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POROUS CEILING AIR INLET AS A POTENTIAL SOURCE OF UNCONTROLLED AIR EXCHANGE AT NURSERIES WITH EXHAUST MECHANICAL VENTILATION

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ABSTRACT

The purpose of the research was to compare uncontrolled air exchange at nurseries with different air inlet solution. Four identical 400 m^2 nursery departments were investigated. Three of them used porous ceiling as an air inlet, with different area of ceiling designed to be permeable. The areas of porous ceiling tested were 300, 150 and 75 m^2 respectively. In fourth department ventilation air entered the room through, also located in the ceiling, high speed inlet systems. Actual air exchange in the departments was evaluated from H_2O balance. The data required for calculation, i.e. inside and outside temperatures and humidities were being continuously monitored and registered from mid of December, 2000 to early February, 2001 to include first 5 weeks after moving piglets to each departments. Propane consumption was checked every day. U – value for the outside walls was calculated and additionally checked by means of thermovision. The number of piglets moved to each building was counted with further provisions for death or culling losses.

For results analysis, thermovision observations of permeable ceiling at changing ventilation exchange rate with heaters off and on were carried out. Pressure differences through the ceiling were also measured.

It has been found that using porous ceiling as an air inlet in nurseries significantly affected air exchange. Three factors were identified to particularly affect the level of air exchange:

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- ratio of porous ceiling area to the area of all ceiling,
- time and frequency of additional heating operation,
- the rate of continuous minimum ventilation.

Consisting of 10 cm mineral wool porous ceiling appeared to be extremely ununiform as dynamic heat insulation. The average underpressure in the buildings was very low at minimum ventilation rate, with the values below 1.0 or even 0.5 Pa. It changed to overpressure quite often, particularly when heaters were operating. These factors combined seem to be responsible for uncontrolled air exchange in departments with porous ceiling air inlet.

Key words: pigs, nurseries, weaners, porous ceilings, uncontrolled air exchange

INTRODUCTION

Application of porous ceiling as an air inlet reduces heat transmission losses by conduction through the ceiling [14, 15]. Incoming cold air warms up when flowing through ceiling material. In theory, the efficiency of this process depends on air exchange; the higher air exchange the lower efficient U-value [12]. As theoretical calculations suggest, providing the velocity of the air passing through porous ceiling at a level 0,001 m/s, should decrease its conductivity by the factor of two [19].

Porous insulation is usually considered to improve thermal insulation efficiency of the ceiling [3, 13], to improve air quality and hygiene inside a building [6, 13] and to reduce the risk of drafts in an animal occupied zone [3, 19].

There are also some disadvantages of this kind of air inlet solution. Yao et al. [23] suggested that using porous ceiling as an air inlet can result in significant stagnant spots in the building. This suggestion can be linked with proving by Randall [17] that an airflow in buildings with this type of air inlets occurs in a series of rotary patterns which are more characteristic of mixed than plug flow systems [2]. The air entering the inside of the building through a porous ceiling area seems to have no influence on the airflow patterns in it since the speed of the incoming air is at a level of one tenth of that of the recirculatory currents caused by convection from the stock [17]. On the other hand there is some evidence that, at least at winter conditions, the efficiency of ventilation with air inlets through porous ceiling was not any worse than of high speed air inlet system with only slightly higher efficiency fluctuation in breathing ceiling systems [10]. Another problem might be ceiling clogging by dust; the phenomena which can effect its permeability [7, 18]. Special measures should be undertaken at high summer temperatures particularly in sunny days when the attic works as a solar collector which can significantly affect the inlet air temperature [9, 20].

Porous ceiling air inlets have been reported to be successfully employed mostly in animal buildings [3, 6], agricultural storage buildings [7]; but also dwellings [3, 4] and schools, office buildings or sport facilities [13].

Most systems were introduced in three European countries: Norway [6, 7, 13], Sweden [18, 19] and Austria [3]; with some buildings constructed in Canada [8, 21, 22].

The results of preliminary research unexpectedly revealed that much less energy was consumed at department with high speed air inlets than at remaining departments, where porous ceiling insulation system was employed. It has also been shown that air humidities in the room with high speed air inlets were significantly higher than in remaining rooms, what taking into account similar level of 1^{st} step ventilation in all nurseries suggest that using ceiling surface for air inlets can significantly increase uncontrolled air exchange in the building.

