Analysis of air distribution using “age of air” concept in the selected boiler room

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ABSTRACT

The aim of a ventilation system is to provide a recommended amount of air (with the best possible quality) for both industrial buildings, including boiler plants, as well as for any other type of a room or a building. Its effectiveness depends on applied air distribution type, which results from the location of air supply and exhaust elements, as well as from velocity and temperature of supplied air. Influence of a ventilation system on air quality in a room can be determined using the air parameters or the "age of air" concept. For this reason, the numerical calculations of the "local mean age" of air (LMA) were made for the selected industrial boiler plant, located in the city of Lodz in Poland, and the analysis was made basing on the results of experimental measurements. The whole analysis was performed using the DesignBuilder program, which is based on the Computational Fluid Mechanics (CFD) method.

Keywords: boiler plant, age of air, CFD technique

1. INTRODUCTION

Operation of a ventilation system is essential to ensure the required indoor air quality in every room. For this reason, in office and public buildings it is necessary to provide adequate
air parameters in terms of presence of people [1,2], and the main factors that affect air quality are both functioning of people and operation of office devices, such as computer equipment and printers [3]. However, in industrial buildings it necessary to take into consideration also the pollutants that result from technological processes that are taking place in technological devices. The operation of such type of equipment is usually associated with the emission of gaseous and particulate pollutants [3], as well as of significant amounts of heat and moisture [5]. Therefore, ensuring adequate air quality is essential in terms of presence of humans, who can be exposed to contamination and adverse thermal conditions [5].

In boiler plant buildings, the operation of technological installations is related to the heat emission [7] and air pollution [8], resulting from the combustion processes that are taking place in the thermal equipment. Therefore, a ventilation system in a boiler plant room is designed to remove or reduce the concentration of pollutants, and thus to ensure adequate air quality in work area of people operating the plant. This can be achieved by the proper location of the air supply and exhaust elements and by ensuring the proper airflow, which decide on the air distribution in the room [9]. The supply of fresh outdoor air and the exhaust of polluted indoor air can be made e.g. in the mixing or displacement/stratification mode. Whereas, the air parameters, related to the flow of air in a room, can be expressed using different “Indoor Air Quality” (IAQ) indices, such as: airflow stream or air change rate [10], the „local mean age” of air (LMA) and “local mean residual lifetime” of air (LMR) [12], or the air exchange efficiency [14].

The process of supplying fresh air and removing used air can be determined using the “age of air” concept [12], which determines the residence time of a certain volume of fresh outside air (“local mean age” – LMA [12]), flowing through the room because of operation of a ventilation system. The maximum value of the ”local mean age” of air in the room indicates the amount of time necessary to completely replace the air in the room, and therefore it is one of the determinants of the effectiveness of the ventilation system - both throughout the room and in its part [16]. The LMA also allows to identify the ”short-circuiting” areas and air stagnation zones [16]. Calculation of the ”age of air“ complements the knowledge of air parameters in the room and is possible through experimental measurements using ”tracer gas” [17,18], or by performing a numerical analysis based on Computational Fluid Mechanics (CFD) method [16,17]. The last of these methods, the CFD method, is used in a wide range of engineering to analyse fluid flow, e.g. in the design of equipment [19], buildings [20], installations [21], as well as vehicles [22], aircrafts [23], and even cities [24].

In the CFD method, the area analysed was divided into finite number of elements, where the approximate results of mass, momentum and fluid energy equations are found using the numerical calculations. This allows to determine the air parameters at any point in the room, and then to calculate e.g. the thermal comfort indices and “local mean age” of air in the room [17, 26].

2. RESULTS

The analysis of air distribution was performed in the boiler room in the selected industrial boiler plant building, which is located in the city of Lodz, in the central Poland. The air distribution was analysed basing on the “age of air” concept. In the selected room there is a technological installation of total 8.14 MW thermal capacity, intended for thermal
incineration of sewage sludge from adjacent wastewater treatment plant. The boiler room has got the area of about 718.10 m², height of about 16.90 m, and volume of about 12,136.00 m³.

The combustion plant in the boiler room consists of two identical and independent process lines, operation of which depends on the demand for sludge processing. Each process line consists inter alia of the following equipment (fig. 1):

- A – fluidized bed incinerator (furnace);
- B – recuperator;
- C – heat exchanger (boiler);
- D – multicyclone;
- E – bag filter;
- F – chimney/stack.

