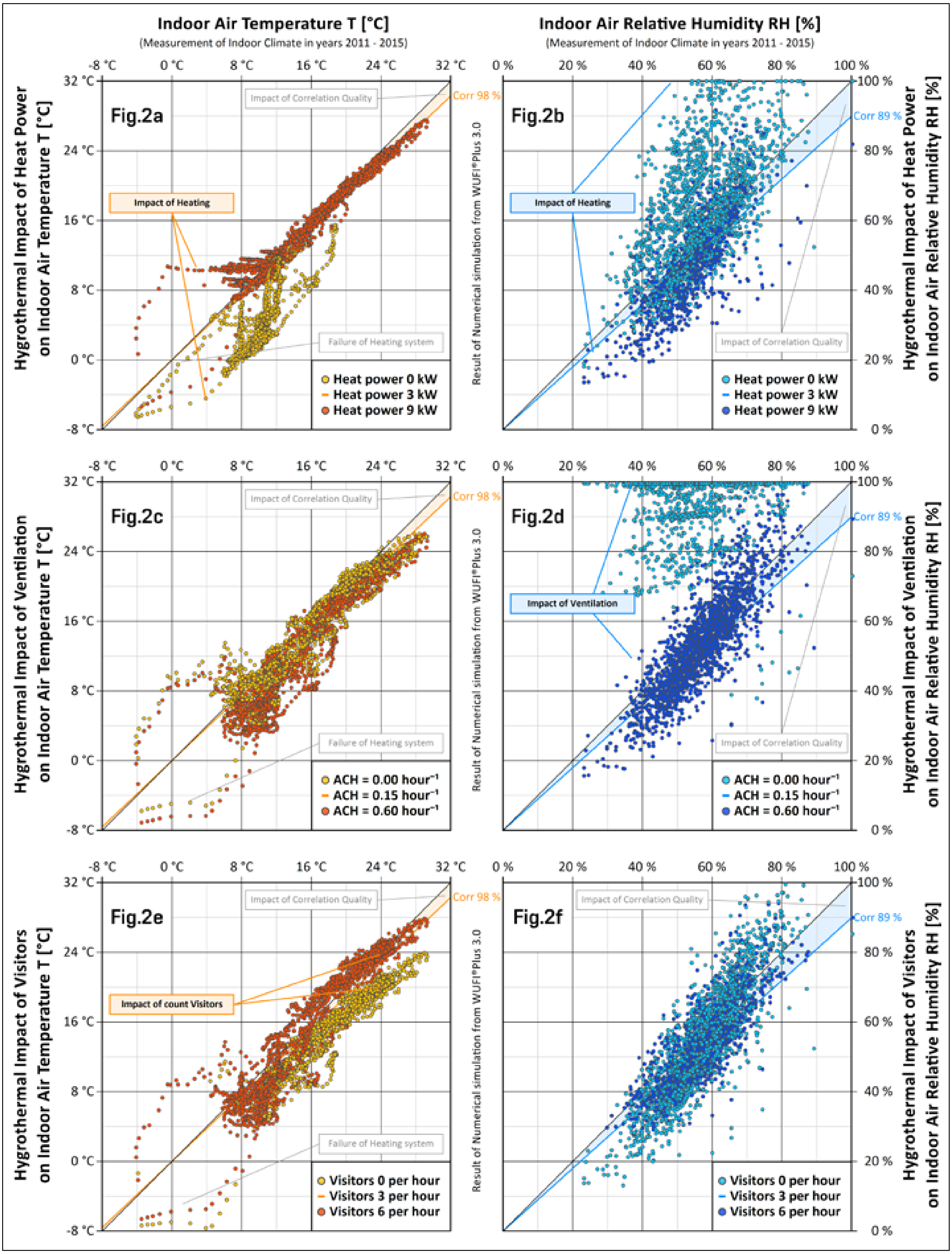

Figure 2 Hygrothermal impact of the heating, ventilation and number visitors on the indoor climate.

indoor air relative humidity, see Fig. 2. The indoor climate was applied as the boundary condition in the hygrothermal diffusion. The hygrothermal diffusion is analysed by the hygrothermal difference between the indoor climate and the surface monitoring of the mural painting, see Fig. 3.

Impact of Heating on Indoor climate

The impact of the floor heating on the indoor climate was studied for the historical state before year 1997 without any heating, and the current state in the years 2011 – 2015 with a heat power of 3 kW and a maximal installed heat power of 9 kW, see Fig. 2a | 2b. The heating system is set at a temperature of 8 ± 2 °C and the electric floor heating uses a power of 3 kW in the current state.

a) The historical state without the floor heating shows an appropriate indoor climate in a frequency of 38 % of the days for the Target range and a frequency of 51 % of the days according to the Historical climate method. An unacceptable indoor climate is reached in a frequency of 25 % of the days which is caused by a Frost risk in 3 % of the days, the Dryness effect in 7 % of the days and a Microbiology risk in 15 % of the days.
b) The current state with a heat power of 3 kW shows an appropriate indoor climate in a frequency of 67 % of the days for the Target range and a frequency of 73 % of the days according to the Historical climate method. An unacceptable indoor climate is reached in a frequency of 12 % of the days, which is caused by a Frost risk in 0.8 % of the days, the Dryness effect in 7 % of the days and a Microbiology risk in 4 % of the days.
c) The maximal heating from a heat power of 9 kW shows an appropriate indoor climate in a frequency of 49 % of the days for the Target range and a frequency of 56 % of the days according to Historical climate method. An unacceptable indoor climate is reached in a frequency of 20 % of the days, which is caused by a Frost risk in 0.4 % of the days, the Dryness effect in 19 % of the days and a Microbiology risk in 0.8 % of the days.

In summary, the hygrothermal impact of the floor heating on the indoor climate shows a positive effect with the lower Microbiology risk and Frost risk, but a negative effect with the increased Dryness effect in the indoor climate. The maximal heating from the installed heat power of 9 kW increases the annual heat energy consumption about 21 %. The impact of the floor heating on the mural painting is shown in the section Impact of Heating on Mural painting.

Impact of Ventilation on Indoor climate

The impact of the intensity of the ventilation on the indoor climate was studied for the theoretical unventilated state by the ACH = 0.00 h^{-1} (0 m^3/h), the current state in the years 2011 – 2015 (see the preview result) with the previously estimated ACH = 0.15 h^{-1} (45 m^3/hour) and intensive ventilation with ACH = 0.60 h^{-1} (180 m^3/hour), see Fig. 2c | 2d.

a) The unventilated indoor climate shows an appropriate indoor climate in a frequency of 0.3 % of the days for the Target range and a frequency of 0.4 % of the days according to the Historical climate method. An unacceptable indoor climate is reached in a frequency of 94 % of the days, which is caused by a Frost risk in 0.4 % of the days, the Dryness effect in 0.1 % of the days and a Microbiology risk in 93 % of the days.
b) The intensive ventilation shows an appropriate indoor climate in a frequency of 52 % of the days for the Target range and a frequency of 56 % of the days according to the Historical climate method. An unacceptable indoor climate is reached in a frequency of 21 % of the days, which is caused by a Frost risk in 0.8 % of the days, the Dryness effect in 16 % of the days and a Microbiology risk in 4 % of the days.

In summary, the hygrothermal impact of the ventilation on the indoor climate shows a positive effect with the lower Microbiology risk. Nevertheless, the intensive heating used for the elimination of the Frost risk increases the Dryness effect. The hygrothermal impact of the intensive ventilation on the mural painting is shown in the section Impact of Ventilation on Mural painting.

Impact of Visitors on Indoor climate

The hygrothermal impact of the number of visitors on the indoor climate was studied for a theoretical state without visitors, the current state according to the real amount of tickets sold in the years 2011 – 2015 with a monthly average of 3 visitors per hour (see the preview result) and double the current state with 6 visitors per hour, see Fig. 2e | 2f.

a) The state without any visitors shows an appropriate indoor climate in a frequency of 49 % of the days for the Target range and a frequency of 53 % of the days according to the Historical climate method. An unacceptable indoor climate is reached in a frequency of 25 % of the days, which is caused by a Frost risk in 0.7 % of the days, the Dryness effect in 18 % of the days and a Microbiology risk in 4 % of the days.
b) Double the number of visitors shows an appropriate indoor climate in a frequency of 54 % of the days for the Target range and a frequency of 58 % of the days according to the Historical climate method. An unacceptable indoor climate is reached in a frequency of 22 % of the days, which is caused by a Frost risk in 0.7 % of the days, the Dryness effect in 17 % of the days and a Microbiology risk in 7 % of the days.

In summary, the hygrothermal impact of the number of visitors on the indoor climate shows a positive effect with the lower Dryness effect, but a negative effect can be seen with an increased Microbiology risk and an increased indoor air temperature in the summer season. The impact of the visitors on the indoor climate is minor in comparison with the floor heating and ventilation effects.

Impact of Heating on Mural painting

The hygrothermal impact of the heating on the surface of the mural painting was studied for the historical state before the year 1997 without any floor heating, the current state in the years 2011 – 2015 with a heat power of 3 kW and a maximal installed heat power of 9 kW. The impact of the floor heating on the surface of the mural painting is expressed by the hygrothermal difference between the indoor climate and the surface monitoring on the mural painting, see Fig. 3a.

a) The historical state without any heating shows a stable indoor climate with a temperature difference of -0.11 ± 0.10 °C (up to -0.88 °C) and a median difference in the water content of -0.69 ± 1.51 kg/m^3 (up to -9.78 kg/m^3). Nevertheless, the floor heating in a historical building is necessary to eliminate the Frost risk, see 3.1a.
b) The current state in the years 2011 – 2015 with a heat power 3 kW shows a temperature difference of -0.16 ± 0.28 °C (up to -1.09 °C) and a median difference in the water content of -0.69 ± 3.29 kg/m^3 (up to -18.3 kg/m^3) with a dependence on the heating season.
c) The maximal installed electric heat power of 9 kW shows a temperature difference of -0.24 ± 0.35 °C (up to -2.61 °C) and a median difference in the water content of -5.72 ± 3.98 kg/m^3 (up to -18.3 kg/m^3). This impact of the floor heating on the median difference in the water content is significant in the winter heating season, see Fig. 3a.

In summary, the intensive heating of the indoor climate increases the risk of a fractal failure in the mural painting and this historically new hygrothermal gradient causes mechanical tension in the original lime plaster layer. Nevertheless, the heating of the indoor climate in the historical building is suitable on the low heat power on the low set-point temperature.

Impact of Ventilation on Mural painting

The hygrothermal impact of the ventilation on the mural painting was studied for the unventilated indoor climate with *ACH* = 0.00 h^{-1}, current state in the years 2011 – 2015 (see result 3.5b) with the previously estimated *ACH* = 0.15 h^{-1} and an intensive ventilation with *ACH* = = 0.60 h^{-1}. The impact of the ventilation on the original mural painting is expressed by the hygrothermal difference between the indoor climate and the surface monitoring on the mural painting, see Fig. 3b.

a) The unventilated indoor climate shows a temperature difference of -0.2 ± 0.33 °C (up to -1.59 °C) and a median difference in the water content of -0.57 ± 1.70 kg/m^3 (up to -5.63 kg/m^3). This small fluctuation in the water content is positive, but the relative humidity of the indoor air over 90 % RH increases the Microbiology risk, as well as the dissolving the colour pigments in the mural painting.

b) The intensive ventilation shows a median temperature difference of -0.04 ± 0.29 °C (up to -1.39 °C) and a difference in the water content of -10.6 ± 10.2 kg/m^3 (up to -26.8 kg/m^3). The intensive ventilation of the indoor climate increases Dryness effect, which is caused by the intensive heating to eliminate the Frost risk.

In summary, the current state in the years 2011 – 2015 with an estimated *ACH* = 0.15 h^{-1} (45 m^3/hour) is suitable and this natural ventilation respects the natural hygrothermal response of the historical building.

CONCLUSION

The hygrothermal interaction of the indoor climate with an original mural painting in the Romanesque Rotunda in Znojmo was analysed by a numerical simulation in WUFI®Plus 3.0 and BSim 2000 + CalA 4.0

Numerical simulation

The 99 % correlation of the WUFI®Plus 3.0 with BSim 2000 software is caused by the identical geometry, identical calculation model, material characteristics, user profile in the zone, and weather file. A range of -0.3 K to -0.1 K was obtained in the difference in the indoor air temperature. A range of 0.5 % RH to 0.7 % RH was obtained in the difference in the indoor air relative humidity . A 98 % and 89 % correlation quality was obtained with the real long-term measurements and for the relative humidity of the air temperature for the indoor climate, respectively.

