Numerical Study of Air-Flow and Heat Transfer Inside a Sports Hall

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Preliminary note

Numerical analyses, performed as a part of a redesign project for an air-conditioning system of a sport hall, have been presented. The existing and redesigned air-duct arrangements as well as different types of air supply outlets have been analyzed using three dimensional steady-state numerical simulations of turbulent air flow, taking into account buoyancy effects. Commercial CFD software Star-CCM+ has been used for fluid flow simulations based on the finite volume method. It was determined that the use of special diffuser type with variable outlet flow patterns for winter and summer operation produced better thermal environmental conditions in air-conditioned space, as compared to existing air grilles. The application of computational fluid dynamics (CFD) methods for air distribution analysis has proven to be a very useful tool in design of modern air distribution systems.

Numerička studija strujanja zraka i prijenosa topline unutar sportske dvorane

Prethodno priopćenje

U radu su prikazane numeričke analize provedene u okviru izrade projekta rekonstrukcije sustava klimatizacije sportske dvorane. Korištenjem numeričkih simulacija trodimenzijskog stacionarnog turbulentnog toka zraka, uz uvažavanje utjecaja prirodne konvekcije, analizirani su postojeći i novoprojektirani sustavi distribucije zraka i različiti tipovi dovodnih otvora za zrak. Komercijalni CFD (CFD - Računalna dinamika fluida) softver Star-CCM+ korišten je za simulaciju toka fluida zasnovanu na metodi konačnih volumena. Utvrđeno je da se korištenjem posebnih difuzora s različitim načinom istrujavanja za zimski i ljetni rad postižu bolji uvjeti lagodnosti u klimatiziranom prostoru u usporedbi s postojećim ventilacijskim rešetkama. Primjena računalne dinamike fluida (CFD) za analizu strujanja zraka pokazuje se kao koristan alat u projektiranju suvremenih sustava distribucije zraka.

1. Introduction

The problem of thermal comfort in rooms is closely coupled with air distribution. It is important to design the air distribution system capable of achieving adequate mixing of inlet air with the room air and thus obtaining a uniform temperature and fresh air distribution. It is also important to avoid the draught, by keeping air velocities within desired limits. Both of these goals are hard to achieve sometimes. That is the reason why the prediction of the flow and mixing conditions prior to the installation of the ventilation and heating equipment is a demanding task, which mostly depends on designer's experience and expertise. In some cases, experimental and numerical methods could be helpful. Experimental and numerical methods have been widely accepted as a means of airflow analyses of optimal building design and indoor ventilation [1-6]. Experimental methods are expensive, time consuming, and sometimes might be impractical.

Some simplifications are possible [2], but those methods are still not common during design of new systems. With recent advancement of computer power, computational fluid dynamics (CFD) are becoming a suitable tool for the design of air distribution systems in buildings, providing a realistic representation of real physical situation.

This paper reports on numerical simulations performed for the case of existing and redesigned air-conditioning system of an athletic hall, to prove the efficiency of the ventilation system redesign. The systems were simulated in both winter and summer work regimes.

2. Existing and redesigned state of air distribution system

Both the existing and the redesigned ventilation system of a sports hall were analyzed in this paper. The sports hall measures 50 m in length, 35 m in width

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Symbols/Oznake

E	- energy, J - energija		u	- velocity, m·s^{-1} - brzina
k	- turbulent kinetic energy, m^2·s^{-2} - turbulentna kinetička energija		ε	- turbulent dissipation rate, m^2·s^{-3} - turbulentna disipacija
p	- pressure, Pa - tlak		λ	- thermal conductivity, W·m^{-1}·K^{-1} - toplinska vodljivost
t	- time, s - vrijeme		μ	- dynamic viscosity, Pa·s - dinamička viskoznost
T	- thermodynamic temperature, K - termodinamička temperatura		ρ	- density, kg·m^{-3} - specifična gustoća

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and a height of 11 m. The southern and northern sides contain panes of glass. The roof and walls are built with thermally insulated panels on steel girders. The geometry of the sports hall, as well as the placement of inflow and outflow vents are shown in figures 1a for the existing and 1b for the redesigned system. In order to be cost-effective and easy to perform, the suggested modifications in the ventilation system were designed to keep the installed air conditioning equipment and change the make, position and number of outflow adjustable diffusers instead. The number of supply air outlets was increased from 20 to 24 and they were spaced evenly through the hall (Figure 1b) unlike the existing setup where they were concentrated in just one area (Figure 1a). Position of the return air inlet has also been changed and it has been placed closer to the floor area.

