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**ENERGY EFFICIENT AIR-CONDITIONING
CONSIDERING COMFORT IN ENCLOSED SPACES FOR
DIFFERENT PURPOSES**

Thesis booklet

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1. ACTUALITY OF THE RESEARCH

In Europe the buildings' energy use is 40% of the total energy consumption. The reduction of energy use and the emission of carbon dioxide can be achieved mainly by limiting the energy used by buildings, as the valid national and international regulations suggest. This process was initiated by the Directive 2002/91/EC of the European Parliament and Council, which deals with the energy performance of buildings. Later in 2010 the European Parliament and Council adopted the EPBD recast directive, replacing the former building energy performance directive. It describes the further actions to be taken, among them introduces the requirements on “nearly zero energy buildings” by 2018 and 2020. In the process, the member states, Hungary among them, developed the calculation method of the energy performance of buildings (decree No. 7/2006 (V.24) TNM), and its revision in line with the recast (decree No. 40/2012. (VIII. 13.) BM and decree No. 20/2014. (III. 7.)). The energy efficient design has a high priority and is also justified by valid international and national regulations.

Air-conditioning represents a significant proportion in the energy use of buildings. However, increasing comfort level must be provided in buildings. It occurs at the same time the need of reducing energy consumption and increasing comfort. The reducing energy consumption can not deteriorate comfort. Therefore, the task to be solved is to continually monitor the comfort according to international practice.

Many technical solutions are being used today to reducing energy consumption. Some of them serve to reduce the heat load and contains methods for compensation of the resultant heat load. Opportunities to reduce energy consumption:

- reduce of the internal heat load,
- reduce of the incoming heat load (protection from environmental influences):
 - „passive” protection: orientation, underground placement, etc.,
 - „active” protection: building structure, shielding, etc.,
- air-conditioning with less energy demand:
 - equipments with better energy efficiency, heat recovery, free cooling, enthalpy control, etc.,
- the proportion of sensible and total cooling power,
- reduce the volume of the introduced fresh air to the required amount,
- mixing of the return air.

2. INTRODUCTION AND MAIN AIMS

Reducing energy consumption makes it possible to analyse a large number of methods. In comfort spaces occurs the need of energy consumption reduction and increasing comfort simultaneously. For this reason I solved these tasks in the following two separate groups:

- thermal analysis of underground located comfort spaces on the basis of a non-steady state model,
- analysis of the indoor air quality and the thermal comfort in enclosed spaces on the basis of probability theory.

Primary aim is to define the changes of air and internal wall temperature in underground spaces in time domain. As an additional aim the change of heat flux through the wall in time domain has been calculated. Based on the heat balance, the dynamic basic equation of the space has been defined. The basic equation is a differential equation which contains the internal heat sources and the heat capacity of the space. For solving the basic equation, the initial condition, the time-varying boundary condition of the third kind and the Fourier's conductivity differential equation are necessary. The convolution integral of the solution function has been obtained by the use of the integral-differential equation acquired by substituting the temperatures and heat fluxes into the basic equation. I worked out a new mathematical solution of the physical model on the basis of this requirement. The solution of the acquired equation can be obtained in a numerical way. My new mathematical approach to the solution of the physical model makes it possible to investigate the air and wall temperatures, as well as the heat flow through the wall in underground spaces.

The energy-conscious design of enclosed spaces for human beings can be only done by maintaining the right comfort level. As an other task needs to determine a measurement and evaluation methodology to assess the air-conditioned comfort spaces with the methods of the probability theory.

3. LITERATURE REVIEW

The literature review related to the subject area divided into two separate groups according to the main aims.

3.1 *Thermoprocess in underground spaces*

An important feature of underground spaces is the higher protection against the climatic influences [1], [2], [3]. The soil temperature follows the external changes with phase delay and with significant attenuation. As a result, the heating and the cooling thermal loads are remarkably lower. A pleasant thermal comfort can be ensured with less energy in underground spaces [4], [5].