The aim of the research was to confirm these preliminary results with the following hypothesis to be verified:

- using ceiling of 2×5 cm layers of mineral wool as air inlet may significantly increase uncontrolled air exchange in the building,
- uncontrolled air exchange depends on the area of porous ceiling employed; the higher porous ceiling area, the more uncontrolled air exchange.

MATERIALS AND METHODS

The research was carried out in 4 nursery departments 25×16×3.3 m (Fig. 1). Only two side walls for each of the department were the outside ones; the other being internal partitions. The outside walls consisted of one and half layer of Alfa hollow blocks with 5 cm layer of mineral wool between the two. To tighten the building envelope 0.25 mm PCV foil was added between inside blocks layer and mineral wool insulation. Floor of the building was insulated at all its surface by means of special type of light concrete based on low U value aggregate.

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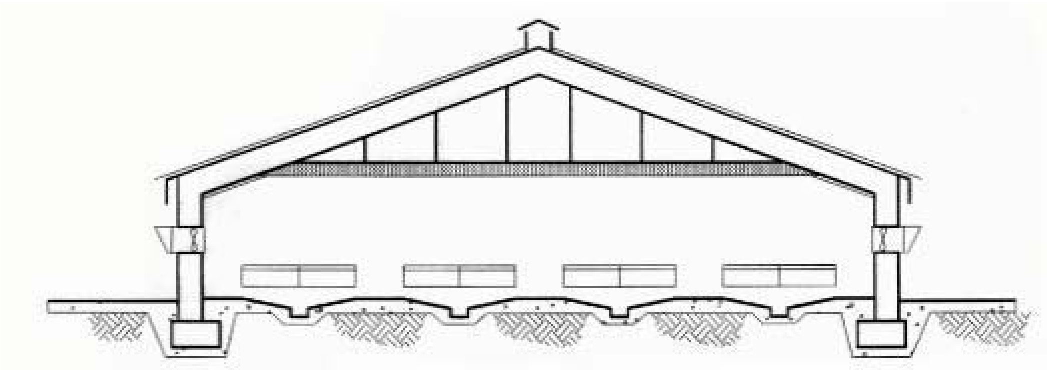
Figure 1. Cross section of one of four investigated departments



In all 4 departments air exchange was provided by exhaust mechanical ventilation consisted of 4 small fans with maximum capacity 1200 m^3/h each. These fans working in various arrangements depending on weaner's weigt were considered as step 1 ventilation. There were 6 additional 4500 m^3/h fans controlled thermostatically and switched on by two, considered as 2nd, 3rd and 4th ventilation step. Each department was equipped with two 28 kW propane unvented gas space heaters using recirculating air. The heaters were located in the opposite corners of the rooms. The air flow of each of them was 900 m^3/h. All the heaters used in nurseries were over dimensioned by about 50% for typical design winter condition at this area of Poland: outside temperature t_e -16°C and outside relative humidity 90% at inside air temperature and relative humidity being assumed at the levels of 27.5°C and 70% respectively. The reason for that was very high uncontrolled air infiltration occurring particularly in nursery departments with air inlet through porous ceiling.

1st step ventilation was manually controlled with the amount of exhausted air being adjusted by the number of running fans and dampers limiting the area of air outlet. The minimum ventilation level was assumed to be 1200 m^3/h for the first 10 days following piglets moving from farrowing. The next 10 days its level was increased to 1600 m^3/h. From 21st to 34th day it was kept at a level of 2400 m^3/h and from 35 day on – to 3600 m^3/h. The EONT (Either-Or-Neither Temperature Control) [26, 27] with 1 K dead band between switching off the heaters and switching on the 2nd step ventilation was employed in all rooms.
The only differences between rooms under investigation were the air inlet solution and the number of piglets moved from farrowing.