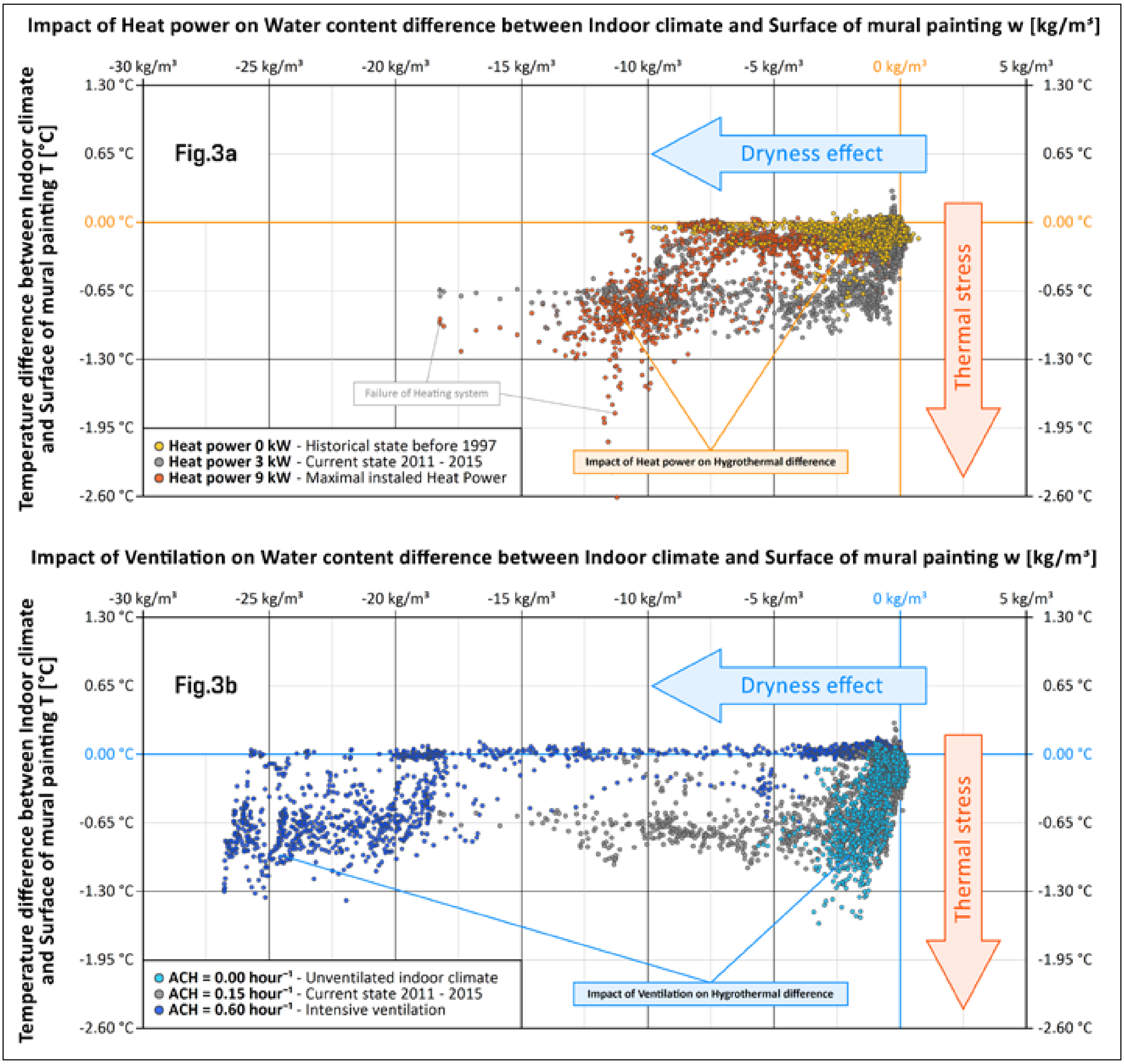

Figure 3 Hygrothermal impact of the heating and ventilation on the surface of the mural painting.

The 97 % correlation of the WUFI®Plus 3.0 with CalA 4.0 software is caused by the identical model, material characteristics and boundary conditions. The obtained difference is caused by the equidistant calculation grid in the CalA 4.0 (336 elements) software versus the adaptive grid in the WUFI®Plus 3.0 (376 elements) software. The diffusion of the liquid moisture according to Equation (7) in CalA 4.0 software was not obtained. A range of -0.2 K to 0.1 K was obtained for the difference in the temperature distribution. A range of -4 % RH to 3 % RH was obtained for the difference in the relative humidity.

Hygrothermal interaction

The hygrothermal numerical simulation for the years 2011 – 2015 shows the impact of the floor heating, natural ventilation and number of visitors on the indoor climate with the subsequent impact on the mural painting.

It is suitable to heat the historical building on a low heat power on the heating system's low set-point temperature. Overheating the indoor climate increases the Dryness effect and the Thermal stress in the mural painting. Oppositely, the historical state without any heating increases the Microbiology risk and the Frost risk.

It is suitable to ventilate the historical building with respect to the natural hygrothermal response of the historical building. The intensive ventilation causes a short-term fluctuation in the indoor climate with a negative impact on the mural painting. Oppositely, the reduced ventilation of the indoor climate increases the Microbiology risk.

The number of visitors to the building increase the Microbiology risk and the indoor air temperature in the summer tourist season. Nevertheless, the hygrothermal impact of the visitors is minor in comparison with the impact of the ventilation and heating on the indoor climate. A strictly defined tourist season and a limited number of visitors to the Romanesque Rotunda in Znojmo is supported.

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Nomenclature

c	thermal capacity [J·kg^{-1}·K^{-1}]
D	conduction coefficient [kg·m^{-1}·s^{-1}]
f	mass condensation [kg·s^{-1}]
G	mass flux of water vapour [kg·s^{-1}·m^{-3}]
H	total enthalpy [J·m^{-3}]
l	latent heat of phase change [J·kg^{-1}]
L	mass flux of liquid water [kg·s^{-1}·m^{-3}]
p	pressure [Pa]
Q	bulk heat flux [J·s^{-1}·m^{-3}]
T	thermodynamics temperature [K]
V	net volume [m^3]
w	moisture content [kg·m^{-3}]
x	absolute humidity [kg·m^{-3}]
δ	permeability of water vapour [kg·s^{-1}·m^{-1}·Pa^{-1}]
κ	permeability of liquid water [kg·s^{-1}·m^{-1}·Pa^{-1}]
λ	thermal conductivity [W·m^{-1}·K^{-1}]
ρ	bulk density [kg·m^{-3}]
τ	time [s]
φ	relative humidity [-]

Subscripts

air	properties of air
cond	conduction
diff	diffusion
int	internal
sat	saturation
solar	solar
source	source
v	water vapour
vent	ventilation
w	liquid water

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Thermal Comfort in Cleanrooms: Findings from Cleanroom Experiments

Tepelná pohoda v čistých prostorách: Poznatky z experimentů v čistých prostorách

In the majority of cleanroom applications, the thermal environment is overshadowed by the contamination control as a priority. As a consequence, the cleanroom users are likely to experience a lower thermal comfort. This study investigated the thermal environment of six research laboratories designed and operated as cleanrooms with the class of cleanliness ISO 5 or ISO 7. A comparison of the various classes of cleanliness and the different air distribution systems enabled the complex analysis in order to determine the issues of the thermal environment. Apart from the calculation of the PMV and PPD indexes, the vertical air temperature difference, risk of draught and homogeneity of the local conditions were also examined. Based on the results, cleanroom users are often exposed to conditions unsuitable for their well-being. The specific requirements of cleanrooms frequently result in high air velocities and inconvenient temperatures that are not tied to the activity and clothing levels of the users.
Keywords: *cleanrooms, indoor environment, thermal comfort, draught*

U většiny aplikací čistých prostor je tepelně-vlhkostní prostředí zastíněno řízením kontaminace, protože dosažení požadované čistoty je zde prioritou. Důsledkem je potom pravděpodobnější výskyt snížené tepelné pohody uživatelů těchto prostor. V této studii bylo analyzováno tepelně-vlhkostní prostředí v šesti výzkumných laboratořích, které jsou navrženy i provozovány jako čisté prostředí třídy čistoty ISO 5 nebo ISO 7. Porovnání laboratoří s různou třídou čistoty a s různými systémy distribuce vzduchu umožnilo komplexně nahlédnout na tuto problematiku za účelem definování možných problémů v souvislosti s tepelně-vlhkostním prostředím. Kromě výpočtu ukazatelů PMV a PPD byl dale stanoven také vertikální rozdíl teplot, riziko průvanu a homogenita lokálních podmínek v laboratoři. Z výsledků vyplývá, že uživatelé čistých prostor jsou často vystaveni podmínkám, které nejsou vhodné pro zajištění jejich spokojenosti. Specifické požadavky čistého prostředí způsobují vysoké rychlosti proudění vzduchu nebo nevhodně zvolené teploty, které nezohledňují stupeň aktivity nebo použitý oděv uživatelů.
Klíčová slova: *čisté prostory, vnitřní prostředí, tepelný komfort, průvan*

INTRODUCTION

Nowadays, the application of cleanrooms is much wider than just in the healthcare sector or space industry that are very well-known from history. High-tech laboratories using the most advanced methods, semiconductor and pharmaceutical industries or food processing are the great examples of cleanroom designs. Generally, a clean environment is required in applications where airborne particles or microbes could affect the ongoing processes, the manufacturing process and the quality of the final product or research and its results.

According to the international standard ISO 14644-1, *"cleanrooms are a specific environment, where the concentration of airborne particles is controlled and classified, and which is designed, constructed and operated in a manner to control the introduction, generation and retention of particles inside the room"* [14]. However, not only the level of cleanliness is controlled, but so too are other variables, such as the air pressure, temperature and relative humidity. Indoor environmental conditions are fundamentally influenced by the required level of cleanliness and the associated air distribution system designed to reduce the airborne and microbial concentrations below the levels required by ISO 14644-1 and the Good Manufacturing Practice Annex 1 (GMP Annex 1).

In the majority of cleanroom applications, the thermal environment is overshadowed by the contamination control system. In some applications, the installed technologies or ongoing processes are temperature and humidity sensitive, therefore, the actual levels of these variables are tightly controlled by precise air-conditioning. Unfortunately, these maintained conditions are, very often, unsuitable for cleanroom users as their level of activity and clothing requirements are not considered, thus, their thermal dissatisfaction is more likely. Unsuitable thermal conditions are a frequently occurring phenomenon, even in applications without strictly determined temperatures, due to the primary focus on the achievement of the desired class of cleanliness and not on the well-being of the users. According to the GMP Annex 1, the temperature and relative humidity are dependent on the product and the type of the ongoing operations [10]. Nevertheless, the cleanliness should not be affected by these variables.

Given the situation and considering the likelihood of the possible inappropriate behaviour of the users, the cleanliness in these applications can be easily endangered.

THERMAL ENVIRONMENT OF CLEANROOMS

Undoubtedly, cleanrooms represent a greater challenge to provide the desired environment than other applications. Due to the primary focus on the cleanliness, the air velocities or temperatures are frequently not tied to the needs of the cleanroom users. However, an indoor environment suitable for the occupants should be ensured whenever possible. Generally, most information about the indoor environment of cleanrooms is available for operating theatres, while, in a majority of other applications, there is a lack of information and or recommendations. Thus, the indoor environmental design and cleanroom operation are even more difficult to set up.

Table 1 Parameters of the analysed cleanrooms

Cleanroom no.	Class of cleanliness	Floor area [m²]	Air change [h⁻¹]	Type of supply/ exhaust outlets	Clothing insulation [clo]	Number of workplaces
1-5	5	35	180	Laminar flow ceiling (70 % coverage) / Perforated wall diffusers, floor height	0.9	3
2-5	5	5	343	Laminar flow ceiling (90 % coverage) / Perforated wall diffusers, floor height	0.9	1
3-7	7	450	17	Perforated laminar diffusers / Perforated wall diffusers, floor height	1	6
4-7	7	550	15	Perforated laminar diffusers / Perforated wall diffusers, floor height	1.1	4
5-7	7	35	25	Swirl diffusers / Perforated wall diffusers, floor height	1.1	3
6-7	7	26	20	Swirl diffusers / Perforated ceiling diffusers	1.1	3

Note: 1-5 represents cleanroom 1 and an ISO 5 class of cleanliness

In the clean environment of operating theatres, as Mora et al. have stated, the thermal comfort is more closely monitored to ensure the best possible conditions for a successful surgery, while among other cleanroom applications, the thermal comfort is hardly considered [6]. As various studies including the study conducted by Mazzacane et al. have pointed out, difficulties in ensuring thermal satisfaction of all the occupants within the operating theatre have been found as a result of the different activities and clothing levels of the users as well as their personal preferences [4]. Rarely, all participants in the surgery are fully satisfied with the current conditions. For example, surgeons require lower temperatures during the surgery than anaesthesiologists and nurses due to the higher activity level and higher clothing insulation.

Another study conducted by Balaras et al. showed that while surgeons evaluate the thermal perception at 21 °C as slightly warm to warm, anaesthesiologists and nurses perceive the same environment as slightly cool to cool as a result of the different clothing and activity levels [1]. The heavier gowns with higher thermal insulation used by surgeons for special surgeries require even lower temperatures down to 18 °C [1]. Murphy has revealed that surgeons expect lower temperatures than the values suggested in the guidelines for operating theatres [7]. Although the thermal comfort of surgeons is important for the concentration and, thus, the success of the surgery, Melhado et al. pointed out that the thermal environment is maintained to achieve suitable conditions for the patient as a priority [5]. As Melhado et al. summarised other studies, temperatures lower than 21 °C may cause hypothermia to the patient, while temperatures above 23 °C are not tolerated by surgeons and other operating staff [5]. Balaras et al. have noted that higher temperatures lower the users' comfort while creating a favourable environment for bacterial growth and their transfer [1]. In particular, the environmental conditions in operating theatres also depend on the type of surgery as some procedures may require a different temperature or illuminance, the equipment used or the number of people, their activity and clothing [5].

A suitable indoor environment, as Hwang et al. have remarked, fundamentally affects the physical and mental state of the patient and shortens the recovery time from the surgery [2]. However, as Khodakarami and Nasrollahi mentioned in their review of thermal comfort in hospitals, not only are the patients affected by the poor environment, but also the indoor environment affects the working conditions, well-being, safety and health of the medical personnel [3]. Due to the diversity of the applications outside the healthcare sector, there are no general requirements with regards to the room temperature. Thus, designers and cleanroom operators are responsible for the actual levels based on the requirements of each individual application and installation. Unfortunately, the occupants' lower thermal satisfaction is expected.

Based on the aforementioned findings and the lack of thermal comfort assessment outside the healthcare sector, this study analysed the issues of the thermal environment of research laboratories designed and operated as cleanrooms. A comparison of various classes of cleanliness and different air distribution systems enabled the complex analysis, in order to determine the fundamental issues of the thermal environment.

EXPERIMENTS

Analysed cleanrooms

In total, the thermal conditions in six research laboratories in two buildings located in the outskirts of Prague were analysed in this study. The experiments mainly focused on the environment of occupied laboratories rather than on the adjacent rooms such, as utility rooms or transfer areas essential for the cleanroom operation. All laboratories were designed and operated as ISO 5 or ISO 7 cleanrooms according to ISO 14644-1 [14]. The cleanrooms differ not only in the maintained class of cleanliness, but also in other design parameters, such as the floor area, number of air changes per hour or in the types and positions of the supply and exhaust outlets. Although the laboratories serve various research purposes, the similarities in the schedule and operation allowed the comparison of the indoor environmental conditions. The level of clothing was determined based on ISO 7730 and a study conducted by Mora et al. [6, 12]. The activity level was assessed as a light activity of a standing person in a laboratory (1.6 met = 93 W/m^2) that corresponds best to the real situation. The parameters of each laboratory are listed in Table 1.

