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The PMV and PPD indices in the selected boiler room

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Abstract. Thermal microclimate in a boiler room is formed by factors resulting from thermal processes that are taking place in combustion units. These factors are negatively affecting the indoor environment by worsening the air quality, and therefore it is crucial to maintain adequate air parameters in the room. It is a consequence of the fact that in the boiler room the operation of technological equipment results in an exposure of workers to adverse effects caused by thermal factors. Therefore, the evaluation of thermal conditions in the work area of people was made for the selected industrial boiler room using PMV and PPD indices (which allow to determine the thermal sensation of employees, regarding their surrounding thermal environment, based on the methodology of ISO 7730 standard). The analysis was based on own experimental measurements and numerical calculations made in the DesignBuilder program.

1 Introduction

Despite the "thermal comfort of people" depends on the individual thermal balance, the issue of the microclimate of rooms and the expected thermal sensation of people who are staying in certain conditions, can be statistically expressed in the form of a thermal sensation scale (for example from -3 to +3) and by analytical calculation of thermal comfort indices of PMV and PPD [1]. At the beginning, the application of PMV and PPD was based on the analysis of thermal sensations of people for determined conditions occurring under controlled conditions, for example for air-conditioned rooms [1]. However, later analyzes of thermal conditions in non-conditioned buildings ("free-running buildings") led to the development of the "adaptive opportunity" theory [2] and to the relation between the comfort temperature and the temperature of outdoor air [3]. At the same time, many years of study on the assessment of the thermal environment to which people are exposed, reflected, among others, in such standards as: EN 15251 [4] and ISO 7730 [5]. Thanks to the researches determining the influence of thermal conditions on the well-being and work of people, a decrease in productivity and reduced motivation to work was observed to be occurring together with an increase in thermal sensations related to the worsening of the thermal environment of work [6, 7]. Also, it is estimated that, during tasks requiring thinking, the drop in productivity, related to the temperature increase above the comfort

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conditions, is comparable to the value of the PPD index [8]. Despite the fact that there are many studies on thermal sensation of people working in residential and office buildings [9], only few authors analyzed the thermal comfort of workers in industrial buildings. As a consequence, there is an insufficient number of scientific studies on the issue of "thermal comfort of people" in industrial buildings, in which there are both large heat gains from technological equipment, and exposure to harmful factors associated with thermal and chemical processes, as a result of which gaseous [10] and particulate matter contaminants [11] are emitted into industrial rooms.

The "thermal comfort of people" is usually expressed in accordance with ISO 7730 [5] standard in a seven-point scale of thermal sensation (table 1) using the PMV (Predicted Mean Vote) comfort indicator, and in percentages, using PPD (Percentage of People Dissatisfied) indicator. The PMV determines the predicted average rating of the thermal sensation, while the PPD determines the percentage of people dissatisfied with the thermal microclimate in the room. What is more, the PMV indicator comprehensively covers the impact of the most important individual and environmental factors on the human's thermal sensation. It also uses the concept of operative temperature, calculated as the weighted average of the air temperature and the mean radiant temperature. Consequently, values between $-0.5 < PMV < +0.5$ [5] are considered optimal, while PMV values below -2 and above +2 indicate the presence of an extreme microclimate, considered harmful to employees [12]. Adverse thermal conditions can lead to disturbances in human heat balance, decrease in productivity of work, irritability and even diseases requiring hospitalization [13]. However, the use of PMV and PPD indices is limited to specific conditions of air temperature (below 30°C), mean radiant temperature (up to 40°C) and air velocity (up to 1.0 m/s). To determine the effect of extreme thermal conditions, the WBGT index [14] of thermal load can be used. However, WGBT index is calculated in a simplified way and thus it does not take into account many aspects of the thermal balance of a human, omitting, for example, the influence of air velocity. Therefore, it does not allow an accurate estimation of the thermal sensation of people, but it can be used for determination of acceptable exposure of the employee to the hot microclimate [14].

Table 1. The seven-point thermal sensation scale [1].