The existing system supplies 8500 m³/h of fresh air that can be heated to 40 ºC at external temperatures of -8

ºC which is sufficient for the heating demands of the hall. However, the distribution of the air throughout the hall is inadequate, which is the main reason for insufficient heating (or cooling during the summer) and influences the comfort of the people inside. The ventilation supply grilles are set at a height of 7.6 m above the floor which due to buoyancy forces makes it difficult for the heated air to reach the ground area intended for athletes. Return air inlets are at a height of 7 m leaving the air circulation confined to the upper level of the hall (Figure 2). The existing ventilation grilles are fixed and thus cannot be used to adjust the direction or speed of the conditioned air entering the hall forcing an identical air distribution during the summer (cooling) and winter (heating). This is least suitable during the summer as the conditioned cool air falls to the hall ground, due to its greater specific density, creating draft zones of faster and cooler air that are particularly discomforting. The inability to change
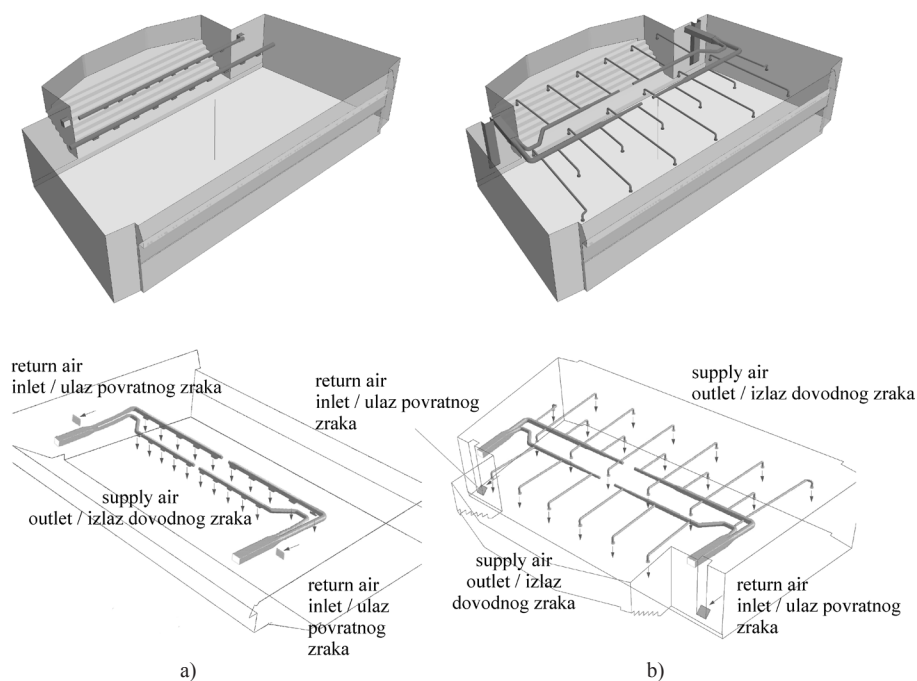

Figure 1. Geometry of the sports hall with the existing (a) and the redesigned (b) ventilation system

Slika 1. Geometrija sportske dvorane s postojećim (a) i redizajniranim (b) ventilacijskim sustavom

the outflow vent area during the winter causes the conditioned hot air to insufficiently penetrate the ground area occupied by athletes and visitors. The existing air distribution was therefore deemed unsuitable for human comfort and required reconstruction.

