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SIMULATIONS AND MEASUREMENTS IN INDUSTRIAL BUILDING RESEARCH

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ABSTRACT

Buildings for industry and production are an integral part of architecture. Buildings for light industry (IT, electricity, textile, etc.) dominate currently in the area. People working in these buildings spend a substantial part of the day stay in their internal environment. It is therefore necessary to pay attention to the creation and evaluation of industrial buildings. Faced with an evaluation of residential buildings or commercial buildings, an evaluation of industrial buildings is significantly in the background. This contribution presents some results from evaluation of internal quality for industrial buildings. The article deals with physical parameter analysis of indoor climate in large industrial space production halls considering the effects and influence on internal environment in winter and summer periods. The paper presents research results of a questionnaire evaluation of building's users themselves, results of daylighting evaluation, an exterior walls moisture analysis, an analysis of energy requirements for operation of industrial buildings, evaluation of overheating in the summer periods and a research of window design aspect. To address these various issues have been used in situ measurements, laboratory measurements and analysis using computational simulations. The results showed that in the case of industrial buildings may not be the procedures for the evaluation of residential or commercial buildings properly. The results also showed that users' requirements for indoor industrial buildings may differ from the requirements for residential or commercial buildings. Based on the results it should be noted that designing of industrial buildings as well as evaluating industrial buildings should be paid attention and to create different evaluation criteria.

Keywords: *Industrial Building, Indoor Environment, Evaluation, Energy, Simulation*

1. INTRODUCTION

The economic transformation of central European countries has brought new important investments, which have become the driving force in various aspects of life. However, a significant part of economic policies of central European countries concentrate on investments into the production sector.

The current trend of industrial development results in buildings with less environmental impact. This is particularly buildings for light industry (IT, textile, electric, automotive, etc..). The issue of design, construction and operation of industrial buildings is not as intensively studied as in a case of residential buildings or commercial buildings. In recent years, it is possible to follow the work that is given to this issue. Generally speaking, criteria for residential or commercial buildings may not always apply to industrial buildings. It is therefore necessary to make certain modifications in models, methods and approaches to evaluate a proposal of industrial buildings. Research in area of design and evaluation of industrial buildings is concentrated into several areas. The first area focuses on evaluation of the impact of buildings on environment in terms of their sustainability. Alarcon [1] modified the criteria for assessing sustainability for industrial buildings. Lombera [2] developed a model for assessing the sustainability of industrial building buildings.

The second area is the evaluation of the energy intensity of industrial buildings. Bawaneh [3] focused attention on the impact of different climate zones on energy consumption. Zhivov [4], Rezaie [5] and Silvestre-Blanes [6] analyzed various

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HVAC systems in order to decrease energy consumption. Effect of window structures on the energy consumption of industrial buildings analyzed Wang [7]. The optimal tool for the analysis of energy consumption is simulation. Specificity of industrial buildings in terms of the relationship of air flow and energy consumption addresses Tanasic [8].

In the case of industrial buildings is a subject of intensive research, the structural analysis of buildings. The most frequently is examined an effect of wind on structures [9, 10, 11], effect of earthquakes [12] or various structural proposals [13].

To ensure indoor air quality for users, the manufacturing requirements for air quality whether heating tasks is associated with different HVAC systems design. HVAC systems for residential buildings or commercial buildings may not be functional for industrial buildings. Chinese [14] dealt with the methodology of space heating system choice. Ensuring a high quality indoor environment is necessary for some operations. An analysis is performed for different systems mainly through CFD simulations. The quality depends on the choice of system [15]. Generally, the efficiency of any HVAC system can be computationally verified. Shea [16] describes several case examples of the role of HVAC operations in vapor intrusion assessment and mitigation. Use of solar panels (Hall R. 2011) or PV panels for operation of industrial buildings is more energy efficient [17].

One of the research areas is the integration of industrial buildings into the environment after industrial production. In the world there are many successful examples. Interesting works are [18-22]. Examples show that industrial buildings can be integrated back into an architectural environment in interesting concepts.

The subject of the research project is the field of the physical components of the internal environment and their mutual interaction in industrial buildings mostly of a hall type. The specificity of the internal climate of industrial production buildings, mainly of a hall type, characterizes the non-homogeneity of the individual kinds of internal climate. This non-homogeneity is characterized by non-stationary energy flows in the building in space and time. Their qualitative and quantitative evaluation in a prediction level is not simple. One of the possibilities to make use of here is the use of integrated simulation methods. Within the framework of research project solution attention is focused on selected physical components of internal environment, especially thermal, humidity and daylighting conditions in close touch with energy demand analysis. The aim of the whole research is to look for ways to optimizing these conditions with regard to the design of a building envelope part in close touch with environmental technique and energy intensity reduction during their operation. The solution of these questions in interaction with architecture and creation of structural detail of industrial buildings should lead to the change in approach to the design of an industrial building. The result should be a stately architecture, environmentally relevant, economically efficient and sustainable industrial building (Fig. 1).