Methodology

All the experiments were carried out during a standard weekday cleanroom operation with the technologies in service and with occupants in attendance. However, the operation of the technologies in each laboratory might be highly variable each day, as well as the presence and movement of the users. In each laboratory, the thermal comfort assessment was carried out following the ISO 7730 standard and was complemented by a subjective evaluation. Questionnaires for the subjective evaluation were created with the guidance of the ANSI/ASHRAE 55 standard [9] and consisted of both general questions regarding the overall perception of the indoor environment, as well as the specific questions aimed at determining the local sources of discomfort and the possible consequent actions of the users.

An Ahlborn thermal comfort set with additional temperature and humidity sensors and omnidirectional thermo-anemometers were used for this experiment. The measurement of the thermal comfort variables was carried out in all the workplaces in each cleanroom at three different heights (0.1, 1.1 and 1.7 m) representing the various points on body of a standing person. Each position was measured in stable conditions for 30 minutes with an average cycle of 1 minute. Besides the calculation of *PMV* (predicted mean vote) and *PPD* (predicted percent dissatisfied) indexes to express the thermal comfort of the users, the local thermal discomfort (vertical air temperature difference and draught) was also assessed. Unfortunately, the widely used estimation of the turbulence intensity as 40 % for a draught assessment was not applicable for these applications due to the different airflow patterns in each cleanroom. To enable the assessment of the predicted draught ratio, the turbulence intensity (T_u) was calculated by the following Equation (1) from ISO 7726 [11]:

$$T_u = 100\frac{SD}{v_a} \ [\%] \qquad (1)$$

where

SD is the standard deviation of the local air velocity [m/s]

v_a is the local mean air velocity [m/s]

Moreover, the homogeneity of the environmental conditions across the workplaces in the two largest laboratories (3-7 and 4-7) was examined. For the plot of the spatial variations in the conditions, the Inverse Distance Weighted Interpolation (IDW) in MATLAB software was used to predict the conditions based on the scattered set of points from the actual results in each workplace.

RESULTS AND DISCUSSION

Thermal comfort

In general, the thermal comfort in the analysed cleanrooms was assessed as a neutral to slightly warm thermal sensation (Table 2). Therefore, the overall thermal satisfaction of the cleanroom users can be expected, however, any incorrectly determined predicted values of the activity and or clothing levels may result in vague results. Firstly, the estimation of the activity level of the cleanroom occupants is difficult as the activity can frequently change during the working day depending on their assigned tasks and, thus, also differs with the occupants. Secondly, the clothing level and related thermal insulation can be hardly estimated as the thermal characteristics of a specific cleanroom's clothing requirement cannot be found in the widely used standards ISO 7730 and ISO 9920 [12, 13]. Clearly, the use of values for casual clothing instead is unreliable. The mistakes in the identification of the clothing and activity levels, as a reason for misleading results, were pointed out in the study of the thermal environment in hospitals conducted by Skoog et al. [8].

According to the results, the average relative humidity met the recommended range of 30 to 70 %, however, the humidity level in 3-7 is close to the bottom value and the need for this low level should be considered. In general, a low relative humidity reduces the comfort of the users in the form of drying their skin, eyes, nose and throat and, thus, increases the likelihood of respiratory problems [3]. Although a lower humidity level is frequently required for special technologies in cleanrooms, the lower amount of moisture vapour in the air can significantly increase the risk of the electrostatic discharge (ESD) that should always be prevented. It may not cause any serious injuries to the occupants, but it can damage sensitive technologies, computer components, etc.

Table 2 Thermal comfort in the cleanrooms

Cleanroom no.	Air velocity		Air temperature		Rel. humidity		PMV	PPD
	Avg.	SD	Avg.	SD	Avg.	SD		
	[m/s]	[m/s]	[°C]	[°C]	[%]	[%]	[-]	[%]
1-5	0.195	0.075	19.76	0.93	57.73	3.47	0.03	5.73
2-5	0.256	N/A	23.73	N/A	43.92	N/A	0.61	12.90
3-7	0.253	0.142	20.52	0.43	33.29	1.39	0.17	6.08
4-7	0.158	0.033	18.37	0.52	44.90	2.08	0.07	5.30
5-7	0.186	0.030	20.61	0.06	47.48	0.32	0.38	7.93
6-7	0.140	0.003	22.77	0.15	46.48	0.32	0.78	17.70

Note: SD represents the standard deviation of the results between workplaces in one cleanroom. The SD in cleanroom 2-5 was not applicable (N/A) due to only one workplace in this room.

Local thermal discomfort

As can be seen from Figure 1 below, the average vertical air temperature difference between the head and ankles in all the cleanrooms was found below 1 °C, and, thus, a very low number of percentage dissatisfied (*PD*) can be expected. The very low values in the cleanrooms with swirl diffusers (5-7 and 6-7) confirmed the ability of these outlets to provide homogenous conditions.

A draught is a frequently occurring phenomenon in cleanrooms due to high amount of air changes, and, thus, high air velocities essential for achieving low concentrations of airborne particles. However, the actual level of the draught is dependent not only on the air velocities, but also on the temperature and turbulence intensity. Thus, the prediction of the draught rate based on the velocity only is not accurate. With higher temperatures, the effect of high air velocities is lowered. Similarly, lower turbulences result in a lower percentage of people predicted to be dissatisfied by a draught (Table 3). In cleanrooms, the effect of a draught might be overestimated as people with higher levels of activity than the light sedentary ones determined in ISO 7730 are less sensitive to draughts and the risk of discomfort is lower. Furthermore, this was confirmed by the respondents who rarely evaluated a draught as an issue despite the high air velocities.

Regardless of the highest air velocity, a low draught can be expected at workplace 2-5.1 in the cleanroom with the laminar ceiling due to the lowest turbulence. Despite the lower air velocities, the risk of a draught was similar at higher levels for the workplace with the perforated laminar diffusers (4-7.1) due to the much lower temperatures and higher turbulences emphasising the effect of the air velocity. Given the results, the position of the exhaust outlets and the value of the overpressure to the adjacent areas influenced the air velocity at a height of 0.1 m. Especially in a colder environment, the lower part of the body can be exposed to a much colder thermal sensation and the risk of a draught. In cleanrooms, the most important aspects that should be monitored are the conditions at the working height. High velocities with significant turbulences at this level may often cause some disruptions to the conducted experiments. One of the examples is the inability to weigh a low amount of bulk materials in these conditions.

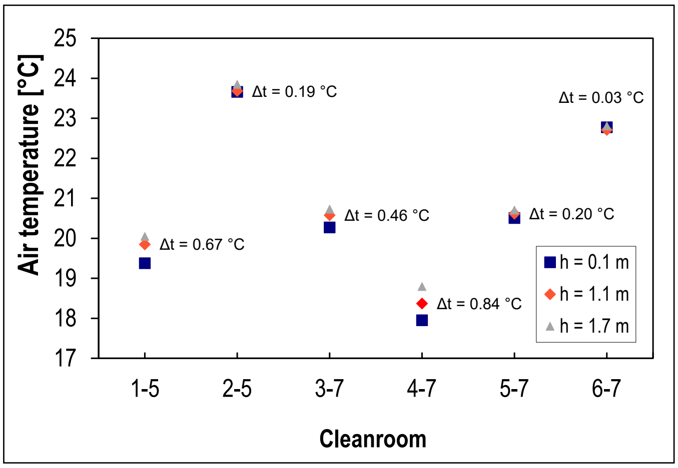

Figure 1 Average vertical air temperature differences in the cleanrooms

Table 3 Comparison of the local conditions at three workplaces in different cleanrooms

Workplace	Air velocity [m/s]			Air temperature [°C]		
	Height of measurement			Height of measurement		
	0.1 m	1.1 m	1.7 m	0.1 m	1.1 m	1.7 m
2-5.1	0.372	0.245	0.152	23.66	23.68	23.85
4-7.1	0.241	0.125	0.070	18.15	18.62	19.14
6-7.1	0.120	0.164	0.139	22.81	22.81	22.97
Workplace	Turbulence intensity [%]			Draught [%]		
	Height of measurement			Height of measurement		
	0.1 m	1.1 m	1.7 m	0.1 m	1.1 m	1.7 m
2-5.1	2.84	4.42	7.22	18.07	13.28	8.76
4-7.1	29.28	33.51	55.74	32.73	14.45	6.05
6-7.1	42.59	33.02	37.18	10.86	14.92	12.50

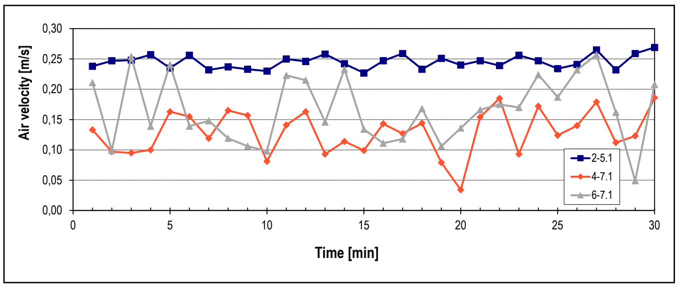

Figure 2 Comparison of the air velocity fluctuations at 1.1 m in height for the different workplaces

As can be seen from Figure 2, the velocity at the working height of 1.1 m at workplace 2-5.1 is very stable compared with the other two cases. Simply, this can be explained by the difference in the air distribution system and, thus, in the turbulence intensity (Table 3). The unidirectional airflow applied in cleanroom 2-5 results in low turbulences to minimise the risk of contamination and to avoid any particle retention within the space. On the contrary, the non-unidirectional airflow pattern used in cleanrooms 4-7 and 6-7 (and in cleanrooms with an ISO 6 class and lower, in general) is responsible for high turbulences to enable the reduction in the particle concentration in the environment by mixing the supply air with the indoor air.

Homogeneity of indoor conditions

The uniformity of indoor conditions is affected by the type of the air distribution system and the position of the supply inlets and outlets. Frequently, the stability and uniformity of the indoor conditions are demanded by researchers and a close control of the environment is essential. Concerning the standard deviations mentioned in Table 2, the most uniform indoor conditions are maintained in cleanrooms with swirl diffusers. In spite of their great impact on the thermal environment, the mixed airflow pattern, as a result of these outlets, is usually not suitable enough for the removal of airborne particles and the installation is appropriate in special cases only.

According to the comparison of the homogeneity of the indoor environment in similar cleanrooms, 3-7 and 4-7, with the same type of air distribution system, a different level of the free area ratio was partially responsible for the exposure to the different local conditions in both laboratories. While in cleanroom 3-7, the actual layout corresponded with the original design and the free area ratio was not reduced (21.3 % of the floor area was used), in cleanroom 4-7, the reality was different. Besides the higher use of the space (33.4 % of the floor area was used), almost half of the exhaust outlets (47 %) were blocked with additional installations. As a result, higher draught rates with local peaks occurred in cleanroom 4-7. Given the situation, the increased risk of contamination in cleanroom 4-7 can be expected as the airborne particles may not be eliminated in some areas and, thus, retained within the laboratory. These facts affect not only the cleanliness, but also the temperature distribution or draught differences across the cleanroom, as the whole concept of the air distribution is changed. As a result, together with the existence of local heat gains, the thermal satisfaction of the cleanroom users can be reduced at some workplaces as the conditions can differ.

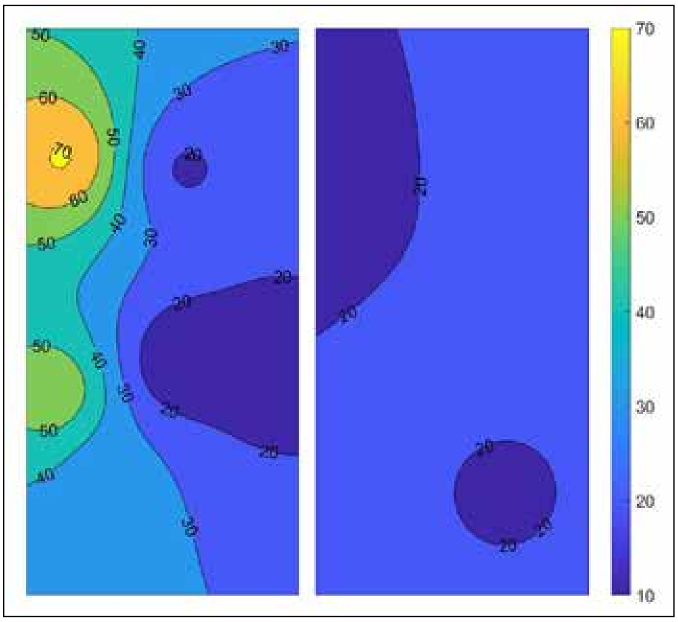

Figure 3 Expected draught homogeneity across cleanrooms 4-7 (left) and 3-7 (right) at the working height of 1.1 m

Especially in large cleanrooms, the achievement of suitable indoor conditions in all the workplaces is difficult and there are always some individuals who will be dissatisfied. Often, the thermal comfort is highly dependent on the actual position of the workplace, whether it is located directly under the supply outlet, as these positions expose workers to a higher draught ratio.

Subjective evaluation

A total of twenty-seven respondents participated in the survey to determine the subjective evaluation of the indoor environment of the clean laboratories. Such a number of respondents is not high enough for a deep statistical analysis; however, it is still beneficial in terms of finding the sources of discomfort for the consequent actions and improvements. Based on the results from the questionnaires, the real perception of the thermal comfort was generally warmer than predicted. The main reason for the differences is given by the personal factors which cannot be measured. Regarding the aforementioned information, a higher thermal sensation can be also associated with increased activity or clothing levels.

