

Design and control of warehouse indoor air quality via numerical modeling

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Abstract. Warehouses are part of the crucial infrastructure of the logistics process of any business. The type of products stored in the warehouse also determines the type of warehouse class. The object of research in the present work is a class A warehouse with a clear height of 10 up to 13 m, equipped with systems for maintaining the indoor air quality within a very specified temperature limit. An air conditioning system is proposed, consisting of roof air conditioners (Rooftop vent), that allow maintaining the microclimate in the specified limits yearly. To achieve the specific requirements, numerical modeling of air distribution in the warehouse was performed, which shows that the use of simplified, systematized methods for the technical design of air conditioners is an unreliable approach. Moreover, the analysis shows that in high warehouses, the stagnant areas that arise cannot be overcome only by rearranging the roofing machines, but also requires the use of additional impulse mixing devices.

1 Introduction

The requirements regarding maintaining of a certain microclimate in warehouses depend on their functional purpose, and for this purpose different classes are defined which is well known [1]. Of the specified classes, only those: A+, A, B+, B have specific requirements for maintaining a suitable indoor air quality, as class A warehouses have a height of 10 up to 13m, the so-called high warehouse.

In class A+ warehouses, the type of product stored, determines the requirements for the maintaining of a certain indoor air quality. Usually, air conditioning systems are designed considering two general parameters - the requirements for product storage (temperature, air speed, relative humidity), as well as the geometric specifics of the air-conditioned volume.

Numerical solution (CFD) of the air distribution in a warehouse room is presented in [2]. The main idea of the research, with a focus on maintaining a certain microclimate all year round, is the use of roof fans, where hot air is supplied from the roof at high speed in heating mode, as in the cooling process it is realized by means of a low-rotation dispersed jet, which, as a cooled volume, slowly descends through the height of the warehouse, the action caused by the Archimedean force. A study of the temperature distribution of the air, as well as the relative humidity of the air in large warehouses, by means of a numerical

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study is presented in [3]. A specific feature of the study is that the warehouse volume is modeled as a porous structure, homogeneously distributed in the processed volume. Numerical studies were also carried out in the analysis of air distribution in potato storage warehouses, where the air is supplied from the perforated floor [4].

Numerical modeling of processes in large halls where internal and external heat removal is present is more complicated [5]. Study shows that the spacing of produce storage racks affects the convection coefficient, and the use of roof partitions such as mezzanines can reduce heat transfer in the warehouse. A similar study of the convection coefficient of a hot jet with positive lifting force is presented in [6].

The study of temperature stratification in large warehouses is presented in [7]. The results of the numerical solution were compared with experimental ones, in which destratification relations were obtained, with the help of which the degree of air mixing in warehouses with air mixing devices can be approximately determined. Air cooling processes in storage warehouses are also of significant interest. The methods of supply and removal of the cooled air, as well as the distribution of the cooling elements (cooling units) are discussed in [8, 9, 10]. The results of the numerical studies indicate that numerical modeling is the only way to predict the distribution of air in large spaces.

2 Problem identification

2.1 Structural features of the warehouse

Main focus of the current study is a storage warehouse of Class A for chocolate products with an area of 43 000 m² and a clear height of 12.5m (Figure 1). The entire warehouse is occupied by racks, as the distance between them is 3.5m, and the total height of the racks is 11m.

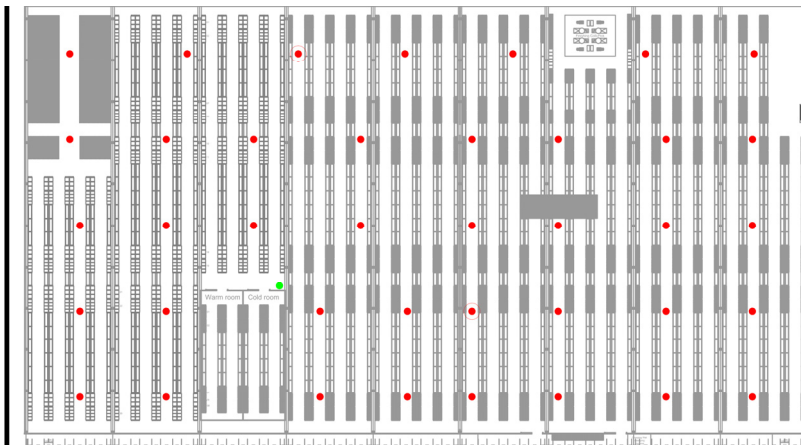


Fig. 1. Layout of the warehouse with regals and location of rooftop HVAC machines (red dots)