Figure 2. Porous ceiling inlet at the area of 300 m^2 (connection of porous ceiling with impermeable insulating panels PW3/A)

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Figure 3. Porous ceiling inlet at the area of 150 and 75 m^2 (connection of porous ceiling with impermeable insulating panels PW3/A and black impermeable foil)

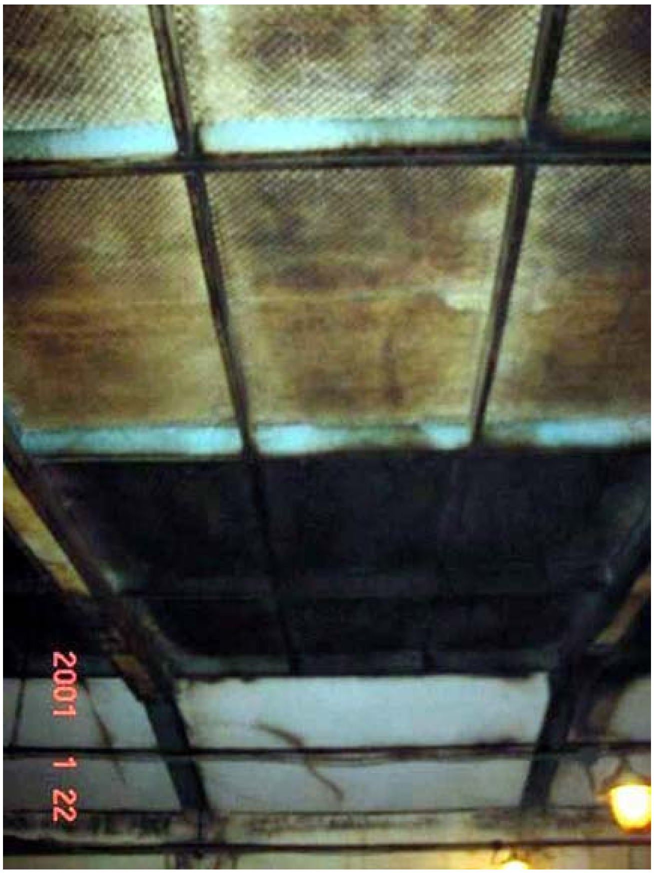

Figure 4. Impermeable ceiling consisting insulating panels PW3/A with high speed ceiling air inlets

In three departments breathing ceiling air inlet solutions were used with 300, 150 and 75 m^2 respectively (Figures 2-4). The construction of porous ceiling were two 5 cm layers of mineral wool mats supported by light wood structure and additionally protected by polyester mesh. In the forth department air supply was provided by 4 high-speed air inlets, located in the center of the ceiling which consisted of polyurethane sandwiches PW 3/A with additional 5 cm layer of mineral wool with total ceiling U – value 0.35 W/m^2K [11].

The following temperature program was used for all departments:

- 27.5°C – 1-10 days after weaning,
- 25.0°C – 11-20 days after weaning,
- 22.5°C – 21-34 days after weaning,
- 20.0°C – 34-49 days after weaning.

For above temperature programs the suitable minimum air exchange levels were assumed to be:

- 1200 m^3/h – 1-10 days after weaning,
- 1600 m^3/h – 11-20 days after weaning,
- 2400 m^3/h – 21-34 days after weaning,
- 3600 m^3/h – 34-49 days after weaning.

Achieved in this way 1st step ventilation was at the level of 60-75% of minimum ventilation required, a bit less than 75%, recommended by Barber [1].
The brief summary of the most important characteristics of the departments are given in Table 1.

Table 1. General description of the departments under investigation

Room name	Room symbol	Air inlet	Piglets number
Impermeable ceiling	IC	High-speed, located in ceiling	643
75 m^2 permeable ceiling	PC75	Porous – 18.8% of ceiling area	738
150 m^2 permeable ceiling	PC150	Porous – 37.5% of ceiling area	732
300 m^2 permeable ceiling	PC300	Porous – 75% of ceiling area	826

The research was carried out since mid of December 2000 to the first days of February 2001.

The inside temperature and humidity were registered at 0.5 to 3 minutes intervals using AHLBORN temperature and humidity capacity sensors with accuracy ±0.5 K and ±3%. The outside temperature and humidity were registered at the farm at 1 minute intervals by HOBO Pro Series temperature and humidity sensors with accuracy ±0.5 K and ±5%, and further verified with the half-hourly data from portable meteorological station located at Urad in close farm neighborhood from where some other meteorological data (i.e. wind speed, sun radiation) were also taken.