Hot	**Warm**	**Slightly warm**	**Neutral**	**Slightly cool**	**Cool**	**Cold**
+ 3	+ 2	+ 1	0	- 1	- 2	- 3

An alternative method can be the modeling of thermal phenomena and analyzing air parameters in a room using numerical methods/programs that are using Computational Fluid Dynamics (CFD) techniques. For example, using the DesignBuilder program, which allows to determine thermal comfort indicators in a building (PMV and PPD values are used to assess the microclimate in a room).

2 Method description

The analysis of air parameters and thermal comfort was carried out in the selected/main technological room of the industrial boiler plant of the Sewage Sludge Thermal Treatment Plant, located in the Group Sewage Treatment Plant in Lodz city, in Poland. In the boiler plant the process of thermal treatment of sewage sludge from the adjacent sewage treatment plant is carried out. The technological/boiler room analyzed is not intended for permanent presence of people, and employees may stay in it for up to two hours during the shift. The area of the room is 718.10 m^2 (35.37 m long and from 19.96 m to 25.88 m wide), height is approximately 16.90 m, and cubic volume is 12136 m^3. In addition, there are eleven different levels of the working platform in the room, intended for maintenance and servicing works (fig. 1). In the boiler room, mechanical ventilation is performed by twelve roof exhaust fans (800 mm diameter) and thirteen rectangular wall air intakes (dimensions: 2000 mm by 1000 mm and 1000 mm by 1000 mm). The air inlets are regulated by actuators, depending on the airflow of the exhaust fans.

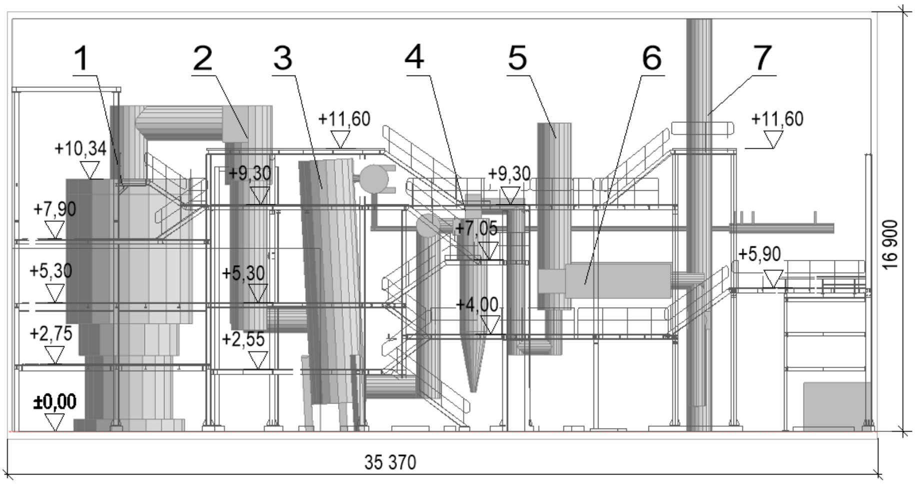

Fig. 1. Location of technological equipment in the boiler room, where: 1 – fluidized-bed furnace, 2 – recuperator, 3 – boiler, 4 – multicyclone, 5 – flue gas cooling device, 6 – bag filter, 7 – stack.

In the boiler room, the technological process of thermal treatment of sludge takes place in two independent process lines, based on fluidized bed technology. Each process line is equipped with a fluidized-bed furnace of thermal power of 4.07 MW, a recuperator, a boiler, a multicyclone, a bag filter, a flue gas cooling device, and a stack. Heat gains from all devices are estimated as 629 kW (with the operation of both technological lines), that is approximately 72 W/m^3 of room area.

In order to determine the boundary conditions for numerical calculations, and to validate the model, experimental measurements were made in the building in the summer season (average indoor temperature of 25.93°C, average humidity 30.96%). A radiation pyrometer with an accuracy of ± 2°C was used to measure the surface temperature of technological equipment, and the air velocity in the section of roof fans was measured using a vane anemometer. Whereas, only one process line and nine out of twelve fans operated during the measurements. The temperature and humidity were measured at five selected points at different heights in the room, always using a psychrometer installed in a digital microclimate meter. What is more, the temperature of the walls and roof was obtained as a result of the building energy simulation in the DesignBuilder program. The data of outdoor air temperature was obtained from the Polish Institute of Meteorology and Water Management [15].