In 1862 Lord Kelvin determined related a very good equation to the change of soil temperature which is still in use today. The descriptive equation is a higher order harmonic model [6]. According to the geographic location and nature of the earth's surface Xing determined the detailed data according to the double harmonic model can be found in his doctoral dissertation, including data for Hungary [7].

Sizing methods of underground spaces can be found in the literature of the 1950s. The starting points of these methodologies are steady state equations. The starting points of these methodologies are steady state equations Bogoszlóvszki et. al. [8] and Macsinszki [9]. Sizing methods can be found for dynamic processes of the warm-up period and providing constant temperature. Design methods approximate time-varying boundary conditions of the heat conduction differential equation with time constant boundary conditions of the first and second kind: Lakos [10], Barcs [11], Gráber [12], Kokits [13] and Straub [14]. In Budapest University of Technology and Economics, Department of Building Services and Process Engineering Erdósi and Kajtár applied time-varying boundary condition of the third kind to describe the thermal process of underground spaces [15]. New dimensioning methods found in literature are primarily engaged in the evaluation of thermal comfort and comparison of underground spaces. Yanqiang et. al. [16] developed the thermal comfort evaluation with the development of thermal indices for subway, underground shop and underground hotel. They carried out objective and subjective measurements with thermal questionnaires based on PMV-PPD and the developed new thermal indices. C. van Dronkelaar et. al. [5] were engaged in theoretical studies of underground space heating and cooling energy demand.

3.2 *Examination of enclosed spaces*

Thermal comfort is the state of mind which expresses satisfaction with the thermal environment. It is possible to objectively evaluate this subjective sensation using metrological methods. In the beginning of XX. century started the scientific thermal comfort experiments based on an objective method that can be utilized well for technical practice. One of the earliest method is the Kata thermometric measurement in early 1900s. The method and the experience gained in the measurements were described detailed by C. E. A. Winslow in 1916 [17].

The measurement with Kata thermometer is in use today, however, because its limits of use it became necessary to apply new methods for measuring microclimate indicators. As a result, the measuring method of the effective and then corrected effective temperature was developed later [18], [19]. Modern comfort studies go back only a few decades ago, when the comfort became a high priority research field. In 1970 the modern methods were development by Professor P. O. Fanger and his research team from Denmark, we consider him the pioneer of today's modern comfort researches [20]. This method has taken into account six parameters, two of that take into consideration personal factors, and four take into consideration the physical characteristics of the thermal environment:

- air temperature,
- mean radiant temperature,
- air humidity,
- air humidity,
- activity level,
- clothing insulation.

The method can be used to determine the characteristics of the thermal environment (PMV: Predicted Mean Vote) and the acceptance level with the thermal environment (PPD: Predicted Percentage of Dissatisfied). The PMV-PPD method gives a thermal comfort index of the human body as a whole that is typical of the thermal environment. The surrounding environment is typically inhomogeneous, therefore the development of further thermal environment description method has become necessary. Fanger and his research team developed a methodology for analysing and quantifying the so-called local discomfort factors. The local discomfort factors are as follows:

- draught,
- vertical temperature difference,
- radiant asymmetry,
- warm and cold floors,

- warm and cold ceilings.

Fanger methods are also recorded later in international standards and regulations (e.g.: ISO 7730, ASHRAE 55). Requirements are also specified in standards (CEN CR 1752, EN 15251, etc.). The PMV method was generally accepted for air-conditioned spaces, so I chose this as a comfort test method in enclosed spaces.

3.3 *Conclusion of literature review*

As a result of the related literature review, I can conclude that the sizing of underground spaces was approached with time-varying boundary condition of the first and second kind, the connected international literature is well-known. The real thermal process is described by the differential equation of the thermal conductivity with time-varying boundary condition of the third. There is only limited literature available for this Robin boundary condition problem. This is why I deal with this subject in detail in my doctoral dissertation.

Literatures of on-site comfort measurements can be found in large numbers. Some of them deal with new thermal comfort theories and the definition of new thermal indices, others examine the validity of the generally accepted Fanger PMV-PPD method for its applicability in a given geographic region, third of them report scientifically useful results and experiences of on-site comfort measurements.