What is further called actual air exchange was calculated daily for each department using heat balance method.
The results obtained were averaged to daily values and analyzed by means of one way Anova test.

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RESULTS

The effects of ceiling solution and the area of its permeable part on daily inside air RH values, actual air exchange, actual to planned air exchange ratio and daily propane consumption have been illustrated at Table 2.

Table 2. The effects of ceiling solution and the area of its permeable part on daily inside air RH values, actual air exchange, actual to planned air exchange ratio and daily propane consumption

Characteristics of air exchange and heat consumption in nursery	Type of ceiling in nursery				
	IC	PC 75	PC 150	PC 300	P
Relative humidity (%)	62.60	56.20	54.80	50.90	P < 0.0001
Actual air exchange (m^3/h)	2246.00	2985.00	3212.00	3805.00	P < 0.0001
Ratio (actual/planned air exchange)	1.20	1.62	1.87	2.25	P < 0.0001
Propane consumption (m^3/day)	6.48	10.69	10.86	14.62	P < 0.0001

The average inside relative humidity was highest at department with high speed air inlets and impermeable ceiling (IC – 62.6%) and lowest at department with 300 m^2 porous ceiling (PC300 – 50.9%). The average inside relative humidities in departments with (150 m^2 – PC150) and (75 m^2 – PC75) porous ceiling, respectively 54.8 and 56.2%, were significantly lower than for IC and significantly higher than for PC300. There was no significant difference between inside RH at PC150 and PC75.

The average estimated air exchange for first 34 days after weaning at IC equaled 2246 m^3/h, and was significantly lower than at remaining departments, 2986, 3212 and 3805 m^3/h at PC75, PC150 and PC300 respectively, which is 32.9, 43.0 and 69.4% more than at IC.

Probably the most important factor allowing for the analysis of uncontrolled air exchange in the building is the ratio of estimated (actual) air exchange to minimum continuous ventilation provided by mechanical ventilation. Its lowest value 1.20 was found at IC room, what means that air exchange provided at this department by mechanical ventilation was in average exceeded by as low as 20.0%. The ratios showing estimated (actual) air exchange to minimum continuous ventilation provided by mechanical ventilation were much higher for the other departments with almost linear tendency to grow with the increase of porous ceiling area. The values of air exchange provided at these departments by mechanical ventilation were exceeded respectively by 62% at PC75, 87% at PC150 and as much as 125% at PC300.

The lowest value of daily propane consumption (6.48 m^3) was at IC department. Its daily consumption at rooms PC75 and PC150 were almost the same (10.69 and 10.86 m^3) respectively. The highest daily propane use was at PC300, reaching 14.62 m^3, which is 125.6% more than at IC and approximately 36% more than at PC75 and PC150.

The amount of propane consumption on each department is of particular importance for searching the reasons for the value of uncontrolled air exchange. The best predictor for actual/planned air exchange ratio which seems very well to describe uncontrolled air exchange has been propane consumption itself since it had explained about 43% of original variability of the model (Beta = 0.654; $p < 3.11E^{-17}$) [16].

Interesting material for more detailed analysis of the possible reason for uncontrolled air exchange through porous ceiling was obtained by thermovision measurements.

At Figure 5 the effects of air exchange provided by mechanical ventilation on inside ceiling surface temperature and uniformity of ceiling permeability have been illustrated.

Figure 5. Distribution of ceiling surface temperatures at various ventilation rate: a) 0 Air changes per hour (A.C.H.), b) 1.33 A.C.H., c) 3.0 A.C.H., d) 7.5 A.C.H., e) 15.0 A.C.H.