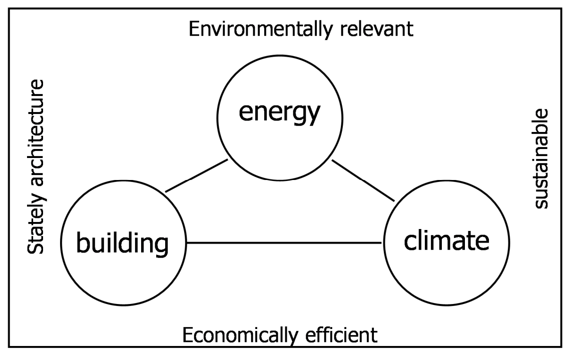

Fig. 1 Scheme of aspects for industrial building design

2. THE PERCEPTION OF INDUSTRIAL BUILDINGS AND THEIR ENVIRONMENT

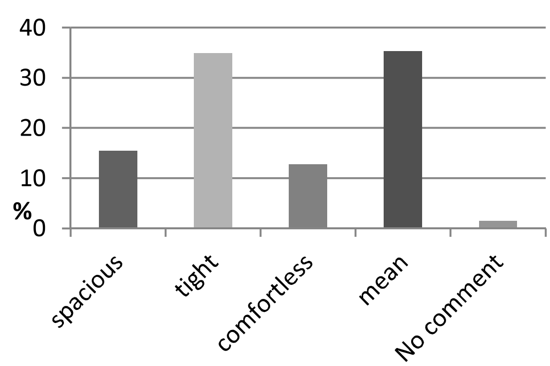

Fig. 2. Evaluation of overall feelings in building. Question: How Do you feel in the building?

For the purpose of the perception of the internal environment of industrial buildings (Fig. 2) a questionnaire survey of evaluation of the internal environment in industrial production halls was conducted by the employees themselves [23].

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According to the survey results the worst work conditions are in summer period. 64% of the employees in the survey designated this period as the most unfavorable for work (Fig. 3).

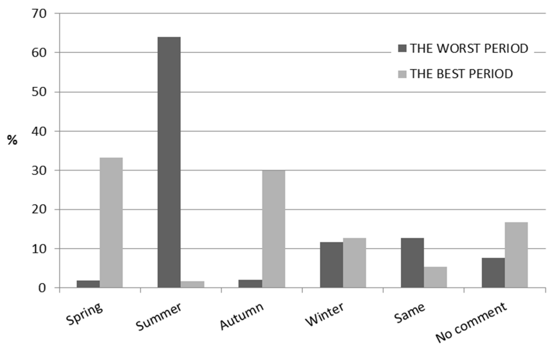

Fig. 3 Evaluation of seasons of the year with regard to comfort at work

From further evaluation of the individual components of the internal environment the following were experienced as the most significant: abnormal cold (especially in winter month), insufficient air exchange (especially in summer months) and excessive noise (Fig. 4).

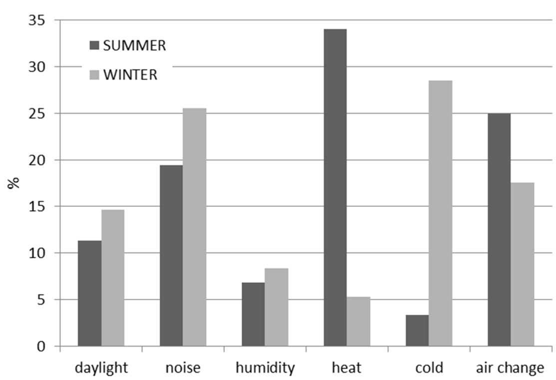

Fig. 4 Evaluation of selected parameters of internal environments with regard to seasons of the year. Question: What hinders you the most at work in the winter/summer months?

3. EVALUATION OF THE HUMIDITY REGIME OF EXTERNAL ENVELOPE

Two types of porous concrete, porous concrete PB using fly ash (further AC PB) and silica sand porous concrete X (further AC X) have been selected to be studied in this part of the project [24]. They are frequently used in constructions of residential houses, as well as non-residential buildings and production halls. AC PB is a light concrete with silica filling – ash and gas silicate or more frequently gas concrete; mixed with foaming additive (aluminium powder) macropores are created. AC X is a light concrete with silica sand and lime – cement (gas silicate) or less frequently gas concrete; mixed with foaming additive (aluminium powder) macropores are created.

3.1 Measurements and Material Properties

As a material we used two alternatives of autoclaved aerated concrete. Cement lime plaster was used as external finish and as internal was used gypsum plaster (Fig. 5).

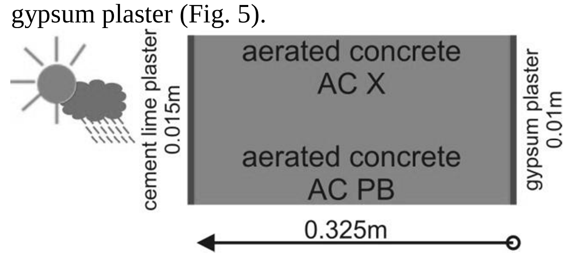

Fig. 5 Scheme of the analyzed building's envelope

Moisture storage function for AC X and AC PB compared to AC 600 (old style) (WUFI 4) are showed in the Figure 6.