In order to ensure that the racks can be loaded with produce, a distance of 30 cm is provided between two racks that can easily be serviced by electric trucks. The height of each rack, depending on its location, varies from 1.8 to 2.3 m. The width of the racks varies from 1.05 to 1.2 m, and the horizontal distance between them is 0.2 m (Figure 2).

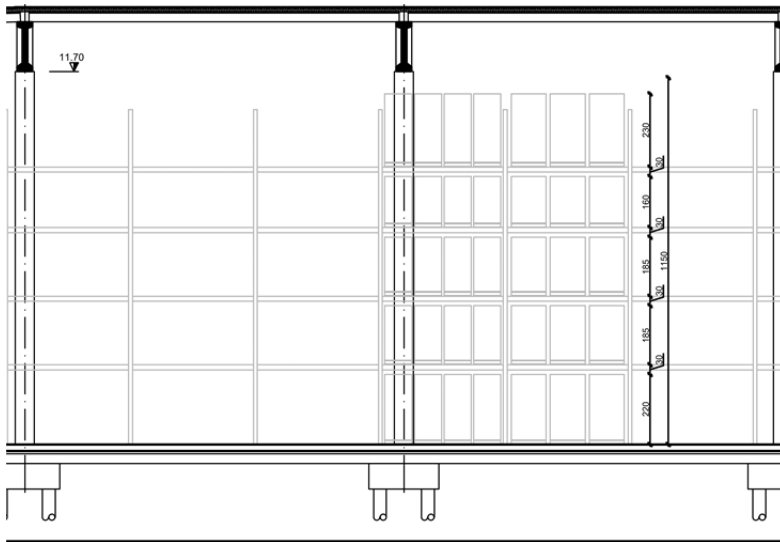


Fig. 2. Vertical layout of the warehouse with regals available (dimensions in cm).

2.2 Heating and cooling modes of the warehouse

The number and type of machines (HVAC units), shown in Figure 1 is determined based on the heating and cooling needs of the warehouse. Based on the local climate features, the heating and cooling loads of the warehouse were calculated as 825 and 744 kW respectively, which determine respectively 75 and 65 W/m² heat losses and gains (determined with the methodology “Energy Performance of Buildings Directive”). In the table 1 are presented the specified operating parameters both in heating and cooling modes.

Table 1. Mode parameters of HVAC units in heating and cooling modes

Parameter	Heating mode	Cooling mode
Fresh air temperature, °C	-12	32
Relative fresh air humidity, % RH	90	40
Room air temperature, °C	18	18
Relative extract air humidity, % RH	30	-
Extract air temperature, °C	20	20
Inlet air temperature, °C	45	8
Return air temperature, °C	35	14

Chocolate products require a very narrow storage temperature range - between 14 to 18°C, and relative humidity up to 60%. This temperature range must be maintained on yearly basis and 24 hours per day. Outside the specified temperature interval, the qualities of the stored product deteriorate, as well as the commercial appearance of the product changes. Below 14 °C the chocolate products "turn white" and above 19 °C the melting

process of the product begins. In both cases, the stored products cannot be sold commercially.

2.3 Specifics of HVAC units

The most reasonable solution based on the warehouse and products specifics is to maintaining indoor air quality with Rooftop vent, that supply the air in a specific way for both heating and cooling modes (Figure 3a).

In the "heating" mode, a strongly swirled hot jet is supplied to the room, which, reaching the floor of the warehouse, reverses its direction of motion and warms the air around the racks loaded with products (Figure 3b). In the "cooling" mode, the cold jet is pulverized and, based on Archimedean force, descends from the top of the warehouse to the floor (Figure 3c). Conditional direction of the jet is presented in Figure 3b and Figure 3c.