Besides, the general evaluation of the thermal comfort, the questionnaires pointed out the local issues and sources of discomfort. With a view to the higher thermal satisfaction, more than 90 % of the cleanroom users responded that they have to make some behavioural adjustments as a change in the optimal room temperature is usually not possible. However, some of their actions are not suitable for a clean environment. The most common action was a change in the amount of the clothing layers or the type of clothing (51.9 % of the respondents) and the need to drink more water (48.1 % of respondents).

Unfortunately, their selection of clothing materials rarely corresponded to the clothing policy, and the cleanrooms might end up with a higher risk of contamination. As a remark from the onsite investigation, the choice of a cotton hoodie due to the perception of a draught and cold environment is far from an ideal solution to enhance the thermal comfort regarding the contamination control. Obviously, this may further result in a higher energy consumption, operational costs and delays in the performed research or manufacturing. Higher classes of cleanliness require different sets of cleanroom clothing with various impacts on the user's thermal satisfaction. However, this fact is very often not taken into account when designing and operating a cleanroom and suitable clothing or thermal conditions are not ensured.

CONCLUSION

As this study highlighted, cleanrooms represent an example of the environment that is not designed to provide an optimal working environment for the occupants as a priority. Thus, a lower thermal comfort is likely. Hardly any studies are focused on the thermal comfort of cleanroom users besides the studies conducted in operating theatres; however, other applications are no less important. Nonetheless, the suitability of the thermal environment should be considered when designing and operating these places, as poor thermal conditions may result in a higher risk of contamination and lower cleanliness. Consequently, cleanroom users take adaptive actions to increase their thermal satisfaction that do not always correspond with the cleanroom operational guidelines, and, thus, the desired cleanliness may be threatened. As a result, the expenses for the cleanroom operation are much higher. When possible, the room temperature should reflect the activity levels and clothing requirements that differ in each cleanroom and the class of cleanliness, while also considering the requirements of the ongoing processes and energy consumption. Admittedly, the temperature optimisation is frequently not possible, and the best option to increase the thermal comfort of the occupants is to offer clothing alternatives with various thermal insulation properties.

Undoubtedly, cleanrooms are among the special applications whose demanding indoor environmental conditions present a challenge for both the designers and cleanroom operators. Any changes in the cleanrooms, especially in the class of the cleanliness or the air distribution, should be carefully discussed from various perspectives before implementation, as these changes affect not only the indoor environmental conditions and required clothing, but also the operating costs. Besides, the reckless installation of equipment or the blockage of exhaust outlets to create additional storage space should be avoided as they may change the airflow patterns and endanger the desired cleanliness.

As can be seen from the current situation around COVID-19, the importance of the use of these special environments cannot be questioned. The rapid development and trend of using the latest high-tech technologies in many sectors show that the need for cleanrooms will continue to rise and their design and operation will be subject to even higher technological demands and a greater emphasis on energy efficiency. In the majority of cleanrooms, ISO 5 to ISO 8, despite the wide use of automatisation, people are still necessary in cleanrooms and unfortunately, present the major source of contaminants. Therefore, the well-being of occupants should receive more attention as their behaviour is not only responsible for the efficient manufacturing of high-quality products due to their productivity, but can also influence the level of contamination.

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Gas Consumption Analysis for Educational Buildings

IBPSA-CZ

Analýza spotřeby plynu ve vzdělávacích budovách

A vast energy consumption database is available in the framework of the research project entitled "Large Scale Smart Meter Data Assessment for Energy Benchmarking and Occupant Behaviour Profile Development of Building Clusters". The database contains consumption data for approximately 10,000 buildings. Amongst the smart metered buildings, there are both residential and non-residential types. This research aims to identify different consumer groups and energy consumption profiles for various building types. For this study, a small sample was selected, which includes 76 school buildings. The energy consumption data are examined by using different clustering techniques: K-means, Fuzzy K-means, and Agglomerative Hierarchical Clustering Methods. In this article, the current state of our research is summarised.

Keywords: *energy consumption, cluster analysis, k-means clustering, fuzzy k-means clustering, hierarchical clustering*

V rámci výzkumného projektu s názvem „Posouzení monitorovaných dat ve velkém měřítku pro energetické srovnávání a vývoj profilu chování osob pobývajících ve skupině budov". Databáze spotřeby energie obsahuje údaje o spotřebě 10 000 budov. Mezi monitorovanými budovami jsou obytné i nebytové budovy. Cílem tohoto výzkumu je identifikovat různé skupiny spotřebitelů a profily spotřeby energie pro různé typy budov. Pro tuto studii byl vybrán malý vzorek, který zahrnuje 76 vzdělávacích budov. Údaje o spotřebě energie se zkoumal pomocí různých technik shlukování, jako: K-means, Fuzzy K-means a Aglomerative Hierarchical Clustering Methods. V tomto článku je shrnut současný stav probíhajícího výzkumu.

Klíčová slova: *spotřeba energie, shluková analýza, k-klastrování, fuzzy k-klastrování, hierarchické klastrování*

INTRODUCTION

Smart meter technology [1] is becoming more and more popular and is currently available in several buildings [2]. With the help of smart meters, vast amount of energy consumption data can be collected and analysed. A deeper knowledge of different energy consumption types – not only their amount, but their profile as well – can point out peak and off-peak periods in daily and longer-term energy use, and can provide essential information to better deal with demand side management (DSM). Some of the objectives of DSM are to balance the energy production and energy consumption, decrease the cost of energy, reduce the energy losses and improve the energy efficiency [3]. However, load shifting is the only DSM aspect which also includes a set of tools to improve the user's behaviour in saving energy. The development of appropriate DSM strategies requires an understanding of energy consumption and identification of the consumer group. In this research, a cluster analysis was used to examine the gas consumption of Hungarian school buildings, which is one of the objectives in the "Large Scale Smart Meter Data Assessment for Energy Benchmarking and Occupant Behaviour Profile Development of Building Clusters" research project. In the case of heating, it is, theoretically, an option to use heat storage to shift the load from the day to the night, but it would require having a large storage tank, thus, the storage losses would be significant as well, so this solution is not applied in practice. However, analysing the data consumption of the improper operation, behavioural problems can be detected and energy management can make actions to improve the situation. In addition to this, by examining the gas consumption of schools, buildings with a higher consumption can be filtered out.

METHODOLOGY

The methodology of our research is summarised in Fig. 1, which shows the flowchart of our study.

Data collection

The data collection was undertaken in the framework of the project mentioned above.

Data selection

The examination started with the data selection. The database contained empty periods and false, registered data; thus, these buildings were removed from the database. Overall, 76 school buildings with at least 1 year-long hourly gas consumption data were analysed.

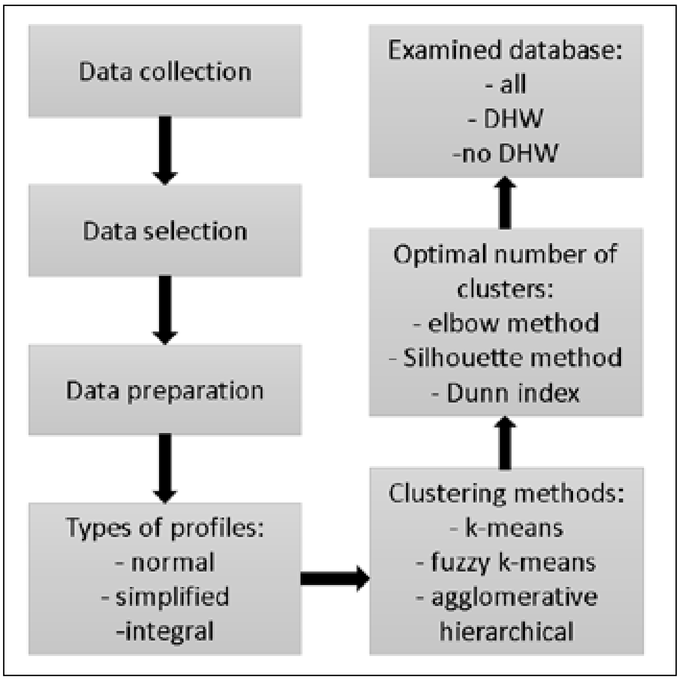


Figure 1 Flowchart of the examination process

Data preparation

In the data preparation step, the daily representative gas consumption profile was determined for each building based on the hourly state of the gas meters. The correction of the gas consumption is necessary if the heating demand is supplied with a gas boiler due to its dependence on the outdoor temperature. The available outdoor temperature database [4] - which contains detailed, hourly data for different locations - was defective for certain periods. The possibility of filling in the missing data was examined, but it could only be performed with an unacceptable level of accuracy. The original, full temperature database was compared with the refilled database - in which case, a database of the missing data, i.e., hour 1, 2, 3, … 23, was created and refilled by the mean value of the surrounding data – and the correlation coefficient between them was calculated. The acceptable value of this coefficient was determined to be at least 0.9. The weather in Hungary can greatly change in a short period of time, in such an extent that the level of accuracy in the correction is acceptable if only 1 hour of missing data is replaced. In our case, more data points were missing in the majority of places and, thus, the correction of the gas consumption based on the outdoor temperature could not been solved. The derogation caused by the weather conditions was taken into account by the non-dimensionalisation of the hourly data series by the total daily consumption for each day and each building. For each building, one typical daily consumption profile was created with an hourly resolution as the mean value of the given hourly consumption of all the examined weekdays.

Types of profiles

Three different profile types were compared to each other: a normal, hourly consumption profile, a simplified consumption profile and a daily integral consumption profile.

The simplified consumption profile was used by Yilmaz et. al [5] as well. Looking at a normal daily profile reveals that the maximum of the profile occurs in a single time interval, but rarely at the exact same time. So, by averaging the consumption data for periods longer than the sampling time (in this case longer than one hour), this effect can be reduced. In this case, periods of three hours long were used, and each point in the simplified profiles represents the mean hourly consumption for the three hours. At the x-axis, the middle of the interval is shown. In this way, the shape of the daily profiles become smoother, thus the nature of the consumer behaviour could be identified more clearly. In such a way, for example, the buildings, where there is a long heating up period before the start of education, would be classified into the same cluster, even though this period starts at 4 o'clock or 5 o'clock in the morning in some cases.

The integral profile is basically a cumulative representation of the normal profile. It is non-dimensionalised by the daily consumption. Fig 2 shows examples of the three different types of consumption profiles.

Clustering methods

To analyse the gas consumption data, three different clustering methods were used: k-means, fuzzy k-means and agglomerative hierarchical methods [6].

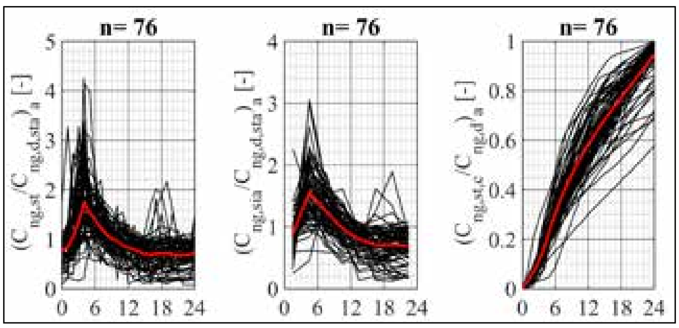


Figure 2 Examined data types (normal, simplified, integral)

The k-means clustering is a hard-clustering technique which clearly orders the consumption profiles into one cluster. At the beginning of the process, the number of clusters (*k*) has to be determined and k initial profiles need to be supplied as the centroids of the k clusters. After that, the distance between the m profiles and the k centroids has to be calculated. The profiles are ordered into the cluster from which the centroid's distance is a minimum. In the next step, the centroids of the clusters are calculated as the mean value of the profiles in the given cluster and the classification starts again. This iterative procedure lasts until the changes drop below a determined level.

In this research, the distance between the profiles and the centroids was determined by calculating the Euclidean distance. The final result of the k-means method depends on the first cluster centroid sets and, therefore, different cases should be examined and compared. In our paper, fifty different initial centroid sets were used: the result of the hierarchical clustering and another forty-nine sets were generated based on the available profiles. For each set, the silhouette was calculated, and the final result was chosen to maximise the silhouette. The iteration was repeated in every case until the difference between the centroids in two successive iterations became zero.

The fuzzy k-mean clustering method is a soft-clustering technique which means that the profiles are ordered not only to one cluster, but into every cluster with a determined probability. This probability is the membership degree calculated by the distance between the given profile and the cluster centroids. To determine the membership degree, the fuzziness parameter has to be given, which determines the fuzziness level of the clustering method. In our case, it was set to 1.5; however, in the literature, the usually recommended fuzziness value is 2 [7]. The reason is the following: when the recommended fuzziness parameter was used, the final cluster centroids for this dataset were too similar to each other and, therefore, the clustering became meaningless. The fuzzy k-means clustering calculation method is similar to the k-means clustering technique, but the cluster centroids are recalculated considering the membership degree. The iterative procedure was repeated, in this case, until the changes in the cluster centroids dropped below 1% in two successive iterations.

The agglomerative hierarchical clustering method works in steps and there is no need for any iteration in this case. In the first step, every profile is in a different cluster, so the number of the cluster is equal to the number of the profiles and their centroids are the consumption profiles. There are several types of solutions to represent the clusters and calculate the distance between them to be able to determine which ones should be merged. In this paper, the distance between each cluster's centroids are calculated and the two nearest clusters are merged. The centroid of the merged cluster is the mean value of the profiles belonging to it. For this clustering method, there is no need to predetermine the number of clusters, only the calculation has to be stopped at the required level.

Each parameter influences the final results: the used distance formula, the initial cluster centroids and the number of iterations in the case of k-means and fuzzy k-means methods and the fuzziness parameter in the fuzzy k-means method. The effect of these parameters has been analysed before [7], [8] but more investigation is required.