The numerical calculations were made in the DesignBuilder program, based on the finite volume method, for the following boundary conditions:

- the outdoor air temperature: 23.3°C;
- total ventilation airflow volume: 97020 m^3/h;
- the temperature of surface of the technological equipment: 37.0°C–117.6°C;
- the temperature of surface of partitions: 18.0–33.8°C.

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The numerical calculations were made using the "k-ε" turbulence model and the "Power-Law" discretization scheme for the room area divided into more than 2.9 million cells, and the calculation residue was 10^{-5}. The correctness of the calculation model was checked by comparing the calculated air temperature with the results of experimental measurements in five selected points of the room (the error was on average ± 3.7%).

As a result, the air temperatures and velocities were obtained, and were used to calculate PMV and PPD thermal comfort indices in the selected boiler room. The following assumptions were used:

- employees work in a standing position;
- there is a light (1.6 met) or medium (2.0 met) metabolic activity of employees (corresponding to the activity of employees in light industry);
- clothing insulation is 0.8 clo (as clothing containing work overalls);
- 30% of air humidity.

3 Results

The results of the analysis of thermal comfort parameters in the boiler room are shown comparing the values of PMV and PPD for light (1.6 met) and medium (2.0 met) metabolic activity of workers who are using work clothes (0.8 clo). Three exemplary locations PA1, PA2 and PA3 were selected (fig. 2) in the work area at the heights of working platforms, for which the expected thermal sensations were discussed. The PA1 was located between the fluidized-bed furnaces, while PA2 and PA3 were located on the communication route.

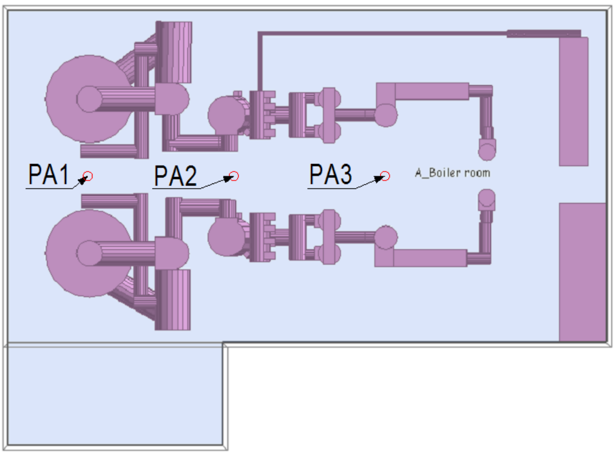

Fig. 2. Selected locations in the work zone.

Based on the analysis, in condition of 23.3°C of outdoor air temperature, the operative temperature in the working zones ranged from 21.55°C (at + 0.10 m) to 29.45°C (at + 13.30 m) and air velocity was from 0.09 m/s to 0.36 m/s. The PMV indicator ranged from - 0.02 to 1.66 in the case of light activity, and from 0.47 to 1.87 for medium activity (fig. 3). This means that in the analyzed points the value of PMV = 2, corresponding to the negative feeling of warm, was not exceeded. Therefore, the microclimate of the room could be classified as moderate.

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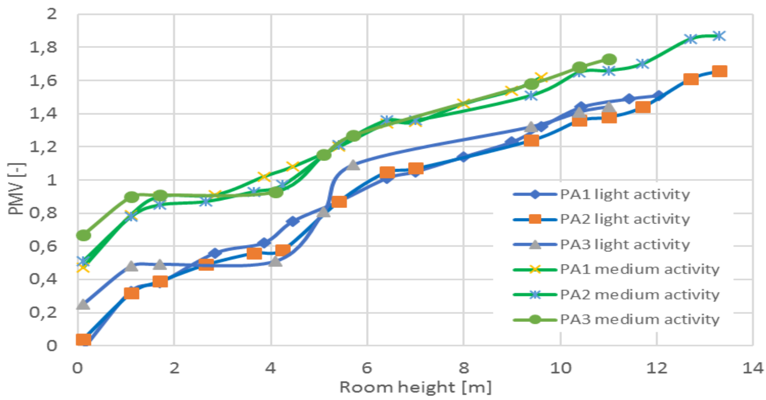

Fig. 3. Values of the PMV indicator in work zone in relation to room height.