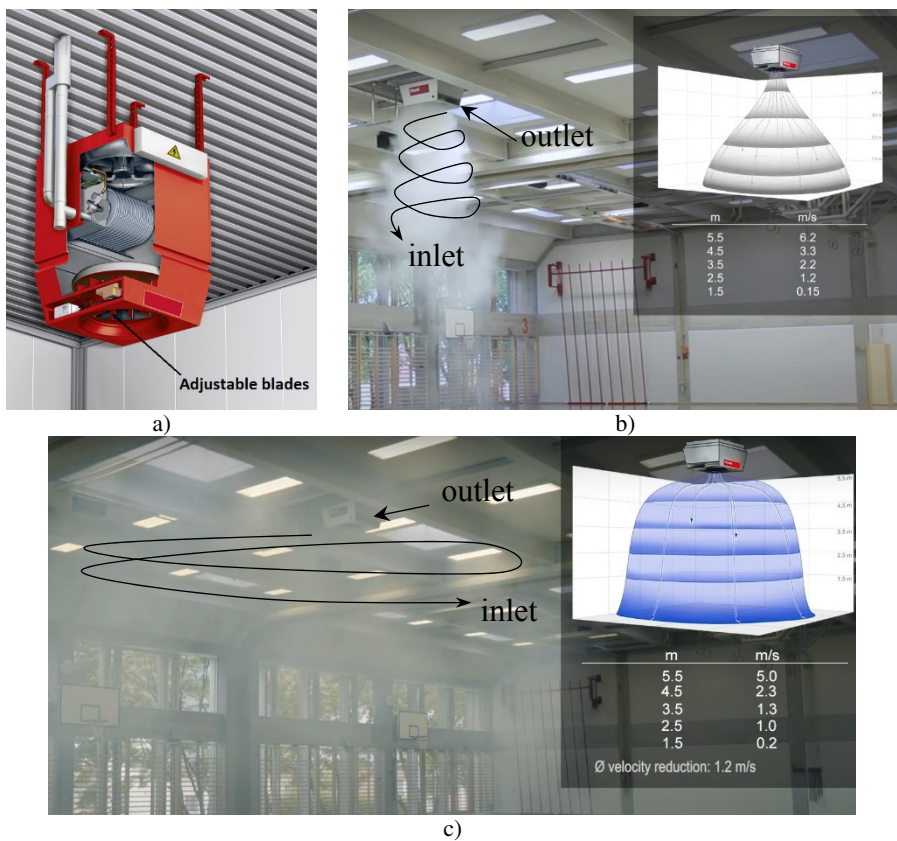


Fig. 3. HVAC unit specifics: a) 3D model of the unit [11]; b) Heating mode air distribution [12]; c) Cooling mode air distribution [12].

3 Numerical modeling

The jets produced by this type of air conditioning system are defined as turbulent swirling jets with a high average turbulent intensity. To ensure the heating mode in the warehouse, a highly swirled jet with a significant propagation range is generated, in order to reach the floor of the warehouse. In cooling mode, atomization of the jet is sought, so that a cold jet layer of sufficient area is formed, which by means of negative lift reaches the floor and

cools the surrounding space. The task, on one hand, is complicated by the fact that during its propagation, the jet passes through shelves filled with products, which are a kind of porous media. On the other hand, interaction between different air jets creates very complicated flow completely different from the single unit. Due to the above, only numerical modeling of the distribution of air in the warehouse will give a proper temperature and velocity distribution, as well as will be highlighted the areas with zone outside of the preliminary accepted limits.

3.1 Geometry modeling

A three-dimensional model of the warehouse was prepared in SolidWorks, and Figure 4 shows only a part of the volume. The model shows the position of the racks, as well as the volume conditioning machines described in item 2.3. Considering the large volume of the warehouse, the numerical studies are focused on only part of it, where the most unfavorable conditions (heaviest modes) are present - the presence of two external walls, i.e. significant heat losses and heat inflows (red line).