Optimal number of clusters

To determine the optimal number of clusters, different measures can be used. In this paper, the elbow [9] and silhouette methods were used and Dunn's index was calculated [10]. Using the elbow method, the distances between the profiles and the centroids of their clusters have to be summarised and plotted according to the number of clusters. The 'elbow' of this line presents the optimal number of clusters. The silhouette method determines the silhouette value, which measures the goodness of the clustering result. The closer the profiles are in the same cluster and the further the profiles are in the different clusters, the better the results are. The optimal number of clusters is at the maximum silhouette value. The idea of the Dunn index is similar to the silhouette value calculation, but it measures the maximum distance in a cluster and the minimum distance between the different clusters. The maximum Dunn index indicates the optimal number of clusters. In the literature, there are several different calculation methods of Dunn's indexes, but only one of them was used in this research.

Examined database

The school buildings were divided into two groups depending on their hot water production type and their consumption was analysed for two different time periods. The time periods are the 'summer' period from May to September when there is, most likely, no heating and the 'winter' period from October to April when heating is necessary. First the 'winter' gas consumption of all the buildings ('all') was examined. Then the buildings were divided into two parts according to their 'summer' consumption. In the process of deviation, nine different cases were examined: 3 types of data X 3 types of clustering methods. The buildings that hardly had any gas consumption in the summer were in the 'no DHW' buildings at least 5 out of 9 times. In these buildings, no gas equipment was used other than for reasons of heating. The other group is 'DHW' buildings, where gas boilers were used for heating domestic hot water (DHW) or gas ovens were used for cooking. The applied clustering methods are particularly useful if we do not know the building, but just have the monitoring data. Therefore, the division into 'DHW' and 'no DHW' clusters was based purely on the consumption data analysis. In the case of the 'DHW' buildings, the 'summer' and the 'winter' consumption were both calculated, but in the case of the 'no DHW' buildings, only the 'winter' period was examined.

COMPARISON OF DIFFERENT OPTIONS

Optimal profile type

First, the impact of the profile types was examined. Tab. 1 shows the fuzzy k-means clustering results of 'all' the buildings for the 'winter' season. The results were calculated for three clusters with different profile types. The results for the normal profiles were selected as the reference and the simplified and integral data were compared to that. The buildings were colour coded in the normal profile type clustering, thus, each cluster had a specific colour and the buildings' colour code was not changed for the simplified and integral profile type clustering. Ideally, for all the profile types, the clustering results would be the same, but Tab. 1. proves that the type of the profile affects the result of the clustering. It is visible that both the classification of the consumption profiles and the size of the clusters vary as well. It is essential to choose the profile type carefully: despite the cluster centroids – the shape of the representative profiles – could be similar to each other (Fig. 3 and Fig. 4), where different buildings are clustered into the same group. From the DSM point of view, it means that the methodological choice affects the consumer group in which the given building shall be classified into and, as a consequence, the applied tariff as well.

Optimal clustering method

The clustering method plays the most critical role in the clustering process and has the most significant effect on the results. The hierarchical clustering technique proved to be improper for these buildings. Because of its nature, irregular consumption profiles were first selected and classified into separate clusters. However, the large groups of buildings, which otherwise should be divided (by both visual inspection and according to the k-means or fuzzy k-means clustering) into more groups, stayed in the same group. So, this kind of clustering method is very sensitive to incorrect data and could not separate the other buildings effectively.

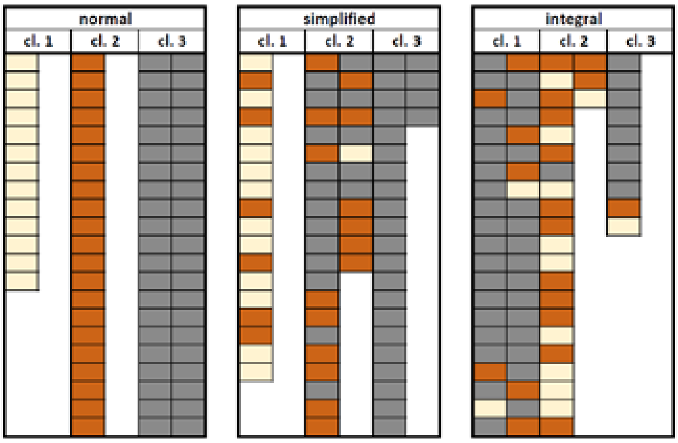
The result of the k–means clustering is not as consistent and repeatable as the hierarchical method because it iterates several times and its final result depends on the initial centroids. Still, it is also sensitive to the irregular data, if the number of clusters is higher. This method was modified to eliminate the problem of one profile cluster: only clusters with at least 3 profiles in them were accepted. However, the results were not acceptable because the shape of the final cluster centroids were very different compared to the results given by the other clustering methods, thus, this idea was rejected.

Optimal number of clusters

Fig. 5. shows the value of the different indexes by the different methods for the selection of the optimal number of clusters. In the case of the silhouette method and the Dunn index calculation, the maximum values objectively show the optimal number of clusters. However, in the case of the elbow method, the 'elbow' of the line has to be found by visual inspection. It is visible that the value of the optimal number of clusters is influenced by the used clustering method and index. Therefore, using the different techniques, different consumer groups could be identified.

The optimal number of the clusters applying the various different methods for the different databases ('all' buildings 'winter' period, 'DHW' buildings 'summer' and 'winter' period, 'no DHW' buildings 'winter' period) was determined and the final clusters were examined. In every case, the optimal result was chosen between the three cluster index options. Even though the result could not be determined objectively using the elbow method, this method appeared to be the most appropriate.

Table 1 Fuzzy k-means clustering results for 3 clusters



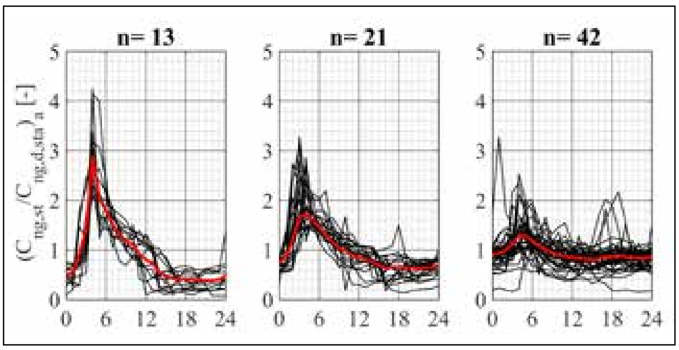


Figure.3 Clustering results with normal data

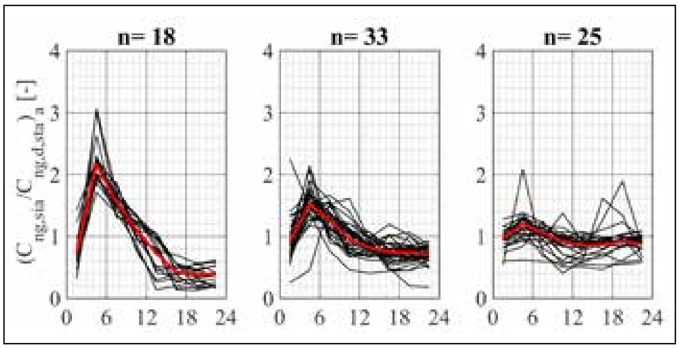


Figure 4 Clustering result with simplified data

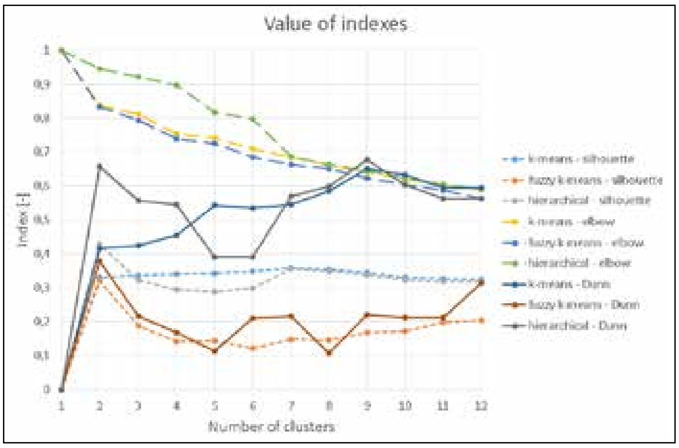


Figure 5 The value of the different indexes in all the buildings in the 'winter' season

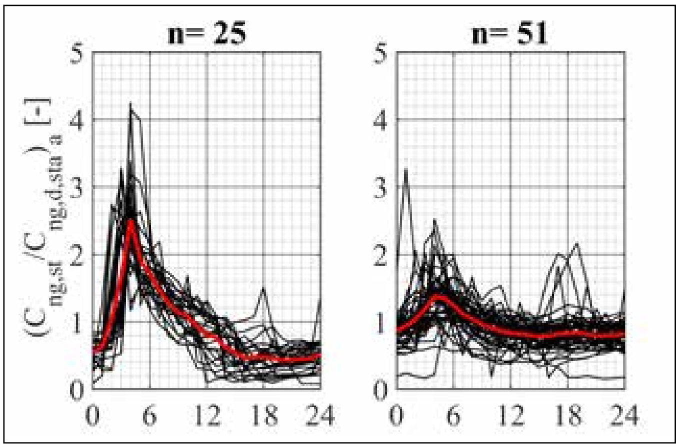


Figure 6 Clustering results of 'all' the buildings in the 'winter' period

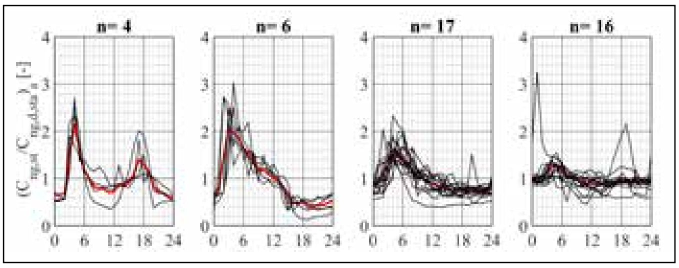


Figure 7 Clustering results of the 'DHW buildings in the 'winter' period

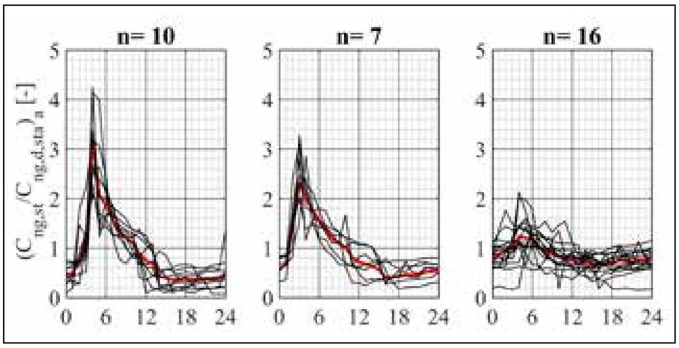


Figure 8 Clustering results of the 'no DHW' buildings in the 'winter' period

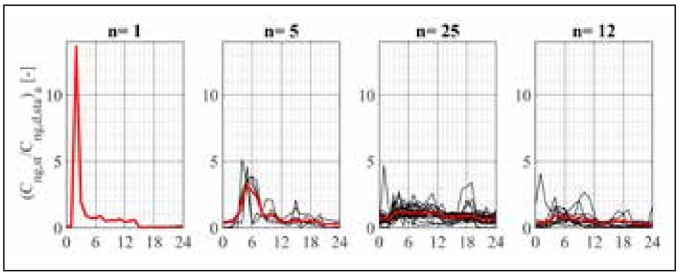


Figure 9 Clustering results of the 'DHW' buildings in the 'summer' period

So, in conclusion, for the normal profiles, the fuzzy k-mean clustering method and the elbow method were the best fit for the purpose. These results are selected to identify the characteristic energy consumption profiles.

RESULTS

The 'winter' period was examined for three different groups of buildings: 'all' the buildings, the 'DHW' buildings and 'no DHW' buildings. The optimal number of clusters was 2 in the case of 'all' the buildings (Fig. 6), 4 in the case of the 'DHW' buildings (Fig. 7) and 3 in the case of 'no DHW' buildings (Fig. 8). In every case, there is a heating up period before the education starts, only the amplitude and the length of this period changes.

In case of the 'DHW' buildings, one cluster shows another high peak in the evening. In this case, it is reasonable to assume that the buildings belonging to this cluster are schools with dormitories. In these buildings, the students consume domestic hot water for showers and/or to warm up their rooms before sleeping. The figures also show that the gas consumption is not reduced below the afternoon level in many buildings during the unoccupied hours. This behaviour can lead to high energy losses.

The 'summer' (Fig. 9) and 'winter' (Fig. 7) period consumption of the 'DHW' buildings were compared. The 'summer' consumption seems to be higher than the 'winter' consumption, but these are non-dimensional values. Small consumptions during a low consumption period could result in a high relative value. During the 'summer' period, the heat up term can be observed in one cluster only. These buildings either have huge heat losses and some heating is required in May or September or the DHW is prepared during this off-peak period and is stored for further daily use. One cluster contains one consumption profile only, which can be an incorrect one and that is the reason why it is selected separately.

CONCLUSION

Despite the limited number of educational buildings with appropriate consumption data, many different options were examined and compared.

First, the type of the data was analysed. The type of the data is very important and effects the results of the clustering methods. Small modifications can lead to significant changes. The integral profile type is inadequate to express the occupant behaviour and control strategy. Therefore, it is not recommended to be used in the process of a daily gas consumption profile determination.

Second, different clustering methods were compared. From the examined methods, the fuzzy k-means technique was the most appropriate because it could handle the incorrect data as well. Despite the recommendation, β =1.5 was selected as the fuzziness parameter. The reason given is that if the recommended value of β =2 was used, the final cluster centroids were too similar to each other. The mathematical background is: if the value of the fuzziness parameter is higher, all the profiles have a larger influence on all the cluster centroids.

Third, the optimal number of clusters was searched. To determine the optimal number of clusters, the elbow method was the most useful despite the fact that the results of this method could not be determined objectively.

In conclusion, the most accurate clustering results are obtained if the normal data type was used and the fuzzy k-means clustering method was applied. The optimal number of clusters could be determined most reliably with the elbow method.