The main elements of the ventilation system are (fig. 1):

- Su – air intake;
- Ex – exhaust vent.

![Figure 1. Geometrical model of the boiler room](image)
In the boiler room there is an industrial ventilation system, which is operating depending on the temperature value of the indoor air. The elements of the ventilation system in the boiler room are: eight rectangular air intakes with the dimensions of 1,000 mm per 1,000 mm and five of 2,000 mm per 1,000 mm, mounted in external walls at the +2.49 m level (fig. 2), and twelve exhaust fans of 800 mm diameter (fig. 3). The exhaust fans are located on the roof, above the main technological equipment, and the air intakes are located at the bottom of the room, which aims in an effective removing heat gains derived from the combustion process, that is taking place in the combustion units.

![Figure 2. Air intake in the external wall](image1)

![Figure 3. Exhaust vents in the roof](image2)

The numerical analysis in the boiler room was performed using the DesignBuilder software. In the first stage, the geometrical model of the room and technological equipment was made (fig. 1). Then, the boundary conditions, based on the performed building energy simulation and on the results obtained from the experimental measurements, were introduced into the program. The outdoor air temperature was 23.3 °C, the temperature of partitions ranged from 18.0 °C to 33.3 °C, the temperature of technological equipment was 37.0 °C to 117.6 °C, and the total airflow was 97,020 m³/h. During experimental measurements only one
technological line was active, therefore in the numerical calculations also a model including operation of one process line was adopted. Then, the analysed room was divided into a finite number of elements in which numerical calculations of the "local mean age" of air (LMA) were made.

Arising from ventilation airflow (97,020 m$^3$/h) and room volume (12,136 m$^3$), the average air exchange time was about 450 seconds and the total air change rate was about eight per hour. Whereas, the calculated "local mean age" of air in the room analysed was from 0 to about 480 seconds. The lowest values of the LMA occurred at the line of air supply, id est at the bottom and in the centre of the room. The distribution of the fresh outdoor air of 0 to 50 seconds of LMA is shown in the figure 4. Outdoor air was discharged into the room at a high speed (about 1.9 m/s), which resulted in rapid delivery of fresh air in the line of air supply. However, the occurrence of low values of the LMA in the vicinity of technological equipment was related to a computational error resulting from limitations of the numerical method used.

**Figure 4.** Local mean age of air (0 – 50 seconds)
The distribution of LMA near the external wall, in which the air intakes are mounted, is shown in the figure 5. Local mean age of air was the smallest in the vicinity of the air supply vents and did not exceed 100 seconds, while in the upper part of the room it was up to 400 seconds. Also, there was an increase in the LMA along with the height, although the “age of air” in the central part of the room was lower by 28% compared to the rest of the area.

![Figure 5. Local mean age of air in the cross-section of air intakes](image)

The influence of the air intakes on the LMA in the lower part of the room is shown in the exemplary height of + 2.65 m (fig. 6). In the line of air supply up to the technological equipment, the "local mean age" of air was less than 100 seconds, and in the remaining area it was about 100-200 seconds, wherein in the surroundings of the furnace it raised to more than 300 seconds. This means that the fresh air was effectively mixed in mainly in the central part of the boiler room.

The supplementation of information of the LMA distribution at the height of the air intakes (fig. 6) was to determine the distribution of air velocity vectors (fig. 7). The supply air at a velocity exceeding 1 m/s coincided with an area of LMA lower than 30 seconds. This means that the high velocity of supplied air has resulted in low values of the LMA in the central part of the room. On the other hand, there was air stagnation zone of “local mean age” value exceeding 300 seconds in the surroundings of the furnace shut down.

The highest LMA values were found under the ceiling (fig. 8), on the site of the non-operating process line. This means that the used air stayed the longest (about 480 seconds) in this part of the room. This indicates an uneven removal of used, polluted air, formation of air stagnation zones and associated "short-circuiting" [16].
Figure 6. Local mean age of air at +2.65 m

Figure 7. LMA and air velocity at the + 2.65 m
The "short-circuiting" phenomenon in the boiler room was characterized by a low value of the LMA in the vicinity of the exhaust vents in the roof (fig. 9). In the case of three exhaust vents, LMA value was approximately 250-300 seconds, for seven vents approximately 300-400 seconds, and for last two it exceeded 400 seconds. While an average air exchange time in the room of about 450 seconds. Therefore, the difference between the times of flow of fresh air in the room from inlets to the different exhaust fans exceeds 150 seconds.
**Figure 10.** LMA in the cross-section of the operating process-line

**Figure 11.** LMA in the cross-section of the non-operating process-line
The "short circuit" of air was also observed in cross section of the operating line (fig. 10). This was due to occurrence of the convection phenomenon, resulting in increased vertical movement of the air around the hot surfaces of the technological equipment, and by which it was assisting mechanical ventilation in extracting the indoor air. This resulted both in the quick delivery of fresh air to this part of the building as well as the uneven distribution of fresh air in the room (fig. 8 - fig. 10).