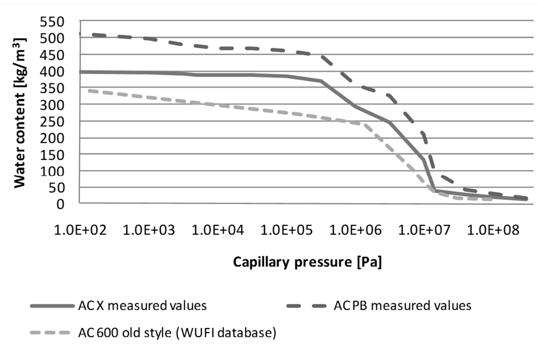

Fig. 6 Moisture storage functions for AC 600 (WUFI 4) and AC X / AC PB

Liquid transport coefficients were approximately calculated by the equation (1) [25].

$$\frac{A^2}{w_f\left(w_f - w_{80}\right)} = \frac{4\left(D_{wf} - D_{w0}\right)}{K\pi \ln\left(\frac{D_{wf}}{D_{w0}}\right)} \qquad (1)$$

$$K = 0.025.10^{\left(-0.4.\left(\log\frac{D_{wf}}{D_{w0}}\right)-3\right)} + 0.61 \qquad (2)$$

Liquid transport coefficients for AC X and AC PB compared to AC 600 (old style) are showed in the Figure 7.

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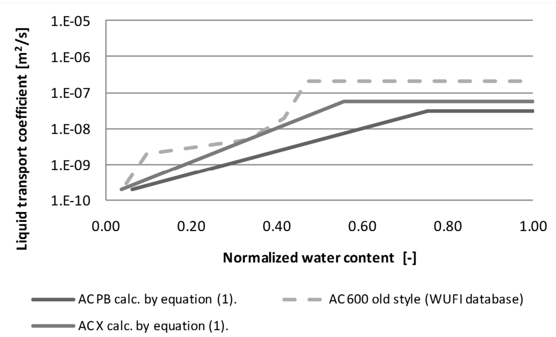
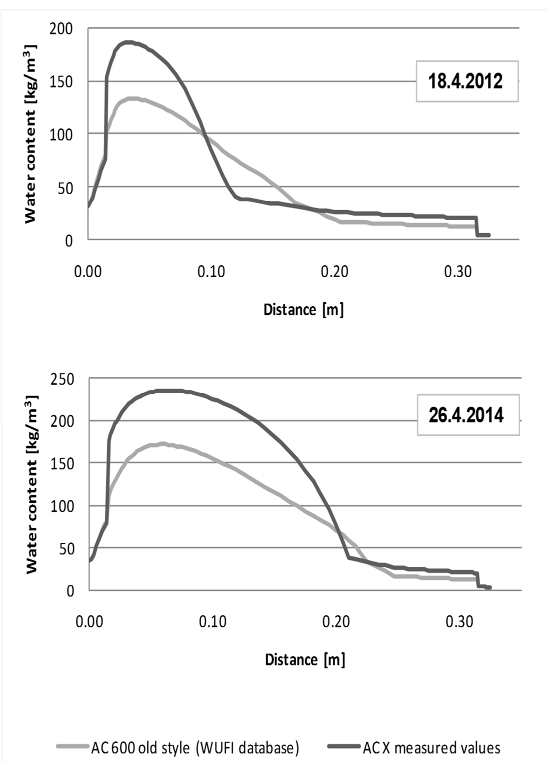


Fig. 7 Liquid transport coefficients for AC 600 (WUFI 4) and AC X / AC PB

3.2 Simulation Results

Figure 8 shows water profiles for AC 600 (old style) from the WUFI database and aerated concrete AC X/AC PB (measured) at two moments (18.04.2012 and 26.4.2014).

Figure 9 shows courses of water content within the simulation interval (1.10.2011 – 1.10.2014). As the figures show (Fig. 8 and 9) the water content stored within the building construction differ. In the case of the selection of similar materials (in this case AC 600 old style) water profiles as well as water courses differ significantly. The difference is up to 38%. It is clear from this analysis, which use of similar materials instead of concretely measured data can lead to significant mistakes in calculations.