Then, the obtained typical profiles were observed to find explanations in the building's operation on the shapes of the graphs. During the 'winter' period, the heating up interval before the start of lessons can always be observed. In one cluster, a high afternoon/night/evening peak appears as well. The reason is that the buildings that belong to this cluster are schools with dormitories. The lack of a setback operation could also be observed in many cases. It means that the heating system still serves the building during the unoccupied periods. This inappropriate operation leads to higher costs and the loss of energy. The 'summer' and 'winter' period results were also compared. The heat up period in the buildings (except for one cluster) disappears in the 'summer'. Only some of the buildings require heating during the transition period and these schools may have high heat losses.

The proposed methodology opens new perspectives in a building's operation. Analysing the energy consumption results, conclusions could me made about the buildings' operation and the consumers' behaviour. The energy-wasting buildings could be filtered out, the gas consumer equipment and the physical status of the building could be predicted without knowing the examined building. The knowledge of any kind of energy consumption could help decision makers to develop effective DSM strategies and determine energy tariffs which encourage people to save energy.

The main results of this research will continue to be used in our future work. We intend to examine different kinds of energy consumption and different types of buildings. The representative consumption profiles of each building type would help to develop effective operation strategies. The energy-saving potential of the Hungarian buildings could be calculated and compared with the national data.

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Nomenclature

DHW	domestic hot water
k	number of clusters
m	number of profiles
n	number of profiles in the same cluster
β	fuzziness parameter
$C_{ng,st}$	the amount of natural gas consumed between two sampling intervals [m^3/h]
$C_{ng,d,sta}$	the amount of gas consumed during the specific day divided by the number of samplings per day [m^3/h]
$C_{ng,st,c}$	the cumulative distribution function of the natural gas consumed for the specific day [m^3]
$C_{ng,d}$	the amount of gas consumed during the specific day [m^3]
$C_{ng,sia}$	the amount of natural gas consumed between two intervals used to construct the simplified profile divided by the samplings per simplified intervals [m^3/h]
subscript "a"	the average of the profiles investigated over the whole year

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Renewable Energy Sources and Rationalisation of Energy Consumption in Buildings as a Way to Reduce Environmental Pollution

Obnovitelné zdroje energie a racionalizace spotřeby energie v budovách jako způsob snižování znečištění životního prostředí

The combustion of fuels, especially non-renewable ones, is associated with the systematic emissions of harmful substances into the atmosphere, which, in turn, adversely affects the quality of the environment and human health, deteriorates the condition of ecosystems and leads to negative climate changes. The aim of the work is to calculate the expected ecological effects of measures, aimed at reducing the energy demand for existing residential buildings, to a level corresponding to the requirements for the thermal protection of buildings in Poland. It has been estimated that, as a result of reducing the energy consumption for heating in buildings to the level of 65-70 kWh/(m²year), over 70 % in energy savings can be achieved compared to 2011. This will result in a general reduction of pollutant emissions of nearly 70 %.
A comparison was made of low low-stack emission reduction when using modern boilers fuelled by various energy carriers (hard coal, wood, natural gas, heating oil) in an educational building. The renewable energy potential of the European Union was also presented. The possibility of using renewable energy sources are illustrated, including an example of the use of geothermal water for heating public buildings.
Keywords: *environmental pollution, renewable energy sources, rationalisation of energy consumption, buildings, ecological effect*

Spalování paliv, zejména neobnovitelných, je spojeno s trvalým vypouštěním škodlivých látek do ovzduší, což nepříznivě ovlivňuje kvalitu životního prostředí a lidské zdraví, zhoršuje stav ekosystémů a vede k negativním změnám klimatu. Cílem práce je výpočet očekávaných ekologických účinků činností zaměřených na snížení energetické náročnosti stávajících obytných budov na úroveň odpovídající požadavkům na tepelnou ochranu budov v Polsku. Odhaduje se, že v důsledku snížení spotřeby energie na vytápění budov na úroveň 65–70 kWh/(m²rok) ize dosáhnout více než 70 % úspor energie ve srovnání s rokem 2011. Výsledkem bude celkové snížení emisí znečišťujících látek o téměř 70 %.
Bylo provedeno srovnání míry snížení emisí v případě použití moderních kotlů na různé nosiče energie (černé uhlí, dřevo, zemní plyn, topný olej) pro školní budovu. Rovněž byl představen potenciál obnovitelné energie v Evropské Unii. Možnosti využití obnovitelných zdrojů energie jsou ilustrovány mimo jiné na příkladu využití geotermální vody k vytápění veřejných budov.
Klíčová slova: *znečištění životního prostředí, obnovitelné zdroje energie, racionalizace spotřeby energie, budovy, ekologický efekt*

INTRODUCTION

According to data from the Worldwatch Institute, in the USA, the construction and operation of buildings absorbs about 65 % of the total energy consumption [38]. In the European Union, almost 50 % of the final energy consumption is used for heating and cooling, of which 80 % is used in buildings. Buildings are responsible for approximately 36 % of all CO_2 emissions in the EU [9, 15]. Currently, the largest share of the global energy production is non-renewable fuels, the combustion of which is associated with the systematic emissions of harmful substances into the atmosphere. This adversely affects the quality of the environment, deteriorates the condition of ecosystems and leads to negative changes in the Earth's climate. The emission of substances from combustion processes, especially particulate matter or polycyclic aromatic hydrocarbons, also poses a significant threat to human health [17, 18].

In recent years, significant progress has been made in the field of environmental protection, reducing the impact of the economic growth the environment. However, limiting the use of natural resources and reducing emissions still remain a significant challenge in implementing the principles of sustainable development and any zero-emission programme. At the 2019 climate summit, representatives of many countries agreed to initiatives aimed at counteracting climate change, including achieving net zero global carbon dioxide emissions by 2050 [31]. The priority of the

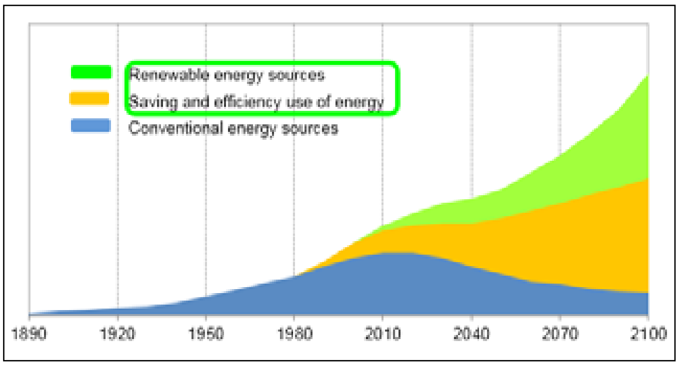

Figure 1 Increase in the global demand for energy and sources of its coverage [33]

European Union's climate and energy policy, valid until 2030, is to reduce greenhouse gas emissions by a minimum of 40 % compared to the 1990 levels, increase the share of energy produced from renewable sources to at least 32 % of the total energy consumption and increase energy efficiency by a minimum 32.5 % [12]. As part of the European Green Deal, the Commission intends to submit a proposal to increase this target level to 50-55 % and also recommends the reduction in greenhouse gas emissions by 80-95 % by 2050 [2, 9]. It is considered that the main way of obtaining clean energy will be through the use of renewable sources and its savings and effective use (Fig. 1.).

A strong stimulus to the development of energy-reducing technology in buildings and to the energy production from renewable sources include, the provisions set down in the Directive on the Energy Performance of Buildings, where all new buildings in the EU member states are obliged, by 31 December 2020, to be classed as nearly zero-energy buildings [9]. Each Member State is committed to establishing a long-term strategy to support the renovation of national housing and non-residential buildings, both public and private, to ensure high energy efficiency and the decarbonisation of those buildings by 2050, enabling the cost-effective conversion of existing buildings into nearly zero-energy consumption buildings [7, 9].

Since the high energy consumption of a large number of buildings is primarily associated with the low thermal insulation of building envelope, thermal modernisation is the first step on the way to reducing energy consumption for heating, and, thus, lowering the level of emissions. In order to reduce energy consumption and emissions, in addition to insulating the building's envelope or replacing the windows and doors, it is also extremely important to reconstruct local boiler houses, replacing boilers with high efficiency models, best powered by gas. Also, the reconstruction of internal heating installations, the insulation of pipes, equipping the installation with measuring elements enabling the weather or time regulation, as well as the liquidation of small local coal heating plants by connecting the buildings to the municipal heating network are all needed. It is estimated that due to the thermal modernisation, the annual energy savings in 2030 may reach approximately 26 % of the consumption in 2013 [21]. The possible potential of the energy savings of the thermal modernisation in buildings as part of individual activities is estimated at: 50-80 % for the modernisation of domestic hot water preparation systems using renewable energy sources, 33-60 % energy savings thanks to the improved thermal insulation of walls, 16-21 % from the modernisation of ventilation systems, 14-20 % from improving the thermal insulation of windows and doors and 10-12 % from regular inspections and repairs of central heating boilers.

Improving the energy efficiency of buildings is also a step on the way to achieving one of the goals of the current Polish climate policy, to achieve

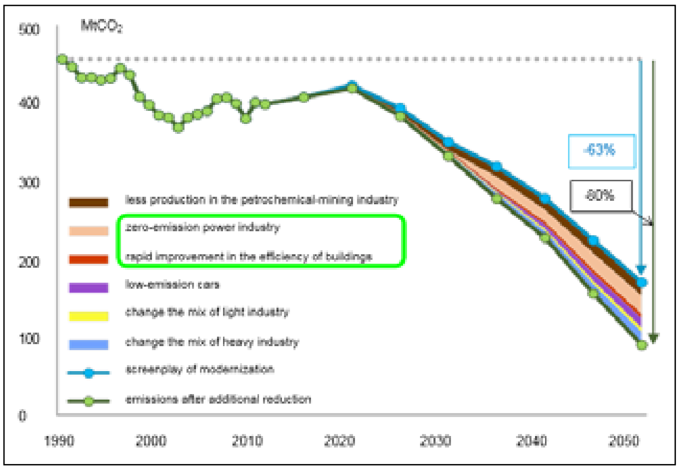

Figure 2 Forecast of greenhouse gas emissions reduction in Poland until 2050 [6]

an 80 % reduction in greenhouse gas emissions by 2050 [6]. To achieve this target, it is also important to promote and implement environmentally friendly technologies based on renewable energy sources and to increase the use of these types of energy sources (Fig. 2.).

Encouraging the continuous development of technology that produces energy from all types of renewable sources is subject to the provisions set down in the Directive on the Promotion of the Use of Energy from Renewable Sources [8]. Despite almost a four times higher growth in the use of renewable energy compared to the increase in the use of other energy sources over five years, the share of renewable energy in 2018 of the total final energy consumption was only 11 %. The share of renewables in the total final energy consumption in buildings was slightly more favourable, at 13.6 % [31].

AIR QUALITY IN EU COUNTRIES AND POTENTIAL RISKS

The policy of the European Union in the field of reducing the emissions of harmful substances into the atmosphere has brought tangible effects, but the concentrations of air pollutants are still too high. It is estimated that around 95 % of European city inhabitants are exposed to pollutants at concentrations higher than levels considered harmful to their health [4]. The most harmful substance in the air, from the point of view of health protection, is particulate matter [1, 18, 20]. Gaseous pollutants such as nitrogen oxides, sulfur dioxide, carbon monoxide, polycyclic aromatic hydrocarbons and heavy metals are also toxic. The percentage share of the individual sources in the formation of these pollutants in EU countries in 2017 is presented in Table 1 [18, 19]. The low-stack emissions of substances is also troubling, which accumulate around the place of origin. One of the main sources of pollutants are low-efficiency furnaces and boilers fired with coal, wood, biomass, and often waste.

Table 1. Percentage share of the sources in the emissions of the chosen pollutants in EU in 2017 [18, 19]

Sources/Pollutions	$PM_{2,5}$	NO_x	SO_2	CO	VOC
Commercial and household heating	53	7	14	42	26
Heat and electricity production	5	18	48	4	3
Construction and industrial activities	17	15	24	23	41
Road transport	12	39	-	26	11

According to the 2018 WHO (World Health Organization) report, about

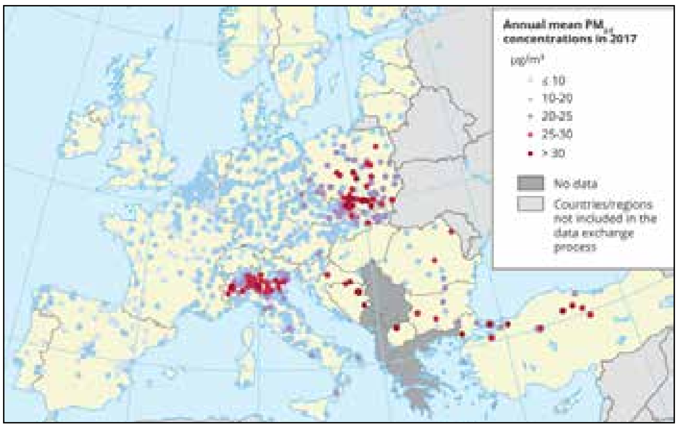

Figure 3 Annual concentrations of PM2.5 in 2017 [4]

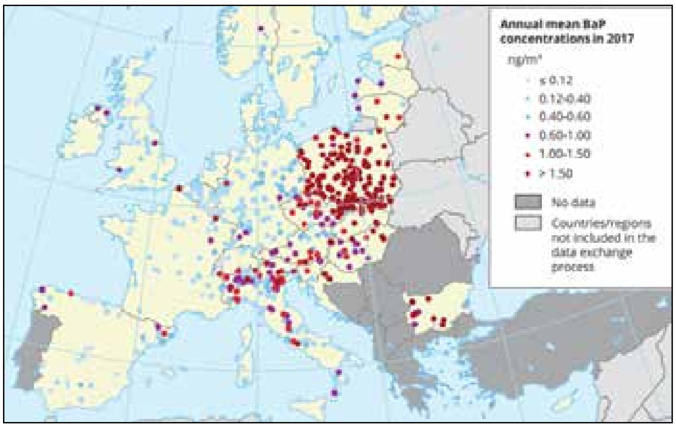

Figure 4 Annual concentrations of B(a)P in 2017 [4]

72 % of Polish, 83 % of Bulgarian and 90 % of Turkish cities exceed the air quality standards related to the limit in the concentration of particular substances [36]. Among the 50 most polluted cities with PM2.5 in the EU, 7 were in Bulgaria (the highest value is 42 μg/m³), 5 in Italy (31 μg/m³), 2 in the Czech Republic (33 μg/m³) and 36 in Poland (41 μg/m³). Since the last report (2019), the situation in Poland has deteriorated in this respect, as there were only 33 Polish cities on the list at that time. Compared to other European Union countries, the air quality in Poland is considered rather dangerous, especially when it comes to the emissions of particulate matter (Fig. 3) or benzo (a) pyrene (Fig. 4) in some areas [4, 34].