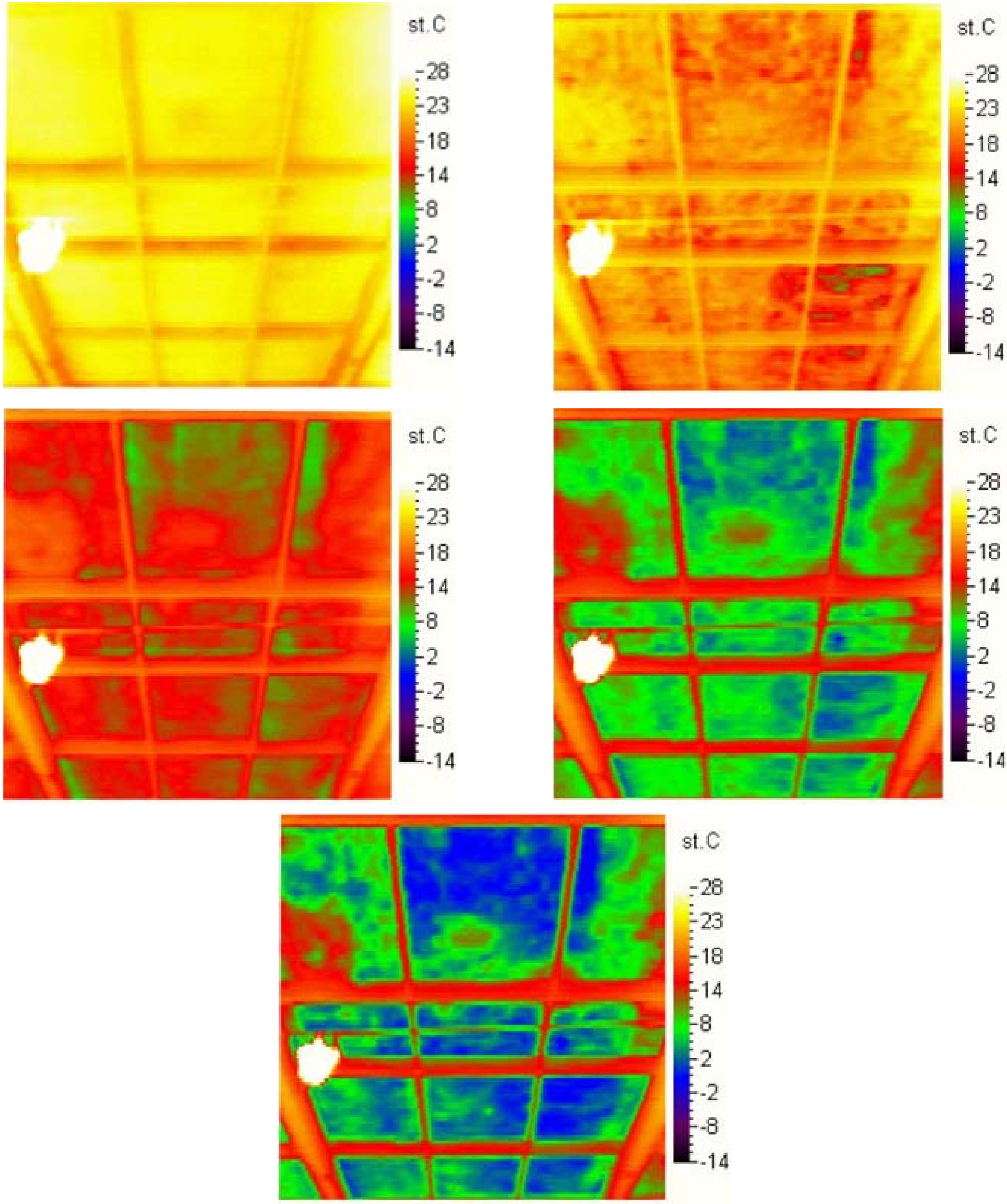

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Table 3. The effect of air exchange on average surface temperature and its standard deviations

Thermal characteristics of ceiling surface	Ventilation air exchange				
	A	B	C	D	E
Average surface temperature (°C)	24.17	19.98	14.74	6.31	3.13
Average standard deviation (K)	0.43	1.15	1.94	2.51	3.08

Table 3 illustrates the effect of ventilation rate on thermal uniformity of inside porous ceiling surface, measured in terms of average surface temperature and its standard deviations in 6400 measuring points.

As it can be seen operation of only 1st step ventilation of 1600 m^3/h, an equivalent of approximately 1.33 A.C.H. reduced average ceiling temperature by more than 4 K and increased its standard deviations by almost 3 times comparing with the situation with no mechanical ventilation (the difference between ceiling working as a static heat insulation and dynamic heat insulation). With further increasing ventilation to 3 A.C.H. average ceiling temperature dropped down by more than 5 K and its standard deviation increased by almost 50% comparing to ventilation at a level of 1.33 A.C.H.