However, despite the occurrence of a moderate microclimate in the majority (about 90%) of work zone, there was an increase in human dissatisfaction with thermal conditions (PMV and PPD indices) along with the height of the room. This was related to low-intensity of air mixing and occurrence of air stratification, which resulted in low air velocity and increase of temperature along with altitude. Therefore, at the highest level of work (+ 12.70 m), the indicator of anticipated dissatisfaction with the thermal conditions reached the PPD value of approximately 56% for employees engaged in light work, and around 69% for medium work (fig. 4). However, in the PA3 location, at the heights from 2 to 4 m, the PMV indicator changed slightly (by + 0.02), which was caused by a small increase in temperature (by + 0.46 K) and a constant air speed, resulting from the influence of supply air. As to the operative temperature, it exceeded the air temperature value by an average of 0.68 K in the analyzed points, even despite the occurrence of hot (even 117.6°C) technological equipment surfaces, and it was due to their relatively small area affecting the workers in these points. Therefore, according to the method of calculating thermal comfort ([5]), local discomfort associated with the radiation of partitions and equipment did not have a significant impact on the thermal comfort of employees, and the "hot wall" effect contributed to the PPD increase by less than 10% [17].

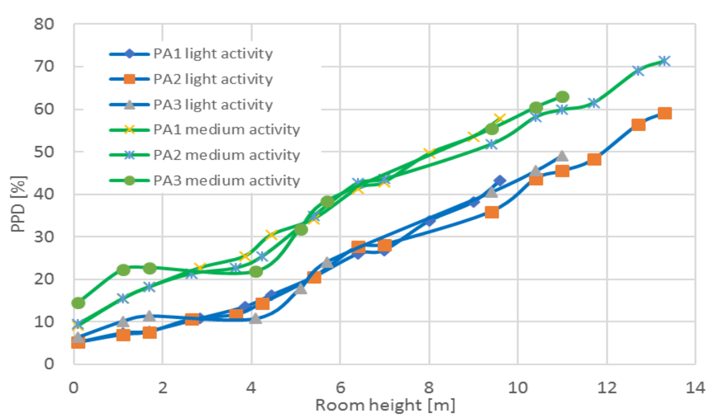

Fig. 4. Values of the PPD indicator in work zone in relation to room height.

However, with light metabolic activity of workers, the thermal comfort conditions (PMV < + 0.5 and PPD < 10%) occurred only up to 2 m. For example, at a height of

1.10 m, at temperature below 23°C and air velocity up to 0.36 m/s, on the majority (60%) of the area there were PMV values from + 0.09 to + 0.50.

In addition, the analysis of thermal comfort of medium activity workers at + 12.70 m (fig. 5), that is at abdominal height of the person working in a standing position on the top floor of the working platform, showed that the most adverse thermal conditions prevail in the surroundings and over the technological equipment. The PMV indicator exceeded 2.00 in these places, with PPD above 70% for both light and medium activity. However, in the remaining part of the work zone, the PMV did not exceed 1.90, indicating the presence of a warm, but still moderate microclimate.