Literatures dealing with the comfort measurements determine the distribution of comfort characteristics as a one-sided distribution, some of that are treated as normal distributions. One of my aim is to investigate the multimodality and the type of distribution.

The vast majority of literatures dealing with the categorisation of comfort spaces by differentiated comfort categories qualify the thermal environment assuming stationary or quasi-stationary processes. The real comfort parameters are time-varying physical quantities, their probability evaluation requires a probability theoretical approach. I did not find any literature on the combination of measurement methodology and evaluation methodology. It is only possible to determine the exact comfort characteristics of the environment with a properly constructed measuring system and evaluation method. Therefore, to developing a measuring method and evaluation method that meets the expectations is my other main aim.

I also did not find any literature that would have investigated the comfort with various air-conditioning systems. I have done the design, the conduct and finally the evaluation of the on-site measurements by considering these criteria.

4. NEW SCIENTIFIC RESULTS

4.1 Thermal analysis of comfort spaces located underground based on non-steady state model

I have developed a method for novel solutions of the thermal design of the underground spaces. Thesis 2 contains the description equation of the surface temperature of the wall and the change of the heat flow through the wall. Thesis 1 contains a mathematical model for the thermal design of the underground space and the procedure of numerical solution.

Thesis 1.

I developed a non-steady state mathematical model for the thermal design of underground spaces. The model is interpreted in the soil depth of the near-steady-state (quasi-stationary) temperature in time domain. From the point of view of engineering practice, it begins with a depth of 8-10 m (depending on geographic location and soil type), where the temperature fluctuation amplitude is 0.2-0.6°C. The integro-differential equation describing the air temperature variation of the underground space in the time domain:

$$\frac{dt_a(\tau)}{d\tau} + k_1 t_a(\tau) + k_2 \cdot \left[\int_0^{\tau} [t_a(\tau - u) - t_a(0)] \cdot g(u)|_{x=0} du + t(x, \tau)|_{\tau=0, x=0} \right] + k_3 = 0$$

where:

$$k_1 = \frac{A\alpha + \dot{m}_s(c_{p,a} + x_a \cdot c_{p,s})}{c_{p,a} \cdot V \cdot \rho_a},$$

$$k_2 = -\frac{A\alpha}{c_{p,a} \cdot V \cdot \rho_a},$$

$$k_3 = \frac{\dot{Q} - \dot{m}_s(x_a \cdot r_0 - h_s)}{c_{p,a} \cdot V \cdot \rho_a},$$

$$x_a(\tau) = Z_1 + x_s - e^{-Z_2\tau \cdot (Z_1 + x_s - x_a|_{\tau=0})}$$

$$Z_1 = \frac{\dot{m}_m}{\dot{m}_s},$$

$$Z_2 = \frac{\dot{m}_s}{V \cdot \rho_a},$$

$$a = \frac{\lambda}{\rho \cdot c}.$$

Initial condition:

$$\tau = 0 : t_a(0) = t(x, 0) = \text{const.}$$

The solution of the integro-differential equation can not be expressed in a enclosed form as the solution function can not be produced analytically. Therefore, numerical methods were used for the solution. **The discrete solution has been reached by implicit linear multi-step method with implicit formula. The numerical process has been carried out by using Dormand-Prince method and Adams-Moulton integrators in different phases of the numeric scheme. In the initial steps (up to the fourth step) I used the eighth order embedded Dormand-Prince method, while in the remaining parts of the calculation the sixth order Adams-Moulton formula was utilised.**

The discrete solution of the convolutional integral was determined by an interpolating quadrature formula to reach higher accuracy. For calculating the numerical quadrature I applied the composite Simpson formula. The fit of the interpolation quadrature is of fourth-degree.

To reduce the numerical calculation steps, the argument of the complementary error function was divided into several intervals in a non-uniform way. Due to the physical process, it is enough to do this on the field of positive real numbers but the method is also suitable on the field of real numbers. Complementary error function has been approximated by using the eleventh-degree McLaurin formula, as well as the fifth and eighth-degree Chebyshev asymptotic series in different sections of the examined argument.

Related publications: [S4], [S5], [S21], [S22], [S30].