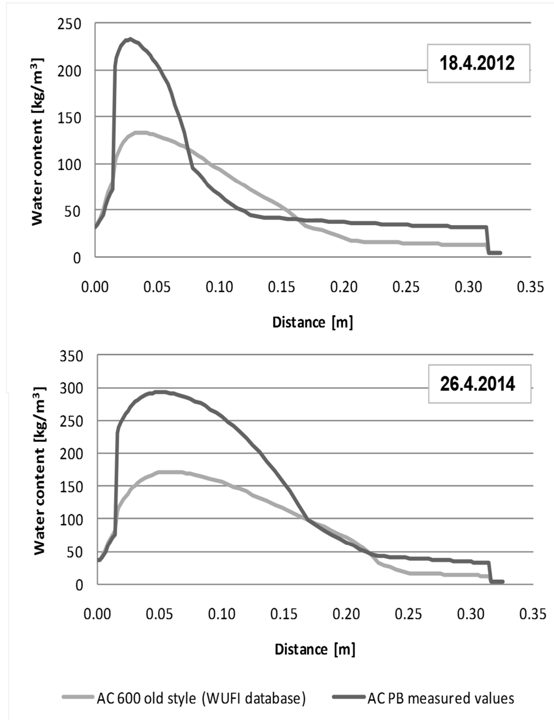


Fig. 8 Water profiles for AC 600, AC X and AC PB

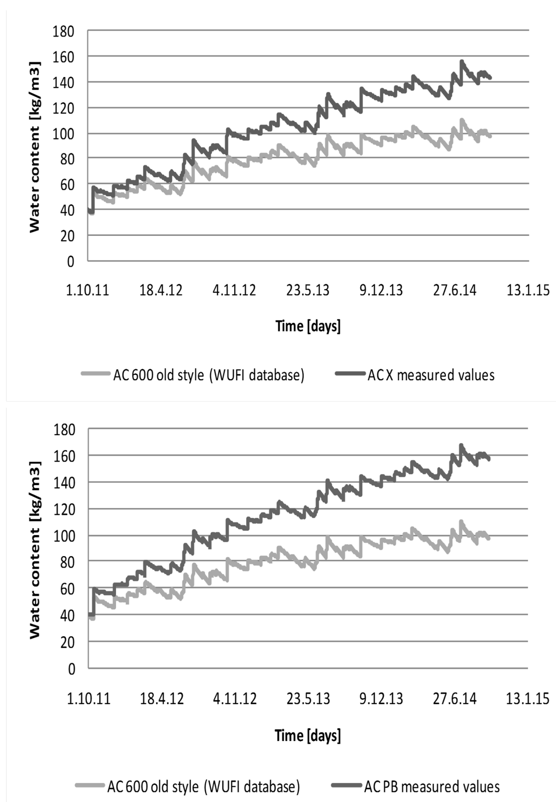


Fig.9 Courses of water content for AC 600, AC X and AC PB

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Water within a material changes properties of the material. From the point of view of building physics changes in thermal conductivity are the most significant. In building envelopes without External Thermal Insulation Composite Systems (ETICS) this change can lead to an increase of the heat transfer coefficient up to 42% in comparison with projected values. After application of ETICS, the main thermoinsulating function is taken up by the thermal insulation. Figures 10 and 11 show water profiles of analyzed building envelopes after application of ETICS – EPS (Fig. 10a, 11a) and MW (Fig. 10b and 11b). The water profile calculated for 1.10.2014 is used as the initial condition (of water content) for hygrothermal performance after ETICS application. The simulation was done for a 3-year period (1.10.2014 – 1.10.2017).

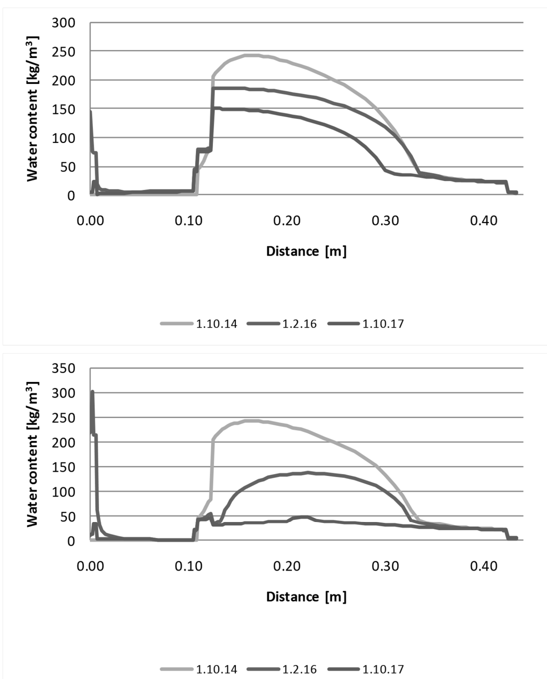

Fig. 10 Water profiles for AC X with ETICS a) EPS, b)MW

Figure 10b and 11b show that better and faster process of drying occurs in case of MW based ETICS. Thanks to diffuse opening of this type of ETICS (lower μ values) a more symmetric and balanced drying is possible than in the case of EPS based ETICS.