Figure 2. Positions of supply and return air grilles
Slika 2. Položaj ulaznih i izlaznih rešetki

The proposed adjustable diffusers can change the area of outflow and thus regulate the velocity of fresh air inflow and the penetration depth in the hall area. In order to prevent drafts in the cooling mode, the supply air must largely be discharged horizontally from the diffuser. However in the heating mode, the diffuser must be able to project the warm supply air vertically downward to achieve fast and efficient heating. Such diffuser ensures optimum air distribution in the cooling and heating modes. The diffuser has a funnel neck connection with an inner and outer basket arrangement. The diffuser has openings around its circumference and at the underside. In the heating mode, the diffuser can be adjusted manually or electronically by the actuator to close off the lateral openings and open the bottom openings. This enables it to create a vertical supply air jet which is more compact and reaches a greater penetration depth, ensuring quicker room heating. In the cooling mode, the outer openings are opened, while the openings at the bottom of the diffuser are closed. The individual supply air jets that are created ensure a high induction, which means that velocity and temperature differentials are rapidly reduced.

3. Geometry and numerical mesh

The computational domain is comprised of the entire hall volume which, as mentioned earlier, measures 50 m in length, 35 m in width and 11 m in height.

The numerical meshes for both cases contained about 2 million of predominantly hexahedral volume cells. All solid walls were covered with multiple layers of prismatic elements to increase accuracy.

The amount of conditioned air was equal for both simulated systems and was 8500 m³/h either heated to 40°C or cooled to 18 °C according to the chosen regime. The external air temperatures for winter conditions were set at -6 °C, and 32 °C for summer. The walls, glass
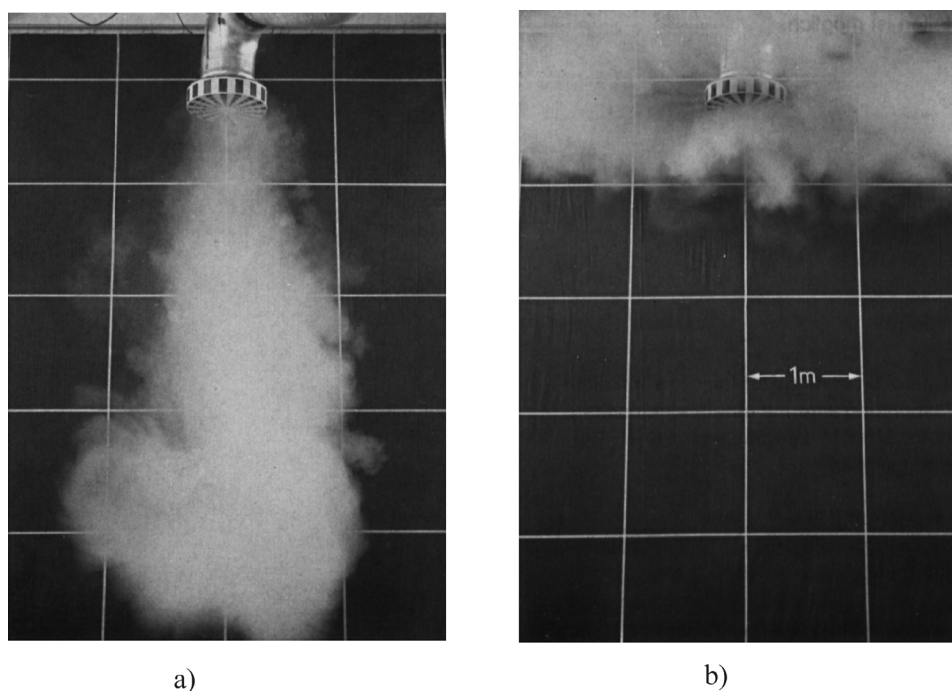

a)   b)

Figure 3. Typical adjustable diffuser smoke test: a) heating mode, b) cooling mode

Slika 3. Uobičajeni dimni test podesivog difuzora: a) grijanje, b) hlađenje

panes, roof and ground floor were all defined with their specific thermal characteristics. Solar radiation has been taken into account as well.

4. Computational model

Conservation equations

The air flow in the analyzed sports hall is assumed to be turbulent and steady-state. The equations representing the conservation of mass, momentum and energy for the 3D model are as follows [7-9]:

$$\frac{\partial \rho}{\partial t} + \nabla\left(\rho \vec{u}\right) = 0, \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho \vec{u}\right) + \nabla\left(\rho \vec{u}\vec{u}\right) = -\nabla p + \nabla\left[\mu\left(\nabla \vec{u} + \nabla \vec{u}^{T}\right)\right], \tag{2}$$

$$\frac{\partial}{\partial t}\left(\rho E\right) + \nabla\cdot\left(\vec{u}\left(\rho E + p\right)\right) = \nabla\cdot\left(\lambda\cdot\nabla T\right), \tag{3}$$

where E, T, u, p, μ, ρ and λ are energy, temperature, velocity, pressure, dynamic viscosity, density, and thermal conductivity respectively.