Thesis 2.

I defined change of the wall surface temperature and the heat flow through the wall of underground spaces according to a non-stationary model in the time domain.

The wall temperature of the underground space:

$$t(x, \tau)|_{x=0} = \int_0^{\tau} [t_a(\tau - u) - t_a(0)] \cdot \left\{ H \cdot \sqrt{\frac{a}{\pi u}} - aH^2 e^{aH^2 u} \cdot \operatorname{erfc}[H \sqrt{au}] \right\} du + t(x, \tau)|_{\tau=0, x=0}$$

Heat flow through the wall:

$$\dot{Q}_w(\tau) = \int_A \alpha [t_a(\tau) - t(x, \tau)|_{x=0}] dA$$

Related publications: [S4], [S5], [S10], [S21], [S22].

4.2 Assessment and qualification of the thermal comfort and the indoor air quality of enclosed spaces on the basis of probability theory

I have developed a measurement methodology and evaluation method that can be applied on-site measurements to qualify time-varying comfort. The method of measurement and the measurement methodology is described in the Thesis 3. The time-varying comfort evaluation and qualification includes the Thesis 4. Thesis 5 details the distribution of time-varying comfort characteristics and the identification of the distributions based on the results of the on-site measurements. Thesis 6 contains comparative results of comfort spaces operating with different air-conditioning systems based on field measurements.

Thesis 3.

I developed a measurement method and a measurement methodology for evaluating time-varying comfort. I applied the PMV model to assess the thermal comfort, which takes into account six parameters, two of that take into consideration personal factors, (activity level of the human body, thermal insulation of clothing) and

four take into consideration the physical characteristics of the thermal environment (air temperature, mean radiant temperature, relative humidity, relative air velocity).

The developed method is based on continuous sampling of the air temperature, the mean radiant temperature of the surrounding surfaces and the relative humidity of the air with a sampling rate of 5 minutes. The sampling rate of the relative air velocity measurement should be performed at a higher frequency in order to determine the turbulence intensity and mean relative air velocity. **Evaluation of the measurement results showed that the recommended sampling rate of measuring air velocity was 2 seconds.** If this value is higher than 5 seconds, then the measured values does not describe adequately the changes of air velocity in the comfort space and does not properly estimate the turbulence intensity statistically based on the number of measurement data. **The sampling rate of the carbon-dioxide concentration measurement was set at 5 minutes.** The table below shows the requirements for on-site comfort measuring systems based on the developed measurement methodology:

Quantity	Measuring range	Accuracy	Response time	Sampling rate	Comments
Carbon-dioxide concentration	0 - 3 000 ppm 0 - 0,2 V/V%	$\pm [50 + 0,05 k_{CO_2}]$ ppm	3 min (t90)	5 min	-
Air temperature	10 - +40°C	$\pm 0,3$ °C	3 min (t90)	5 min	protect the sensor from effect of thermal radiation
Relative humidity <i>Partial pressure of water vapor</i>	10 - 90% 150 - 6 500 Pa	± 3 %RH ± 150 Pa *in case if $ t_{i,s} - t_a \leq 4$ °C	3 min (t90)	5 min	-
Globe temperature	5 - 50°C	$\pm 0,5$ °C	20 min (t90)	30 min	-
Air velocity	0,02 - 1,0 m/s	$\pm (0,02 + 0,07 v_a)$ m/s * $\geq 3 \pi$ sr in a solid angle	0,5 s (t63)	2 s	if the sensor is not unidirectional then the sensor shall measure the velocity whatever the direction of the air

Related publications: [S3], [S7] [S11], [S23].

Thesis 4.

I developed a mathematical model and a PC program for evaluating and qualifying the time-varying comfort. The examined properties were treated as probability variables, so the measured values can be statistically characterised. Experimental density functions can be formed from the values of the time series. After evaluating

the measured data sets we can obtain a representative quantitative image of the given comfort space by analyzing the statistical characteristics. **The measurement results were processed and evaluated based on the 95% confidence interval, comparing with the requirements of comfort categories.**

Related publications: [S2], [S12], [S16], [S17], [S18], [S19], [S26], [S27], [S28], [S29].