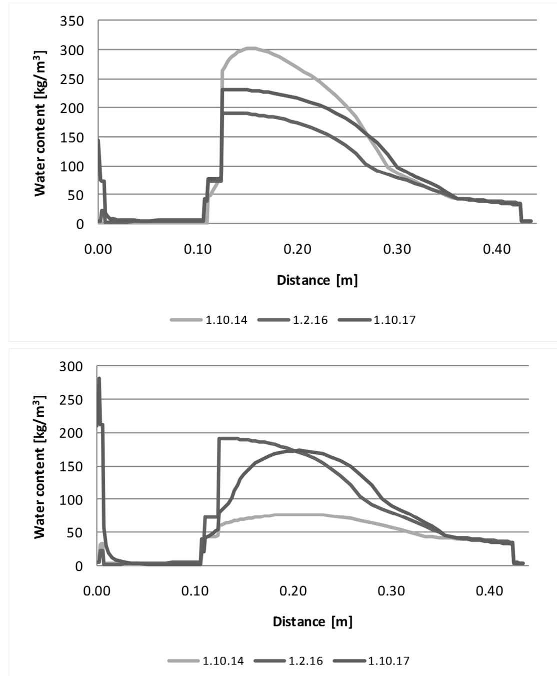

Fig. 11 Water profiles for AC PB with ETICS a)EPS, b)MW

Today, moisture inside of building envelopes is evaluated according to approximate models of calculations. This simplified procedure is not capable of recognizing real processes happening with a building material, or to evaluate its behaviour during the analyzed period. As the present numerical analysis showed, sensitivity of these methods to quality of input data is very high. Where relevant input data exist, application of simulation models is very broad.

4. DAYLIGHTING SIMULATIONS

Another subtask of the research project was the analysis of the qualitative and quantitative state of daylighting in the hall-type industrial buildings [26]. The primary objective was the comparison of the results of computer simulation of daylighting with the values measured in situ in real conditions of a selected industrial building.

From the measurements results there ensued that the side illumination, e.g. illumination from sides only and not from above produces significant deficit of illumination in the zones (areas) which are remote from transparent fillings (Fig. 12). In evaluating the level of daylighting based on normative calculation procedures in the SR, simplified and in principle extreme external conditions are used. Present development of calculation software makes it possible to solve time

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demanding extensive problems in order to achieve a more accurate result in a relatively shorter period of time. Despite the fact that at present time it is not common to utilize sophisticated simulation programs in design practice, especially for large hall type buildings in the conditions of the Slovak Republic. It will be inevitable to determine marginal conditions of the calculation itself, e.g. to extend the TRY-structure.

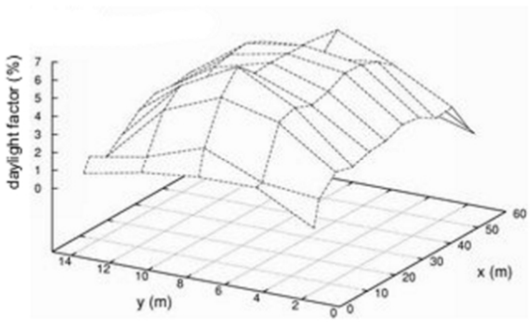

Fig. 12 Quantity level of daylighting in hall type building

Only on the base of the marginal conditions reflecting the specifics of the conditions of the SR it will be possible to effectively designate the conditions and the level of daily illumination of indoor environment in a real interior.

5. MEASUREMENT OF THE INTERNAL ENVIRONMENT IN WINTER PERIOD AND THEIR EFFECT ON ENERGY NEEDS

Experimental measurements in situ were carried out in hall-type industrial buildings that have identical design but the orientation of which is in contrary compass points [27]. The energy consumption for heating of the selected hall buildings were so evaluated by measurement and different calculation. During the winter period heating energy consumption measurements in situ were carried out in this chosen hall buildings. Evaluation of the measurements was carried out according to criteria valid for housing buildings and civil constructions, with several regression dependences taken into consideration in resultant evaluation of energy consumption for heating. There are many calculation methods for energy consumption of residential buildings. Furthermore, it is possible to perform measurement of the energy consumption of these buildings in situ, too.

5.1 Measurements

The measurement of energy consumption was conducted from December 23 to January 24 (Fig. 13). The measurement was carry out in the winter period at external air temperatures below zero. This resulted from the fact that according to national standard the measurement interval does not have to drop under 30 days. The average daily temperatures of internal and external air were stated. Internal air temperature was taken along height in seven points, in the middle of the considered operation, which is not in compliance with the requirement for one sensor to cover by measuring in a characteristic space maximum 50 m^2. In this connection it is necessary to remark that stating of generally valid criteria for the calculation of an average daily temperature of internal air inside an industrial hall is difficult in view of the fact that the dynamics of temperature parameters in the space and along the height, e.g. in horizontal and vertical direction is very high.