As to the non-functioning process line (fig. 11), the LMA of less than 100 seconds occurred up to about 5 m in the middle of the boiler room, and it was associated with supply of fresh air at the +2.49 m height in its central part. Despite a relatively even deployment of air intakes, there was a significant difference in air distribution in surroundings of the operating (fig. 10) and non-operating technological equipment (Figure 11). The uneven distribution of fresh air in the boiler room caused a difference in indoor air quality in the occupied zone, with more unfavourable conditions occurring near the inactive process line.

![Figure 11. LMA in the cross-section of the non-operating process-line](image)

In addition, the "short-circuiting" of fresh air occurred in the vicinity of the operating exhaust-fumes-cooling device (fig. 12). The difference between the LMA above the operating and off device exceeded 100 seconds (despite relatively symmetrical location of the air supply and exhaust elements). This has resulted in better air quality near the operating equipment at the expense of creating an air stagnation zone near the non-operating equipment.

At the +7.60 m level, low values of the LMA occurred in the surroundings of operating process line and in the middle of the room (fig. 13). Wherein the highest LMA values (above 290 seconds) were noted near the external wall on the site of non-operating equipment. Despite a relatively even deployment of the air supply and exhaust elements, the fresh air flowed even four times faster through the central part of the room than in the rest of the area. This means that the crucial influence on the flow of outdoor air in the boiler room analysed had the phenomenon of convection of air heated up from the technological equipment. What
is more, the lower values of the LMA in the middle of the room, and in the surroundings of the operating equipment, indicates the short time of fresh air delivery to those places and the removal of used air, which is particularly important for presence of people in this zone.

**Figure 12.** LMA and air velocity in the cross-section of the devices

**Figure 13.** Local mean age of air at + 7.60 m
The effect of the operation of technological equipment on the air distribution in the boiler room was shown both in the horizontal view and cross-section through the room (fig. 14). LMA near the multicyclone was about 50-80 seconds and increased with the distance from the central part of the room. This was related both to the decrease in air velocity and to the rising distance from the air intakes. In addition, there was a strong association between the low "local mean age" of air and the high flow velocity both on the air supply line and near the operating equipment. This indicates uneven distribution of fresh air throughout the whole boiler room.

![Figure 14. LMA and air velocity near the devices](image)

3. CONCLUSIONS

Operation of an industrial ventilation system in a boiler plant building should provide an adequate quantity and quality of air in it. This is done, among others, by distributing fresh air through the supply vents and extracting used/polluted air through exhaust vents. In the boiler room analysed of the industrial combustion plant, the air distribution was carried out basing on the supply of fresh outdoor air in the bottom, through the air intakes mounted in the external walls, and on the exhaust roof fans located above the main technological equipment. Value of the "local mean age" of air increased along with the distance from supply elements and with the approach to exhaust vents in the roof. However, in the upper part of the room, there were air stagnation zones on the side of the non-operating line and uneven distribution of time of fresh air flowing from the supply vents to the symmetrically distributed exhaust vents.

The distribution of flow of fresh air differed considerably in the case of operating and non-operating process line. The LMA was significantly lower in the vicinity of hot surfaces of
technological equipment. What is more, distribution of the LMA coincided mainly with the air velocity distribution in the room, which resulted from the operation of the mechanical ventilation system [28], as well as the convection phenomenon [30]. Due to the relatively symmetrical deployment of the supply and exhaust elements in the analysed case it was found that the decisive impact on the uneven distribution of the LMA in the selected boiler room had the operation of technological equipment and the associated occurrence of the convection phenomenon.

Obtaining the knowledge of the distribution of flow of fresh air in a room, and thus the removal of used/polluted air, is possible by analysing the air distribution based on the concept of "age of air" using the CFD method [16]. This approach allows for acquiring the knowledge about the air distribution in a room or a building, depending on location of ventilation system components [34], and location and power of the heat sources [36].

References