The analysis of data given by thermovision suggest that another factor responsible for the values of standard deviations of the temperatures at inside area of porous ceiling is running of heating equipment.

At Figure 6 the values of inside surface ceiling temperatures and their standard deviations have been illustrated.

Figure 6. Distribution of ceiling surface temperatures at heating mode: a) start of heating operation, b) 9'50'' after heating start, c) 17'42'' after heating start

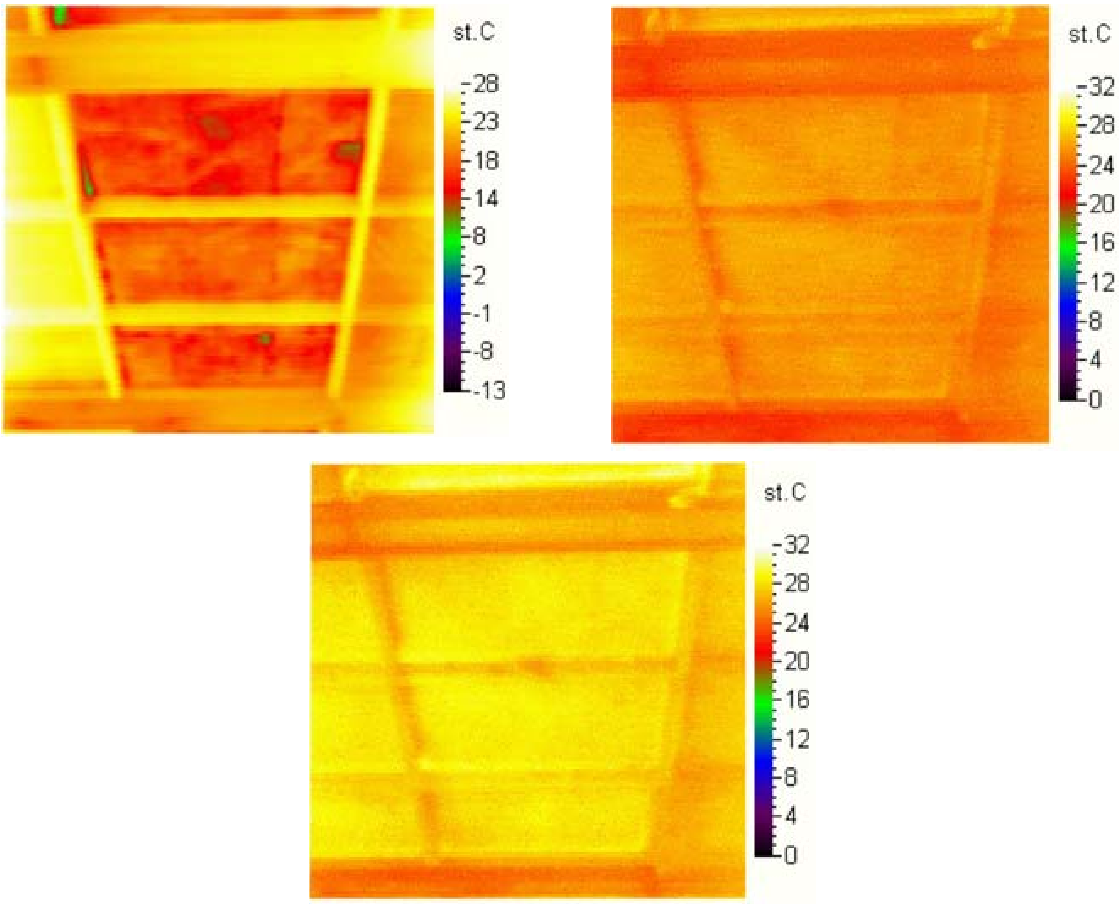

Table 4. The effect of heating on average surface temperature and its standard deviations

Thermal characteristics of ceiling surface	Time passed from switching the heaters on		
	A	B	C
Average surface temperature (°C)	16.84	25.84	28.87
Average standard deviation (K)	1.18	0.48	0.45