The air quality in the Czech Republic is constantly improving and is currently considered to be moderately hazardous. According to the IQAir report, the average annual concentration of PM2.5 in the Czech Republic in 2019 was 14.5 μg/m³ (Fig. 5) [1, 22]. The annual mean concentration of PM2.5 according to the WHO can be harmful if it exceeds 10 μg/m³. The WHO applies stricter emission recommendations than the EU, but they do not possess any legal force.

The cleanest city in Europe was Muonio in Finland, where the average PM2.5 level did not exceed 2 μg/m³ [1]. The WHO believes that concentrations above 10 μg/m³ may already be harmful, and air pollution is the greatest threat to health and life. In Poland, 43,000 deaths are attributed

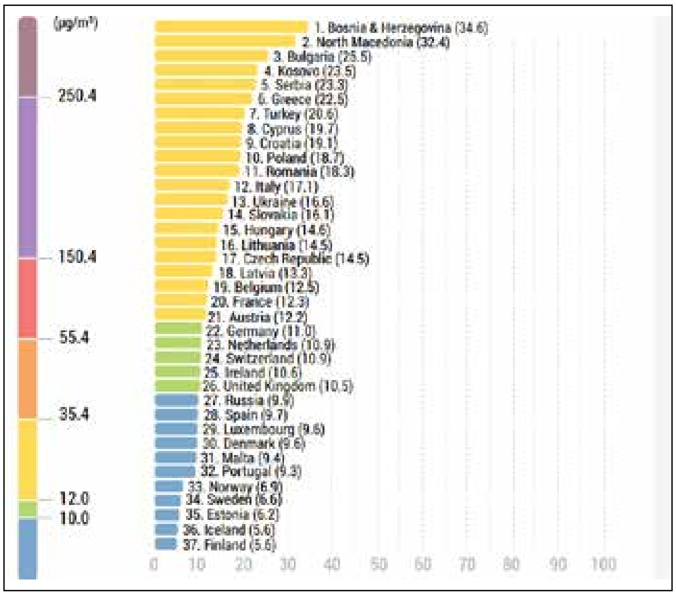

Figure 5 PM 2.5 annual mean concentrations in the individual European countries in 2019 [1]

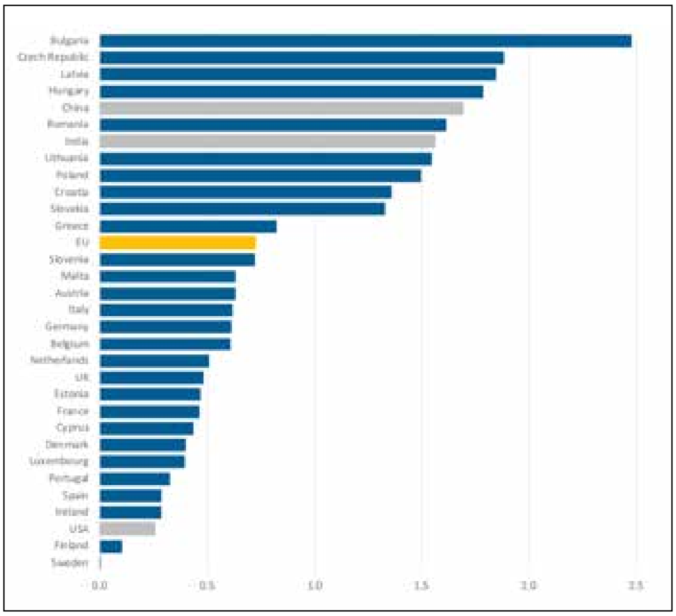

Figure 6 Healthy life years lost due to air pollution per 100 citizens [3]

to exposure to PM2.5 [37], the polluted air in the Czech Republic shortens the lives of 6-8,000 people annually [32]. In the EU, air pollution causes an average of more than 1,000 premature deaths each day, more than ten times the number killed in road accidents [3]. The number of healthy life years lost as a result of the air pollution for one hundred European citizens is shown in Fig. 6.

80% of the premature deaths from air pollution are due to heart disease and stroke. Other causes are cancer and respiratory diseases. Air pollution may cause up to twice as many deaths per year as previously assumed. It is estimated that the emissions of harmful substances into the atmosphere caused 790,000 additional deaths throughout Europe and approximately 8.8 million additional deaths worldwide [25, 26]. EU policies and legislation on clean air requires an improvement in the air quality, similar to the quality recommended by the WHO, using stricter, however, legally non-binding emission recommendations.

THE ECOLOGICAL POTENTIAL OF THERMAL MODERNISATION OF RESIDENTIAL BUILDINGS IN POLAND

The comprehensive and thorough thermal modernisation, leading to a reduction in energy consumption in buildings, at least to the level for which the optimal technical and economic parameters have been defined, should cover the largest possible range of optimal improvements presented, and the level and method of support for the measures should be specified by the state and indicate the scope of the works that the investor must finance from private funds. In addition to the energy effects, the economic effects (resulting from savings in the energy consumption, the development of the economic activity, an increase in the number of new jobs in the areas related to the thermal modernisation), social (resulting from the reduction of energy poverty and social exclusion) and ecological (resulting from the reduction of local air pollution and carbon dioxide emissions leading to climate change, the degradation of ecosystems and affecting human health) are expected after the thermal modernisation. The total economic benefits of investing in the thermal modernisation may exceed 1.5 times the value of the energy savings. Hints to the scale of the potential profits can be obtained by analysing previously conducted thermal modernisation programmes. Under a two-year support programme implemented in the Czech Republic, each 1 Euro invested resulted in 2.47 Euros in budget benefits. In Germany, support for thermal retrofitting and passive houses resulted in budget benefits estimated at 7.2 billion Euros. These countries are more advanced than Poland in the implementation of their thermal modernisation programmes. As part of improving the energy efficiency of buildings, Slovakia has spent 5.5 Euros per person annually, the Czech Republic 2.5 Euros per person, while less than 0.2 Euros per year was spent in Poland [15, 21].

In the European Union, there are approximately 200 million buildings in use (of which, approximately 6 million are located in Poland). The construction and operation of buildings in European Union countries is associated with approximately 40 % of the total energy consumption, but this value is higher in Poland [11, 15, 24]. According to the data given by the Polish National Energy Conservation Agency, the level of unit energy consumption in many buildings in Poland is around 120-300 kWh/(m^{2}year), while this figure does not exceed 50 kWh/(m^{2}year) in other European countries [11, 15, 21]. The greatest potential for energy efficiency is found in residential buildings, which are one of the main consumers of energy in the modern economies of developed countries. Buildings constructed in different years have different energy characteristics, and are also powered by energy sources with different levels of efficiency and based on different types of fuel. In Poland, coal is mainly used, while in other European Union countries gas predominates. An analysis into reducing energy consumption in residential buildings, and consequently the emission of pollutants generated during the production, clearly shows the highest efficiency in activities related to spatial heating, accounting for about 60-70 % of the energy intensity of a building and is the direct cause of the relatively high operational energy intensity of these facilities [13, 14]. Such activities may be carried out in the quantitative scope related to the reduction of energy demand for spatial heating by adapting to energy requirements, or in the qualitative scope related to the reduction or elimination of the emissivity of energy generation sources for heating.

In order to determine the estimated level of energy and ecological efficiency of Polish residential buildings, a simplified quantitative characterisation has been made of the potential effects of the activities that reduce the energy consumption for heating residential buildings on a scale of the whole country. The focus was on reducing the energy consumption for the heating of buildings to a value of 70 kWh/(m^{2}year) in multi-family buildings and 65 kWh/(m^{2}year) for single-family buildings. These values result from the requirements that will apply from 2021 and omits the estimates of the energy consumption for hot water preparation. Attention was focused on a group of residential buildings that were inhabited and heated. The detailed data on the residential buildings in Poland come from the general population and housing census conducted every 10 years, most recently in 2011, therefore, the efficiency analysis refers to this year [5, 23]. The aforementioned group included 5,182,330 facilities, and the usable floor area of the flats located there was 868,084.1 thousand m^2 in total (Table 2).

Table 2 Residential buildings built in Poland in different years

Construction period of residential buildings	Number of residential buildings		Unit energy consumption for buildings heating	
			single-family	multi-family
	thousand	%	kWh/(m^{2}year)	
before 1918	404.61	7.81	367.66	264.31
1918-1944	809.22	15.61	306.10	191.31
1945-1970	1363.48	26.31	265.22	172.74
1971-1988	1407.82	27.17	230.25	156.52
1989-2010	1197.20	23.10	183.36	125.67

When estimating the level of the energy consumption for heating buildings, the statistical data of the Central Statistical Office, available in the database in the form of thematic studies or metadata contained in files and other studies were used [5, 23, 27, 29, 35]. The data were identified in terms of suitability for the analysis and served as the input data for the performed calculations. The possible energy savings for heating residential buildings with its reduction to the above-determined level are introduced in Table 3.

Table 3 The potential energy savings by reducing the energy consumption for heating in residential buildings

Construction period of residential buildings	The potential level of reduction in the unit energy consumption of residential buildings heating			
	single-family	multi-family	single-family	multi-family
	kWh/(m^{2}year)		%	
before 1918	297.66	199.31	81.0	75.4
1918-1944	236.10	126.31	77.1	66.0
1945-1970	195.22	107.74	73.6	62.4
1971-1988	160.25	91.52	69.6	58.5
1989-2010	113.36	60.67	61.8	48.3

After comparing the potential possibilities for reducing the heat consumption in all residential buildings, energy savings of 72.3 % were achieved.

On the basis of the estimated reduction in the energy consumption for heating purposes for residential buildings, the reduction of harmful substance emissions into the atmosphere was estimated. Lowering the energy consumption will reduce the emissions of particulate matter and carbon dioxide, which is particularly harmful to the environment and people. The ecological effects of reducing the energy consumption for heating single-family and multi-family residential buildings to the above-adopted values are presented in Table 4.

Table 4 Reduction of pollutant emissions as a result of the reduced energy consumption for heating in residential buildings

Type of pollution	Pollutant emissions	Emission reduction by	Percentage reduction
	thousands of tonnes		%
Particulate matter $PM_{2.5}$	61.35	41.40	67.5
Particulate matter PM_{10}	103.76	70.02	67.5
Carbon monoxide	1,622.32	1,094.89	67.5
Sulphur oxides	219.18	147.92	67.5
Nitrogen oxides	67.51	45.56	67.5
Polycyclic aromatic hydrocarbons	0.13	0.08	61.5
Carbon dioxide	49,440.57	35,738.35	72.3

The environmental effect may be increased by modernising heating and ventilation systems in the analysed buildings and replacing the heat source for the heating systems that currently use coal with a source powered by gaseous fuels. This solution is particularly important for buildings built before the 1960s. Connecting the existing buildings to the district's heating network can have a similar effect.

TYPES OF FUELS AND LOW-STACK EMISSION REDUCTION

The elimination of heat sources powered by coal is particularly beneficial for the reduction of particulate matter and benzo(a)pyrene emissions as part of the thermal modernisation. A typical two-story school building, erected using traditional technology, partially with a basement, was selected to analyse the level of low-stack emissions reduction resulting from the use of various variants of energy carriers. The walls were made of solid brick plastered on both sides, its flat roof consisted of a ribbed DZ-4 floor slab, filled with concrete hollow blocks - insulated with reed mats. The windows were made of wood and were double-glazed. The main entrance door was made of uninsulated aluminium profiles, the remaining exterior doors were made of wood. Due to the lack of thermal insulation, the building envelope was characterised by high heat transfer coefficients: U = 1.4 W/(m^{2}K), the flat roof U = 0.68W/(m^{2}K), the ceiling above the basement U = 1.14 W/(m^{2}K), and the ground floor U = 0.73 W/(m^{2}K). The heat transfer coefficient of the windows was 2.6 W/(m^{2}K), external aluminium doors U = 6.0 W/(m^{2}K), and the remaining wooden doors U = 3.5 W/(m^{2}K). The building was heated from its own coal-fired boiler room located on the ground floor. The worn-out boiler, old sectional heaters, ribbed convection heaters (Favier heaters), and the lack of insulation of the pipes caused a very low efficiency of the central heating system, at a level of about 40 %.

A standard comprehensive thermal modernisation project was proposed for the building, consisting of the thermal insulation of the building envelope and the replacement of the windows and doors. Due to the limited possibilities of the investor, as part of the modernisation of the boiler room, it was proposed to replace the old coal-fired boiler with a new higher-efficiency boiler, as well as to use elements of the automatic regulation and control of the system. It was also recommended to modernise the central heating system, hot water heating, to install heating elements with low thermal inertia and thermostatic valves, to install lagging on the central heating pipes, to replace the ineffective electric heaters with a centralised heating from their own boiler room, as well as to increase the heating interruptions. Reducing the heat transfer coefficients of the building envelope by about 60-80 % to the applicable requirements and over 100 % improvement of the heating system efficiency contributed to about 55 % decrease in the energy demand of the building.

The consequence of lowering the heat demand of the considered building was the reduction in the emissions of harmful substances into the atmosphere from the coal combustion process (Table 5). The emission factors were adopted on the basis of the data provided by the National Center for Emissions Management [10]. After the thermal modernisation, the emissions of the particulate matter PM10 and PM2.5 to the atmosphere decreased by about 55 %. The decrease in the emissions of benzo(a)pyrene and other harmful substances was at the same level.