In order to complete this set of equations, additional relations are required to link thermodynamic and transport properties of air. Air properties can be assumed to change according to the ideal gas law.

$$\frac{p}{\rho} = RT, \tag{4}$$

where p is the pressure, ρ density, R gas constant and T temperature.

The dynamic viscosity of the air is a function of temperature and is obtained from Sutherland's law. Turbulence was taken into account using the realizable k-ε turbulence model [10].

5. Result analysis

Winter regime – heating

The contours of temperature in characteristic cross-sections show a more even vertical temperature distribution in the hall with the redesigned ventilation system. The temperatures in the part of the hall occupied by people are higher while the temperatures in the upper regions are lower than before, making heat losses towards the exterior lower as well.

The air flow velocity in the zone occupied by people is also slightly lower in the redesigned solution providing better comfort (Figure 5). These temperature field characteristics and air speeds are the result of using adjustable diffusers which enable the fine adjustments of flow direction and velocity. This results in a deeper penetration of heated air into the region occupied by people clearly visible by comparing the streamlines flowing out of the installed grilles and the reconstruction adjustable diffusers (Figure 6).

The existing system makes the heated air, with its lower density and speed, rise vertically to the upper regions heating only the upper part of the hall, which is the space without people. Increased temperature in that part results in higher heat losses through the roof.

Summer regime – cooling

The cooling regime also shows a more even vertical temperature distribution in the redesigned ventilation system showing an improvement in the occupied area with lower temperatures (Figure 7) and air velocities (Figure 8). The cool air in the existing system drops vertically to the floor creating a heterogenous temperature field in the occupied area with the increased air flow velocity creating a discomforting drafty feeling.
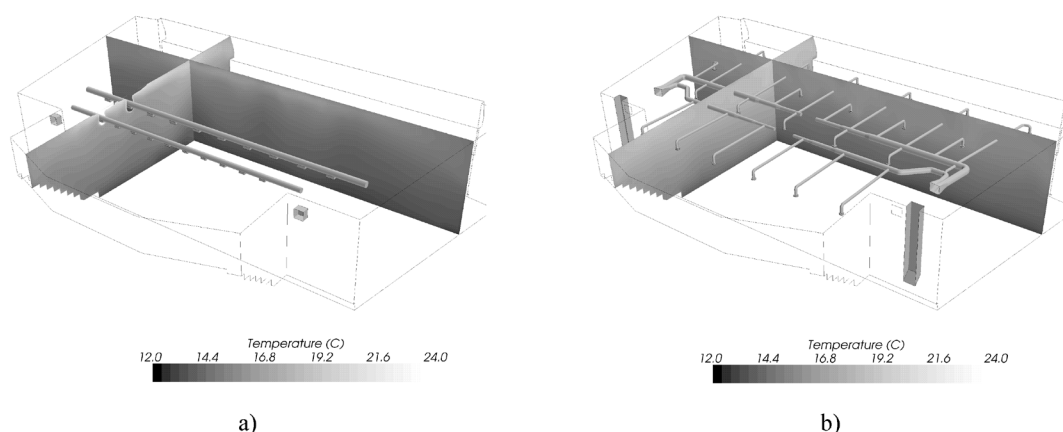

Temperature (C)
12.0   14.4   16.8   19.2   21.6   24.0

a)

Temperature (C)
12.0   14.4   16.8   19.2   21.6   24.0

b)