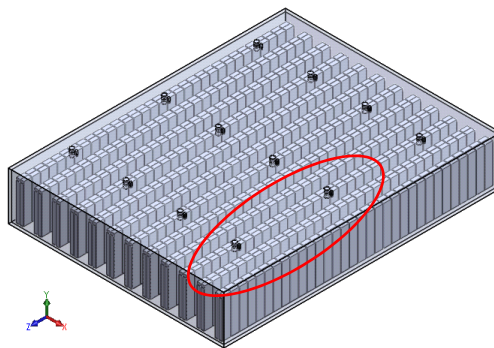


Fig. 4. 3D model of the warehouse

3.2 Initial and boundary conditions

The numerical studies were carried out in both modes of operation of Air handling units – heating and cooling modes. In heating mode, the air supply temperature from the machines is 45 °C, and in cooling mode – 8 °C. It should be clarified that the heat transfer modeling was done with propagation jet range in heating mode and maximum atomization in cooling mode. These are the two modes of operation in extreme outdoor conditions – the lowest external air temperatures in heating mode and the highest ones in cooling mode. The guiding blades of the device supply air with temperature, velocity, direction and intensity in terms of the needs of warehouse. In case of the transient modes (lower heating and cooling modes) the units have a possibility to intensify the process of mixing of air in specific zones of the volume. The nominal flow rate of conditioned air from each unit is about 9 000 m³/h. The heat losses and gains through the enclosing elements (75 and 65 W/m²) have been determined in advance and are embedded in the software product. The stationary mode of operation of the systems was studied, i.e. cases of export and import of production in the volume of the warehouse were considered.

Numerical modeling procedure solves the continuity equation, momentum conservation, energy equation, and turbulence modeling. Given that a flow in a confined space is considered, an RNG k-ε turbulence model is chosen. At high speed (heating mode), a value of 0.65 is assumed for the degree of rotation (S). This value was determined on the basis of

performed experimental studies (Figure 3b). For weakly swirled jets (cooling mode), the degree of rotation is assumed to be 0.066.

4 Results

Below are the results for both modes of operation of the air conditioning systems – heating and cooling modes.

4.1 Heating mode

A two-dimensional formulation of the problem was considered, as described in item 3.1.

Analysis from the CFD study shows that supply temperature above 24°C (at the inlet of the Air handling unit (AHU)) increases the air temperature in the vicinity of the top shelves up to 21 degrees which is unacceptable from technological view point. The AHU is able to deliver both fresh air heated up with decentralized heat pump and partial/full recirculation of the exhaust air.

Below are presented the results from the CFD study when the supplied temperature is 22 °C. This is the heaviest case scenario because there are two external walls and one adjacent zone with warm air supplied by different AHU. On Figure 5a and Figure 5b are presented the velocity and temperature distribution.

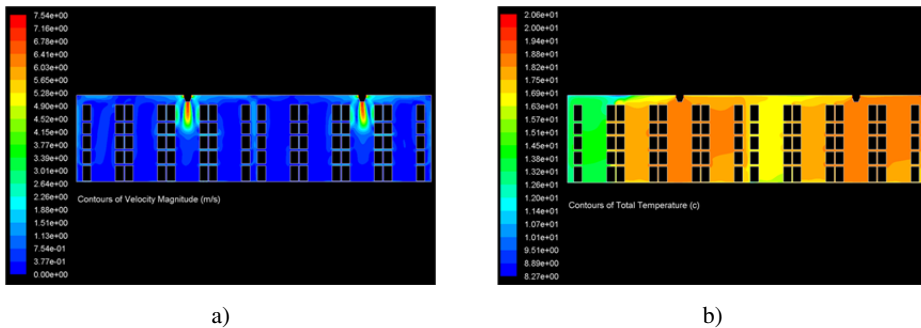


Fig. 5. a) Velocity distribution; b) Temperature distribution;

Based on 5a, the air velocity range is between 0.3 and 6 m/s. The lower velocity is a prerequisite for stagnation points in the warehouse and keeping the temperature lower than the requested norms. Figure 5b shows that temperature changes from 9 up to 20°C. The highest temperature is right below the fans, and lowest temperature is close the external walls and roof.

Figure 6a shows the areas where the air temperature is below the required temperature range, and in Figure 6b – the critical temperature zones in the lower permissible temperature interval.