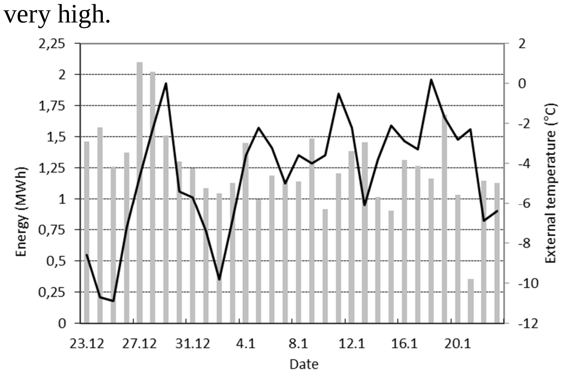

Fig. 13 Measured values of energy consumptions in measured days and course of external temperature

5.2 Evaluation of measured and calculated values

The evaluation of measurement has been conducted by calculation relations for the period of reading, per =1 day, e.g. for 32 points (Fig. 14). As an alternative the evaluation has been conducted for per = 2 days, e.g.16 points and for per = 4 days, e.g. 8 points. From the drawn graph it was evident that the energetic-thermal relations have a linear character gained by linear regression dependence [28]. This has been attained from the file of reading of energy consumption gains for heating and from the temperature difference $\theta_{ai} - \theta_{ae}$, or from day/degrees - D_{per}. The energy consumption for heating as a function of day/degrees is sought by means of linear regression in the form:

$$Ebp = a \cdot D_{per} + b \pm 2 \cdot \sigma \qquad (3)$$

where

a, b are regression coefficients (table 1), σ is a conclusive deviation of the file calculated, Dper - day/degrees. The evaluation of the measurement

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was for the whole heating period determined for climatic day/degrees D = 2834 K.

E_{bpD} = a . 2834 + b [MWh/(V_{bp} .year)] (4)

By the calculation relation the energy consumption for heating E1 is determined, coming on 1m^3 of a built up volume for one year according to the relation:

E_1 = a . (E_{bp}/V_{bp}) . 1000 [kWh/(m^3.year)] (5)

To prove the correctness of measurement the correlation index I_{ED} is evaluated. The measurement can be considered, if the correlation index $I_{ED} \geq 0.7$. The evaluation of the measurement of energy consumption for heating according to various interval (per = 1, 2, 4 days) is given in Table 1.

Table 1 Evaluation of energy consumption

Reading period per (days)	1 day	2 days	4 days
a, (-)	0.0743	0.0779	0.0665
b, (-)	0.1859	0.2677	1.1967
E_{bp}, (MWh/(V_{bp}.year))	254.441	266.842	228.759
E_1 (kWh/(m^3.year))	54.578	57.238	49.069
E_{bpD}, (MWh/(V_{bp}.year))	210.752	221.036	189.658
E_{1D}, (kWh/(m^3.year))	45.206	47.412	40.682
I_{ED}, (-)	0.9889	0.9904	0.9916
σ, (-)	0.2982	1.3500	2.2746

The measurement of energy consumption for heating in situ can be considered in this given case for proven due to the fact, that the correlation index IED is for all reading intervals bigger than the value 0.7 required by the standard.

The highest correlation index is at the reading interval per = 4 days, that is why, the data at this interval can be considered for the result of the evaluation of energy consumption measurement for heating in situ conditions.

When looking for factors that influence the energy use, analysis shows that the heating energy use is more or less constant. In the calculation E1 it can be stated that only linear ascending regression leads to correct results. This regression can be considered for comparable with the calculation of energy consumption according to values read from heat exchanger station.

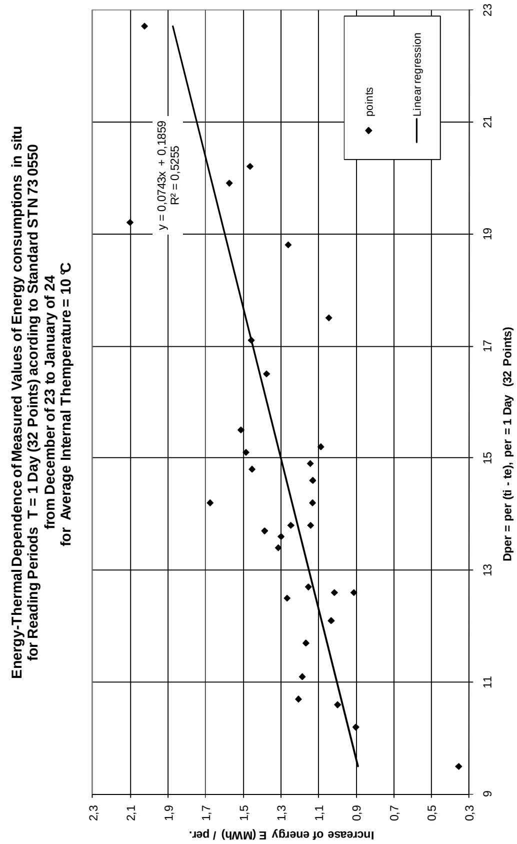

Fig. 14 Measured values of energy consumption in considered hall – reading period 1 day

6. EVALUATION OF SUMMER OVERHETING

As the survey results have shown the most significant problem of industrial buildings is their heat instability in summer period which manifests itself most distinctively in hall – type buildings. The present state in the field of calculation and evaluation of heat stability is oriented more towards residential and commercial.