Figure 4. Contours of temperatures for the heating mode of the existing (a) and redesigned (b) sports hall ventilation system.
Slika 4. Konture temperatura pri grijanju sportske dvorane postojećim (a) i redizajniranim ventilacijskim sustavom
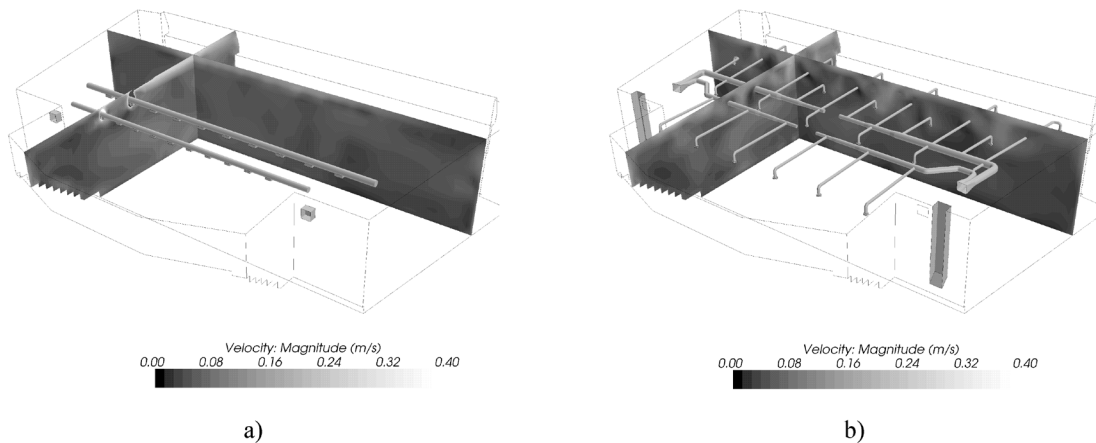
Velocity: Magnitude (m/s)
0.00   0.08   0.16   0.24   0.32   0.40

a)

Velocity: Magnitude (m/s)
0.00   0.08   0.16   0.24   0.32   0.40

b)

Figure 5. Contours of aur flow velocities for the heating mode of the existing (a) and redesigned (b) sports hall ventilation system.

Slika 5. Konture brzina strujanja zraka pri grijanju sportske dvorane postojećim (a) i redizajniranim ventilacijskim sustavom
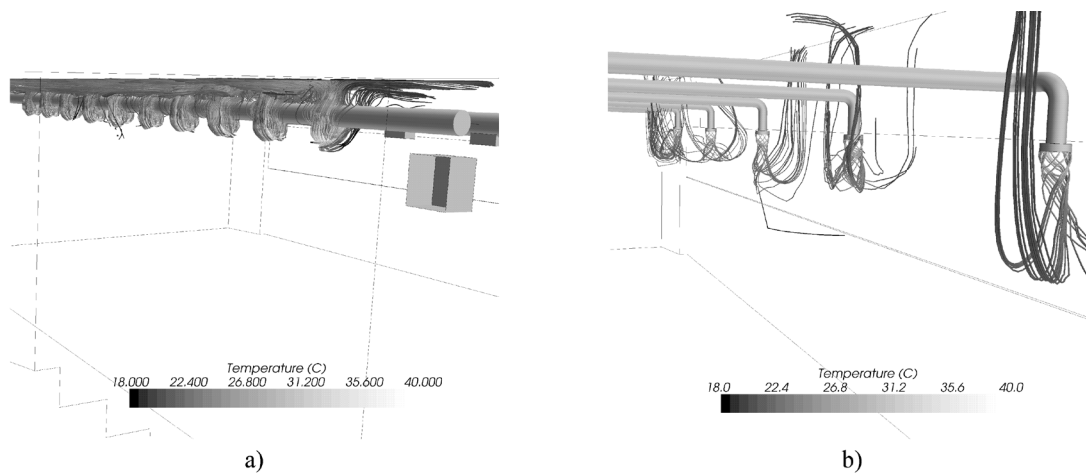

Temperature (C)
18.000   22.400   26.800   31.200   35.600   40.000

a)

Temperature (C)
18.0   22.4   26.8   31.2   35.6   40.0

b)

Figure 6. Streamlines for the heating mode of the existing (a) and redesigned (b) sports hall ventilation system.