Table 4 illustrates the effect of supplementary heating operation on thermal uniformity of inside porous ceiling surface, measured in terms of average surface temperature and its standard deviations in 6400 measuring points. The beginning of the measurements took place immediately before starting two 28 kW space propane heaters on. Air exchange during the experiment was set up at a level of 1600 m^3/h. As can be seen, the ceiling temperature was increasing rapidly from a bit more 17°C to 25°C in about 8 minutes after turning the heaters on. Already 5 minutes after starting heaters operation average standard deviation was reduced by the factor of 2 (decreasing from a bit more than 1.2 till 0.65). In the next 5 minutes its value dropped down to a bit less than 0.5 and has been remaining at this level to the end of heater operation.

Presented above results of thermovision research performed on mineral wool used for 12 years as dynamic heat insulation for porous ceiling at nursery can be summarized as follow:

- it behaved uniformly as static heat insulation (mechanical ventilation off),
- it behaved very ununiformly as dynamic heat insulation (mechanical ventilation on),
- it improved its uniformity as dynamic heat insulation when the supplementary heaters were on (mechanical ventilation on + supplementary heaters on).

DISCUSSION

It is typically assumed that providing by exhaust mechanical ventilation incoming air velocities at a level 0.001 m/s should minimize the risk of backwards air movement through porous ceiling [19]. Providing under pressure in a barn of not more than 1 Pa has been reported to be enough for proper functioning of 25 mm thick wooden wool porous ceiling [3, 19]. It should be also mentioned that the back draft phenomena in porous ceiling is considered rather as a potential reason for water condensation in insulation material than a risk for uncontrolled air exchange [12, 19]. To secure the intended direction of air through the insulation thus avoiding problems with water vapor condensation within insulation material due to backwards air movement, the under pressure of at least 5 Pa was proposed by Sallvik and Gustafsson [19]. The results of their theoretical calculation suggest however that at outside temperature -10°C under pressure considerably lower than 1 Pa should be enough to avoid backwards air movement in the stable.

The vulnerability of porous ceiling to over ventilation in cold and windy weather has been suggested by Graee [7].

Assuming that actual/planned air exchange ratio could be a good measure for uncontrolled air exchange it becomes more important to attempt to analyze which independent variables are responsible for variability in actual/planned air exchange ratio models thus giving some explanation for uncontrolled air exchange in the departments under investigation.

The results of multiple regression analysis performed on actual/planned air exchange ratio model show that the following independent variables seem to particularly affect uncontrolled air exchange in all investigated departments [16]:

- minimum ventilation estimated from the model,
- minimum ventilation provided as step 1 ventilation by exhausting fans,
- difference between inside and outside temperature,
- wind speed.

First variable is estimated from a model based on many other variables and since that rather difficult for direct interpretation.

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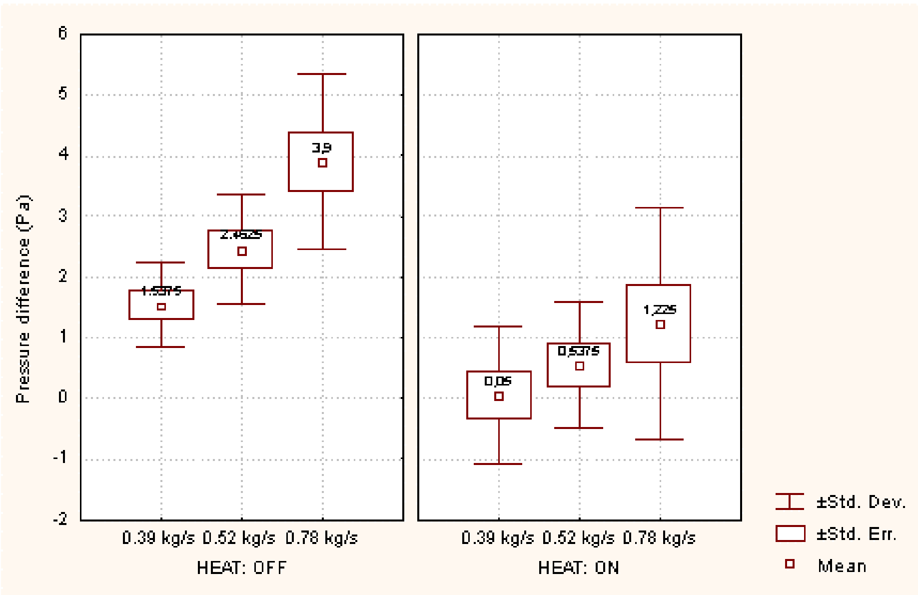
More obvious for interpretation is the effect of three remaining variables. The lower continuous mechanical ventilation, the lower under pressure in the building and the more relative share of uncontrolled air exchange in total air exchange.