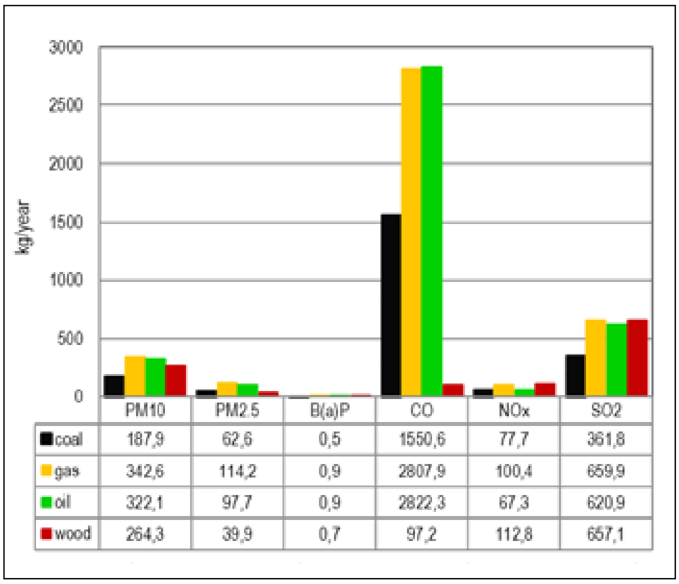

Figure 7 Avoided emission from different types of energy carriers

Table 5. Direct emissions and the reduction in the selected pollutants

Type of pollution	Before thermal modernisation	After thermal modernisation
	kg/year	
SO_2	659.9	298.2
NO_x	141.7	64.0
CO	2,828.5	1,277.9
PM10	342.7	154.8
PM2.5	114.2	51.6
B(a)P	0.9	0.4

An analysis was made of the reduction in the low-stack emissions in the case of using gas, oil or wood boilers instead of a coal-fired boiler. The amount of the avoided pollutant emissions from the different energy carriers is shown in Figure 7.

Replacing the boiler with a more efficient coal boiler resulted in a 55 % decrease in the particulate matter emissions, and, in the case of using a gas boiler, an almost 100 % reduction was achieved not only in the particulate matter, but also with the benzo(a)pyrene, carbon monoxide and sulfur dioxide (Table 6).

Table 6 Percentage reduction in direct emissions

Type of pollution	Type of energy carrier			
	Coal	Gas	Oil	Wood
	%			
SO_2	54.8	~100.0	94.1	99.6
NO_x	54.8	70.9	47.5	79.6
CO	54.8	99.3	99.8	3.4
PM 10	54.8	99.9	94.0	77.1
PM 2.5	54.8	99.9	85.5	34.9
B(a)P	54.8	100.0	95.5	77.4

The most appropriate solution to reduce emissions, especially PM10, PM2.5 and B(a)P, would be to combine the comprehensive thermal modernisation of the building with the replacement of a coal-fired heat source with a gas-fired one.

RENEWABLE SOURCES AS MEANS OF ENVIRONMENTAL PROTECTION

An important part of the Clean Energy package presented by the European Commission in 2016 is the creation of a clear path to low- and zero-emission buildings by 2050, and one of the main goals is the development of renewable energy sources. Already, many European Union

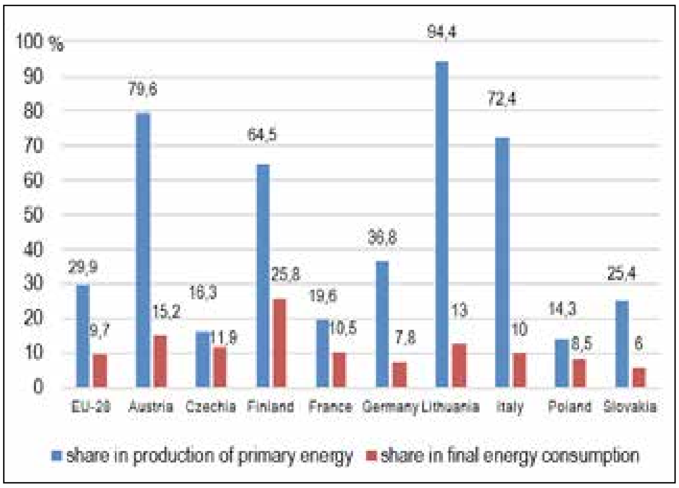

Figure 8 Share of energy from renewable sources in the production of the primary energy and in the final energy consumption [16]

Figure 9 The solar panel system at the specialist hospital in Czestochowa (Viessmann)

countries show a high share of renewable energy sources for obtaining primary energy (Fig. 8), a trend that has been clearly growing in recent years [16].

In Poland, four scenarios for the development of a zero-emission economy by 2050 have been developed [30]. The most favourable scenario seems to assume a 73 % increase in the share of renewable energy sources and the gradual phasing out of coal-based energy. The energy obtained from the renewable sources in Poland in 2018 came mainly from solid biofuels (68.88 %), wind energy (12.55 %) and liquid biofuels (10.33 %). The total energy value of the primary energy obtained from the renewable sources in Poland in 2018 was 367,091 TJ. The structure of the energy production from the renewable sources by the carriers in Poland and other EU countries in 2018 is presented in Table 7 [16]. The differences in the structure of obtaining the energy from the renewable sources in the individual countries are also influenced by the geographic conditions and the possibilities of the resource management.

The energy potential of renewable energy sources in Poland is significant: wind energy - 36.0 PJ, hydropower - 43.0 PJ, energy from biomass - 895.0 PJ, geothermal energy - 1,512.0 PJ and solar energy - 1,340.0 PJ [16].

An example of using solar energy in Poland is the solar panel system in the specialist hospital in Czestochowa. It is the one of largest solar collector installations in Poland (Fig. 8). The solar installation consists of 598 collectors with an area about 1500 m^2. The structure is positioned on three fields located on the roof of the building and directly on the ground level. The solar exchanger technology is based on three buffer tanks, a hot water storage tank, and plate heat exchangers.

Table 7 The structure of the energy production from the renewable sources by the carriers [16]

Individual carriers	CZ	FI	IT	DE	FR	PL	EU
Solid biofuels	67.4	73.9	29.5	28.2	41.8	67.9	42.0
Solar energy	4.7	0.0	8.7	9.5	3.9	0.8	6.3
Hydro	3.6	10.9	5.5	4.1	16.6	2.4	11.4
Wind	1.1	3.5	5.7	21.3	8.2	14.0	13.8
Biogas	13.7	1.1	7.2	18.4	3.5	3.1	7.4
Liquid biofuels	4.6	3.1	3.3	7.8	10.2	10.0	6.7
Geothermal energy	-	-	20.7	0.6	1.6	0.2	3.0
Municipal waste	2.1	2.8	3.2	7.5	5.4	1.0	4.4
Heat pumps	2.8	4.7	10.0	2.5	8.9	0.6	4.9

The total installed capacity is about 1000 kW. The average daily consumption of hot water by the hospital is about 53 m^3. The collectors cover 51.8 % of the power demand, 32.3 % is guaranteed by the economisers recovering heat from the exhaust, and cooperation with the existing 4 gas and oil steam boilers provides the remaining 15.9 % of the power demand. During sunny weather, the solar installation, together with the economisers, can heat all the water needed for the hospital, with a minimum of sunlight reaching an efficiency of about 84 %.

The energy-saving technology of the economisers will significantly reduce the operating costs of the hospital related to the fees for the energy utilities, resulting in the facility saving up to $85,000 a year. The installation of solar panels in hospitals has become very popular in recent years.

The next example shows the possibility of using unconventional energy sources such as low- and high-temperature geothermal water for heating. In Poland, there are several geothermal plants, i.e., Bańska Niżna, with water temperatures of 60-100°C (capacity - 4.5 MJ/s), Pyrzyce has water temperatures of approx. 60°C (capacity - 15 MJ/s), Mszczonów has water temperatures of approx. 40°C (capacity - 7.3 MJ/s), Uniejów, with water temperatures of approx. 67°C (capacity - 2.6 MJ/s) and Słomniki, with water temperatures of approx. 17°C (capacity - 1 MJ/s). The Słomniki heat-generating plant is Poland's only plant that uses low-temperature heat as a lower source [28]. In Silesia, the largest technical potential of geothermal water exists in reservoirs located in the Miechów trough, in the areas of the Czestochowa and Zawiercie districts, as well as in the Cieszyn district [28].

One example of the potential for utilising low-temperature geothermal water for heat-generating purposes is a deep bore-hole in Poczesna (Czestochowa district) [28]. The pumped water volume flux is 24 m^3/h, 40 m^3/h, 50 m^3/h and 80 m^3/h. The source power is 406 kW, 677 kW, 846 kW and 1,353 kW. For the low-temperature geothermal heat-generating plant in the locality of Poczesna, the following facilities have been assumed to be connected: library – 50 kW, office building – 175 kW, school – 320 kW, health centre - 50 kW, preschool - 105 kW, police station - 44 kW, Poczesna Fire Brigade - 25 kW and church - 50 kW. When heating only part of the above-mentioned facilities, a monovalent system

Figure 10 Czernikowo photovoltaic power plant (Energa)

with a heat pump as the only central heating system supply source can be used. In the event, where the heating of all the buildings is assumed, the thermal power of the geothermal water source under consideration would not be sufficient. An additional heat source could be provided by a gas boiler.

According to data from the Energy Regulatory Office, there are 40 photovoltaic installations in Poland with a capacity of over 1 MW. The largest amount of power does not exceed 3.8 MW. The largest photovoltaic power plant in Poland is located in Czernikowo near Toruń in the northern part of Poland. The choice of the location was determined by factors including the favourable natural conditions, the direct proximity to the end users, the proximity to other renewable energy sources and consistency with the local spatial development plan. The installed capacity of the plant is 3.77 MW. The PV power plant in Czernikowo covers an area of approximately 7.7 ha. The installation consists of about 16,000 panels, each with a capacity of 240 W (Fig. 10).

They cover an area of over 22,500 square meters. The annual electricity production in Czernikowo is estimated at 3,500 MWh. This covers the needs of around 1,600 households. The power plant has a container transformer station, which consists of a low voltage switching station, a transformer chamber and a medium voltage switching station with a control room, as well as an underground cable connection to the 15 kV MV line. Currently, in the Lubuskie Voivodeship, near the Witnica commune, close to the Polish-German border, BayWa r.e. began construction of the largest photovoltaic farm in Poland with a capacity of 64.6 MWp.

In Poland, the largest source of electricity from renewable energy sources is wind. According to the data from the Polish Electricity Networks, the installed capacity of the wind farms is currently close to 6.3 GW. The installed capacity of the wind farms accounts for approximately 65 % of the installed capacity in all types of RES installations. The largest wind farm is located in Margonin in the Wielkopolskie Voivodeship. It consists of 60 wind turbines with a total capacity of 120 MW, which meets the energy needs of 90 thousand households.

Figure 11 The wind farm at Margonin (EDP Renewables Poland)

The power of wind sources in Poland is constantly growing, but photovoltaic installations show much greater dynamics in the development.

CONCLUSION

Compared to other European Union countries, the quality of the outside air in Poland, unfortunately, is not satisfactory. Thus, the gradual adaptation of existing buildings, the exploitation of which is one of the reasons for this state of affairs, to the standards of energy-efficient construction and the introduction of innovative technologies and solutions obviously help to combine the energy and economic effects of reducing the negative impact of the buildings on the environment. Therefore, it is necessary to promote and implement environmentally friendly technologies based on renewable energy sources and to increase the use of these resources. Individual countries can create a legal framework that allows the implementation of international standards of ecological and energy efficiency, because care for the state of the environment and the good health of society, while maintaining the current level of production and standards of living is possible only through the rational management of resources and carrying out pro-ecological projects.

The rationalisation of energy consumption in buildings through thermal modernisation is the basis for reducing low-stack emissions especially in the area where buildings with individual boiler rooms or stoves are located. An analysis of the possibility of reducing the energy consumption of residential buildings and the emissions of pollutants to the atmosphere generated during their production clearly indicates the greatest potential for activities undertaken in regards to heating rooms. The calculations show that, as a result of adjusting the energy demand for residential heating to 65-70 kWh/(m^2year), the energy consumption for heating existing residential buildings in Poland can be reduced by an average of around 72 % compared to 2011. Implementing these measures will also reduce air pollutant emissions. Considering the fact that the demand for heating in Poland is about twice as much in comparison with European standards, an improvement in the energy efficiency in this area may result in a reduction in the national energy consumption by over 10 %. This saving would be accompanied by a decrease in the particulate matter and CO_2 emissions on a similar scale. It is estimated that due to the implementation of the EU directives in this area, CO_2 emissions can be reduced by 28 million tonnes per year.

Solid fuels, mainly poor-quality coal and district heating, play a leading role in heating buildings in Poland. Solid fuels are the basic heating energy carrier for single-family houses, and for heat networks for multi-family buildings. The production of district heating takes place in about 75 % of the buildings, also with the participation of coal. However, the centralised production and the use of filters can reduce the negative impact on the environment. The third most used energy carrier is natural gas. This more environmentally friendly fuel is used in 10 % of residential buildings. Natural gas is characterised by about 35 % lower nitrogen oxide emissions and about 97 % lower carbon monoxide emissions. Gas combustion does not properly emit particulate matter, sulfur dioxide and benzo (a) pyrene. Therefore, the solution to the problem of low-stack emissions in cities would be to replace coal boilers with gas boilers or to connect buildings to the network, in addition to a ban on burning wood in open fireplaces. However, in the long term, the conventional power industry based on coal or gas will not be able to meet the growing energy needs due to the limited and fast exhaustion of conventional fuel sources.

Solar radiation, geothermal water, wind and hydroelectricity are widely available renewable energy sources. Renewable energy technology produces clean energy, and the optimal use of these resources minimises the impact on the environment and generates a minimal amount of secondary waste. Supporting the development of renewable energy sources is one of the key elements of sustainable development, contributing to the increase in the energy supply security and economics, as well as the regional and rural development. By reducing the emissions of the pollutants into the atmosphere, climate change is reduced, and the health of society and the state of the natural environment are improved. The production of energy from renewable sources ensures positive environmental effects and, at the same time, contributes to the development of less developed regions.

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