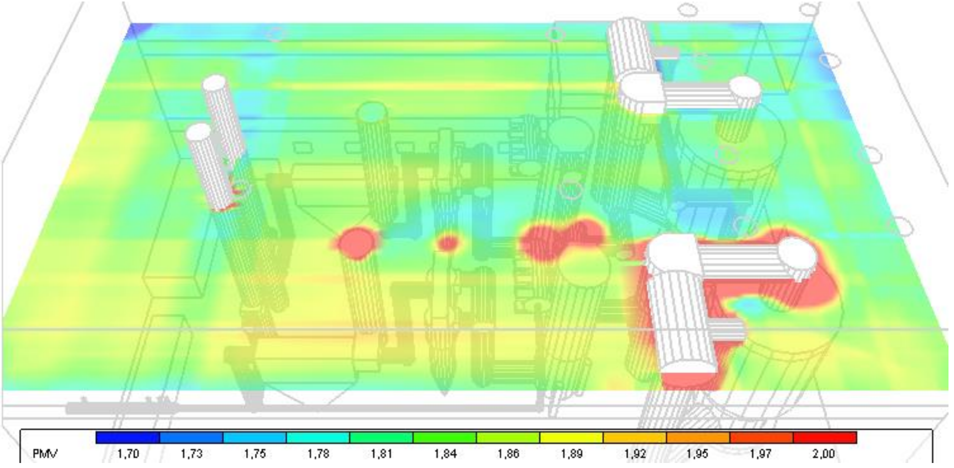

Fig. 5. PMV values at the + 12.70 m level (medium activity).

As the PPD indicator is a function of the PMV value, the distribution of both was characterized by similar relationships. At the + 12.70 m level, the expected percentage of people dissatisfied ranged from around 60% to 80%, and above 80% in the vicinity of the furnace, the recuperator, the boiler and the flue gas cooling device (fig. 6). This indicates the adverse thermal conditions in these places.

Fig. 6. PPD values at the + 12.70 m level (medium activity).

Increased discomfort in the vicinity of combustion units was caused by an intense heat exchange between their hot surface (even 117.6°C) and the incoming air. As a result, the air temperature exceeded 30°C in these areas. In addition, a phenomenon of buoyancy of warmer air was observed, which caused an increase of air velocity even above 1 m/s in these places.

4 Conclusions

The predicted negative thermal sensations of workers in the industrial boiler room were related both to the high operative temperature, and the low air velocity in the work zones. The air stratification, unfavorable for the thermal comfort of workers, was observed in the upper part of the room, and it was related to the buoyancy of warm air, heated from the technological equipment. This resulted in a large temperature difference (over 8 K) between the lowest and the highest storey, and the occurrence of air temperature exceeding 28°C at the highest level of the room. This caused an additional, unfavorable difference in thermal conditions when employees moved to higher floors. In addition, low air turbulence at higher levels of the work platform resulted in low air velocity (below 0.20 m/s) and consequently high PMV (over 1.5) and PPD (over 60%). What is more, the convection of warm air (above 30°C) in the surroundings of hot (up to 117.6°C) surface of technological equipment caused very negative thermal sensations (PMV above 2, PPD above 80%). Nevertheless, the microclimate of the room in the work zones could be classified as moderate (PMV below 2), and the expected thermal sensation as neutral (PMV below 1) and slightly warm ($1 < PMV < 2$) [5]. Therefore, the operation of the second process line in the summer season would probably result in an increase in heat gains and further deterioration of the thermal environment in the room analyzed.

In industrial buildings it is not possible to adjust the type of clothing to thermal conditions and opening/closing windows by employees, which would reduce discomfort (there would be a so-called "adaptive chance") [2]. Therefore, in such an environment the employees can adapt to adverse conditions only by shortening the working time (less than two hours) or by reducing physical activity, which in both cases affects the operation of the boiler plant. An additional adverse factor for workers may be walking up the stairs, being in close proximity to combustion units, a temporary increase in metabolic activity connected with work, and the carrying of heavy tools, which results in increased discomfort and intensification of sweat production. The consequence of this may be a severe disturbance of the body's heat balance.

In summary, it seems that the improvement of the thermal environment in the industrial boiler room analyzed is possible using an appropriate air distribution and encapsulation of industrial processes. Intensification of air mixing should result in unification of temperatures at different heights, and should increase the air velocity in work zones of people. The increase in air velocity has a positive effect on improving thermal comfort in summer [17] and in conditions of increased metabolic activity [18]. Also, improving the efficiency of removal of heat gains, that are coming from the technological processes, will result in lowering the air temperature in surroundings of technological equipment and, consequently, in improving the comfort of workers.

Unfortunately, in rooms not equipped with an air-conditioning system, the thermal conditions depend on the parameters of the outdoor air. It results in a feeling of hot by employees in the summer season [19]. And, in terms of the work of people, the neutral or slightly cool conditions are recommended because the perception, productivity and motivation of employees decreases as the thermal sensation increases [6–8].

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