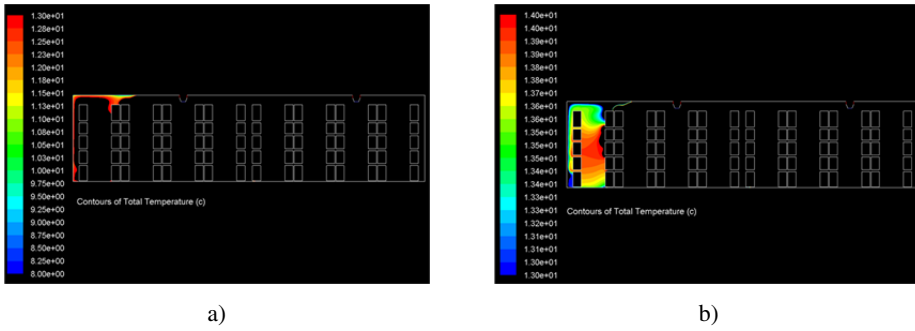


Fig. 6. a) Temperature region outside of the acceptable norms; b) Temperature region from 13 to 14 °C;

4.2 Cooling mode

Analysis from the CFD study shows that supply temperature below 14°C leads to a very low temperature in the vicinity of AHU units. Due to the heat transfer through external wall and air handling volume, the air temperatures close to the external wall is expected to be the highest. Study shows that 22°C could be expected. The air distribution in heating mode is presented on Figure 7a, and the temperature region not meeting the norms is presented on Figure 7b.

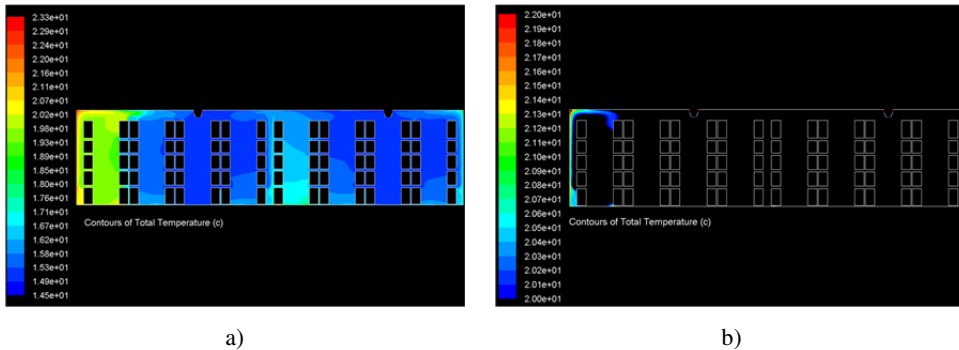


Fig. 7. a) Temperature distribution during cooling mode; b) Temperature region from 18 to 20 °C;

5 Conclusion

In present work, a numerical study of the temperature distribution of the air in a class A warehouse was carried out, for which maintaining of the temperature in the entire volume needs to be upheld all year round. The preliminary design of the installation is based on the approved by regulations methodology for calculating heating and cooling loads, and the arrangement of the devices is based on only analytical relations used for air distribution in a stationary fluid media.

The performed numerical study showed that the behavior of turbulent jets encountering a porous medium (racks), as well as the interaction between the couple of jets, is almost impossible to determine analytically. The way of supplying the air in the room depends on the mode of operation, and the present study shows that for the concerned volume of warehouse, in the heating mode, the degree of rotation is perceived to be 0.65, and in the cooling mode - 0.066. The preliminary design (selection of machines and position) is significantly inaccurate and provides a prerequisite for the occurrence of stagnant zones in

which the flow parameters are outside the permissible values prescribed by technologists for storing of the production.

With the tools of the numerical solution, stagnation zones are identified for the most severe operating modes. On this basis, a suggestion was made to relocate the machines in order to avoid the formation of such zones, and if this is not possible (like in current case), a mechanism for additional mixing is proposed by installation of impulse fans. In separate critical areas, established by the CFD study, a suggestion is made for installation of sensors, when critical temperatures are reached in the volume, as the signals are send to respective AHU unit for changing the angle of the guiding blades for additional mixing of the air.

In addition, the rearrangement of the air handling units (AHU) improves the air distribution and facilitate the mixing through the regals. Thus, the required parameters of the indoor air quality are achieved with optimal operation of the AHUs, therefore with reduced energy consumption, which improve the energy efficiency of the proposed installation.

This study is financed by the European Union-NextGenerationEU, through the National Recovery and Resilience Plan of the Republic of Bulgaria, project BG-RRP-2.004-0005

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