What is the real state in the field of heat stability of hall-type buildings in summer period, was the subject of solution of another subtask of the whole research project. The objectives of the subtask can be summarized in the following points:

- Obtaining factual, real heat values of the internal air by taking measurement in situ in selected hall-type buildings in summer period,
- Verification of usability and accuracy of the chosen calculation methods (The method according to national standard - STN, EN ISO and the calculation simulation by applying ESP-

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r) for evaluation of heat stability of hall-type buildings in summer period (Fig. 15),

- Determination of the effect of the basic and supplementary entry factors and their parameters on the course of heat of internal air by calculation testing (Fig. 16),

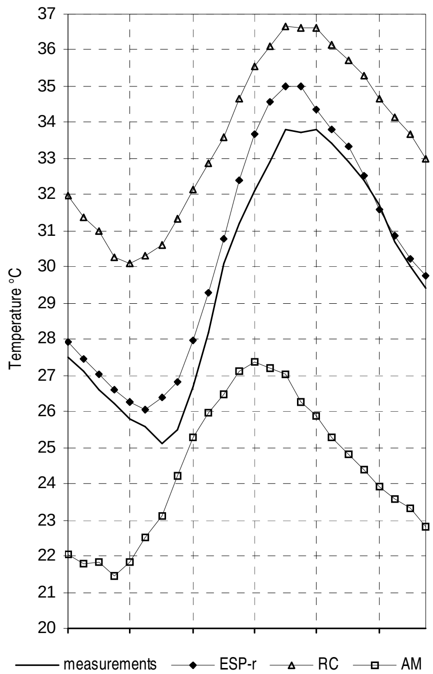

Fig. 15 Comparison of the heat course of selected calculation methods with the heat course according to measurement in situ.

Proposal of requirements for the evaluation of heat stability of hall-type buildings in summer period and the creation of a simplified methodology for evaluation of heat stability of hall-type buildings in summer period, reflecting the proposed requirements.

The measurements results in situ showed that the employee's dissatisfaction with working conditions was well founded. The maximum temperatures of the internal air measured currently exceeded 30°C or even 35°C [29].

On the building model, in which the in-situ measurements were carried out, the calculation method accuracy was then analyzed. Within the framework of theoretical calculations the calculation methods according to the standard STN 73 0540 and according to EN 13791 and 13792 (RC-method and the receptiveness method) and the calculation by the ESP-r program simulation was used. By the comparison with the date measured it was found, that the most accurate results were obtained by the ESP-r calculation program (Fig. 15). Due to the complexity of the calculation the accurate results were also obtained by the calculation method according to EN 13792 (RC-method). The calculation method done according to the standard STN 730540 and the receptiveness method gave non-accurate results [23].

The testing of various factors brought the knowledge, that the used of standard approach to the hall-type building concept is unlikely to supply optimum working condition (Fig. 16).

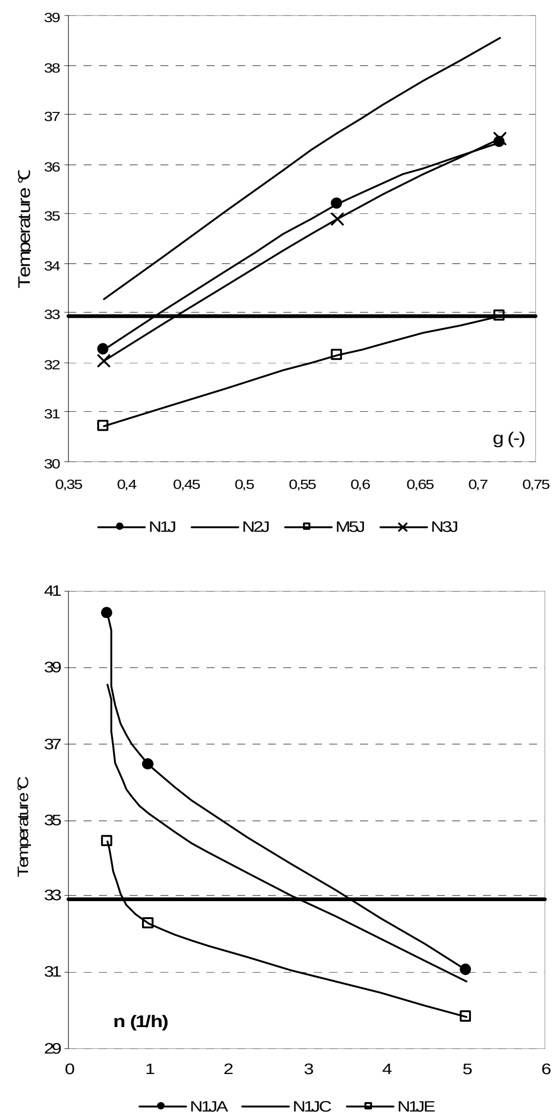

Fig. 16 The dependence $\theta_{ai,max}$ (°C) a) on g - value of glazing of selected simulations combination for the intensity of air change rate n = 1 1/h. b) on the air exchange intensity for selected calculation combinations.