Thesis 5.

Evaluation of the on-site measurements proveded that the distribution of the comfort parameters examined typically follows a multimodal distribution. The distribution can be made as a mixture of normal distributions that can be interpreted and treated well for engineering practice. I found that the optimally defined double mixed normal distribution showed a good fit for the measurement data series, so the measured values follow a double mixed normal distribution.

$$p(x) = \sum_{k=1}^2 [n_k \cdot \mathcal{N}(x|\mu_k, \sigma_k)] ,$$

where:

$n_k \in [0; 1]$ the proportion of each normal distribution component,

$$\sum_{k=1}^2 n_k = 1 ,$$

$$\mathcal{N}(x|\mu_k, \sigma_k) = \frac{1}{\sigma_k \sqrt{2\pi}} \cdot e^{\left[-\frac{(x-\mu_k)^2}{2\sigma_k^2}\right]} .$$

To determine the optimum parameters of the best fitted distribution, I created the objective function using the maximum-likelihood function. The parameters of the distribution are optimal at the maximum of the objective function. I provided the proposed algorithm for this five-variable maximum search task (EM: expectation-maximization and GA: genetic algorithms).

Related publications: [S1], [S6], [S8], [S9], [S13], [S14], [S20], [S25].

Thesis 6.

On-site measurements were made in various office buildings which were operating with parapet fan-coil, ducted fan-coil, and active chilled beam systems. I performed comfort measurement for all systems during the typical summer season. The measurements and the evaluation of the measurements were done according to the method I have developed. Comfort categories were based on the differentiated comfort requirements of the CR 1752. I also make a comparison on the basis of these results into two parts: system types and category comparisons.

Based on comfort category levels

Category „A”:

It can be stated that from the point of view of thermal comfort it is most difficult to ensure the highest level of category „A” expectations (0-22,2%). The situation is better in terms of air temperature (category „A”: 6,1-38,6%), even better in case of draught rate (category „A”: 33,3-90,3%), the most favorable in case of CO₂ concentration (category „A”: 73,7-100%).

Category „>C”:

According to category worse than „C” the following trends can be established. Providing thermal comfort is the most difficult (category „>C”: 11,1-55,6%). The situation is better in terms of air temperature (category „>C”: 15,7-33,3%), even more favorable in case of draught rate (category „>C”: 0-5,6%), the most favorable for the CO₂ concentration, since in the category „>C” there occurs measurement result for any system.

Category „B” and „C”:

The following measurement results were obtained into category „B” and „C”:

- thermal comfort: 16,7-38,9%,
- air temperature: 18,2-42,4%,
- draught rate: 0-66,7%,
- CO₂ concentration: 0-15,8%.

Based on comfort properties

Thermal comfort:

From the point of view of the thermal comfort the best result was provided by the ducted fan coil built with tangential air distribution system, while the worst result was given by the parapet fan-coil system.

Air temperature:

From the air temperature point of view the best result was provided by the active chilled beam system (category „A”: 38,6%).

Draught rate:

From the draught rate point of view the best result was provided by the active chilled beam system (category „A”: 90,3%).

Carbon-dioxide concentration:

Comfort tests have proven that there could be reached significantly better comfort categories for carbon dioxide than thermal comfort, draught rate and air temperature. The difference between the individual systems is also small. This is due to the fact that the CO₂ concentration is basically dependent on the amount of fresh air, less due to the type of air conditioning system. The results were between 73,7-100% according to category „A”.

Related publications: [S3], [S7], [S9], [S11], [S13] [S14], [S15], [S23], [S24], [S26], [S28], [S29].

5. UTILIZATION OF THE RESULTS

The developed method of the thermal design of underground spaces is well suited for engineering practice. The specified procedure can be used to estimate the magnitude of the error with the required accuracy. By knowing the heat flow through the wall of the underground space and the wall temperature of the space additional energy and thermal optimisation can be performed.

The method for measuring and evaluating time-varying comfort can be used to qualify comfort spaces. The obtained results help to set optimum operating parameters for operating air-conditioning systems.

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