The difference between inside and outside temperature and wind speed could be of particular importance when the under pressure in the departments does not exceed 1-2 Pa which was typical for all investigated departments. Average estimated under pressure were approximately at a level of 0.75 Pa for PC300, 1.5 Pa for PC150 and 3.0 Pa for PC75. Taking into account that the outside temperature was very rarely dropping down below -5°C, there should be no backwards air movement at any nursery. As the results of measurements and calculation show however it took place quite often.

In Figure 7 the pressure differences between outside and inside air measured locally at a ceiling level were illustrated. The experiment was carried out 6 times for each of three basic 1st ventilation steps assumed, i.e. 1200, 1600 and 2400 m^3/h. The measurements were taken directly before turning the heaters on and repeated immediately before turning them off.

Figure 7. Effect of supplementary heating process on pressure difference at nursery PC300 with porous ceiling inlet at three levels of 1st step ventilation provided by exhausting fans (under pressure was marked with sign "+" and over pressure with "-")



The most spectacular effects were observed for 1st step ventilation being kept at a level of 1200 m^3/h with average under pressure values close 1.5 Pa, when heaters were off and slightly more than 0 Pa when they were on. The further analysis shows that average underpressure values given for 3 considered 1st step ventilation levels were rather low, leading to quite often local overpressures, which combined with, locally very high, ceiling permeability could have been a probable reason for uncontrolled air exfiltration in the nurseries and in effect higher than estimated air exchanges.

Before the supplementary heating operation was on, slight underpressures at ceiling zone was typically measured with their values being subsequently lowered after heating start. In many cases at the end of supplementary heating operation local overpressures close to 1 Pa were measured. All it happened not only for the first 10 days minimum ventilation – 1200 m^3/h but also when 1st step ventilation was set up at higher level.

The resulting overpressures in building can be explained theoretically [24]. Increase in air temperature results in its tendency to increase its volume. When the room is open this is what actually happens, In semi – tight room the air will be partially increasing its volume (one possible reason for exfiltration) and partially increasing its pressure (the second possible reason for it). The tendency to get local overpressure zones at a ceiling level can be enhanced by strong chimney effect which takes place at heating; with the 10°C temperature difference between ceiling and animal occupied zone.

CONCLUSIONS

1. Very important side effect of applying porous ceiling insulation in nurseries can be uncontrollable air exchange with its level being approximately proportional to the ratio of porous ceiling insulation area to its total area.
2. The effect of uncontrolled air exchange seems to be directly connected with the magnitude of minimum continuous mechanical ventilation; the lower mechanical ventilation, the more significant effect of uncontrolled air exchange with maximum effect when mechanical ventilation is not working at all; the porous ceiling combines then the functions of air inlet and outlet.
3. Uncontrolled air exchange in buildings with porous ceiling was closely connected with time and frequency of additional heating operation; the more heating, the more uncontrolled air exchange. Increase both, air volume and its pressure is probably most responsible for air exfiltration in heating mode. The effect of supplementary heating was of particular significance probably due to high temperature difference, up to 10 K, between ceiling level and animal occupied zone.
4. Even with no additional heat provided there was still considerable uncontrolled air exchange by natural ventilation through porous ceiling area. The reason for that were probably high differences in local ceiling air permeabilities which made the ceiling vulnerable for wind activity as well as disturbances in internal mass and heat flow.
5. The uncontrolled air exchange in nurseries with porous ceiling insulation caused serious problems connected with animal comfort, i.e. very low air humidities, high momentarily temperature fluctuations at animal level.

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