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7. INTERACTION OF FRAME AND GLASS SYSTEM

In an effort to decrease energy consumption as well as simultaneously designing low energy buildings we are lead to the improvement of window thermo technical properties. It is these aspects in which the construction detail of frame and glass system connections is most critical. For this reason the research of interference of a frame system and glass systems and their impact on thermal performance of fenestration system has been conducted [30]. The content of the research is expressed in the following points:

- to select the reference window,
- to carry out laboratory experimental measurements of a selected window construction,
- to gain information on thermo-technical properties interaction in frame and glass systems.

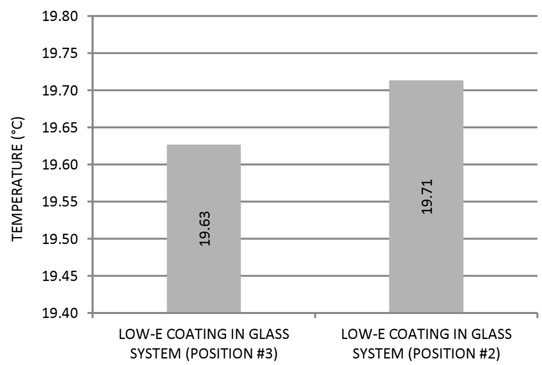

Fig. 17 Impact of low-e coating position on the interior surface temperature θ_{si} (°C)

Experimental measurements in laboratory conditions were performed on the reference window construction in order to obtain thermo technical variables in the required distinctive places necessary for the analysis of individual influences. The aims were to:

- Compare glass systems with the identically stated parameters from different producers.
- To determine the influence of glazing rebate upstand.
- To determine the influence of position and quantity of low-e coating.
- To determine the influence of incorporating additional elements on the inside of a glass system.
- To determine the influence of spacer type.
- To determine the influence of gas type.
- The overall improvement of ΔU - overall thermal transmittance of windows construction.

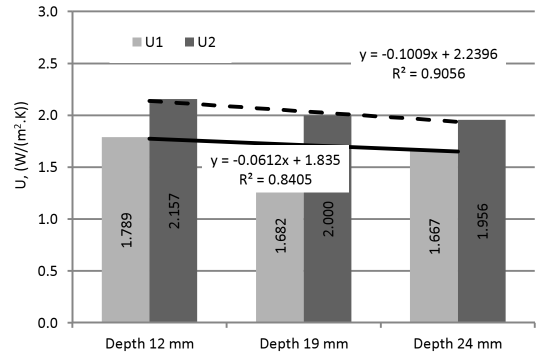

Fig. 18 Thermal transmittance of a bottom fragment of window with (U2) or without (U1) the influence of a glass system in different glazing rebate upstand

Based on the analysis of the performed laboratory experimental measurements the following recommendations can be made for practical use.

With high quality glass systems (insulating double or three glazed units) the change in the position of low-e coating almost does not affect the overall thermo technical properties of a window system (Fig. 17).

To utilize the possibility of increasing the glazing rebate upstand (fitting a glass system into a frame system) (Fig. 18).

Not to use glass systems with incorporated elements (mounting bars) in order to meet architectural requirements, to use pre-fitted decoration constructions from the outside or even from the inside.

In case of increased safety requirements to also avoid the use of glass systems with incorporated elements and to use a wide range of safety glass (toughened, strengthened, laminated) instead, or individual protective constructions (outside protective gratings, blinds, window shutters).

To use spacers made of materials with low thermal conductivity in glass systems, the same applies for both homogenous and built-in composite spacers.

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8. CONCLUSION

This paper describes the research of industrial buildings in the Central European climate conditions. The research was aimed at evaluating the state of the internal environment (summer overheating, daylight evaluation), analysis of building structures (wall moisture transport, interaction of the frame and the glass in window structures) and to evaluate the energy consumption of industrial buildings. Part of the research was a questionnaire survey of industrial buildings perceptions by the users. This study confirmed that users are not satisfied with the conditions in industrial buildings. The solid problem seems to be mainly the summer overheating. Removing the problem is first necessary to solve by building structures and then use the HVAC systems. In terms of daylighting evaluation is necessary to ensure a uniform level of daylight. Uniform level of daylight is required to perform many visually demanding tasks. This is only possible with the use of appropriate lighting openings. Analysis of building structures has shown that even in the case of industrial buildings should be designed quality building construction. Since in industrial buildings can be boundary conditions even more difficult than in residential or commercial buildings, improper design of structures can form significant defects. When we propose industrial building comprehensively, it results in energy consumption reduction.

All the field of research pointed out that industrial buildings are required to modify requirements for the design. Methods used for residential or commercial buildings are not always applicable. The work also showed that for quality evaluation of industrial buildings is appropriate to use simulation methods.

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