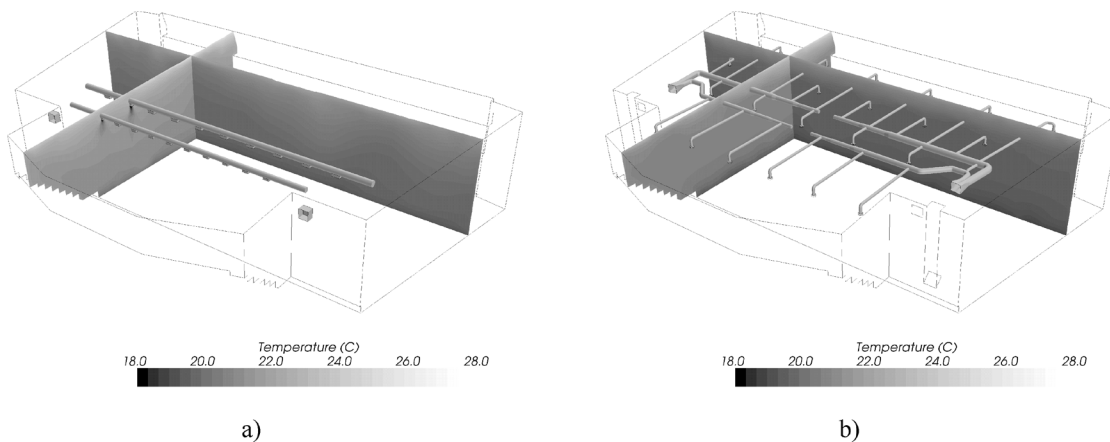**Slika 6.** Strujnice pri grijanju sportske dvorane postojećim (a) i redizajniranim ventilacijskim sustavom

Temperature (C)
18.0   20.0   22.0   24.0   26.0   28.0

a)

Temperature (C)
18.0   20.0   22.0   24.0   26.0   28.0

b)

Figure 7. Contours of temperatures for the cooling mode of the existing (a) and redesigned (b) sports hall ventilation system.

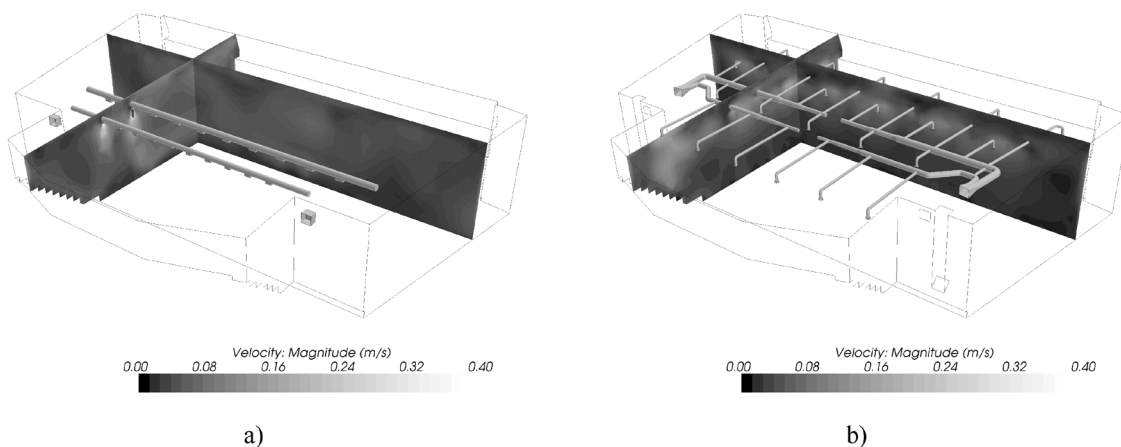**Slika 7.** Konture temperatura pri hlađenju sportske dvorane postojećim (a) i redizajniranim ventilacijskim sustavom

Figure 8. Contours of air flow velocities for the cooling mode of the existing (a) and redesigned (b) sports hall ventilation system.
Slika 8. Konture brzina strujanja zraka pri hlađenju sportske dvorane postojećim (a) i redizajniranim ventilacijskim sustavom

Adjustable diffusers in cooling mode enable a lateral inflow of conditioned air (horizontal stream lines from diffusers, Figure 9) resulting in slower descent of chilled air and providing a more homogenous hall temperature and human comfort.

outflow vents replacing grilles with adjustable diffusers and the relocation of return air inlets. The numerical analyses in the commercial fluid flow solver Star-CCM+ have shown an improvement in thermal comfort
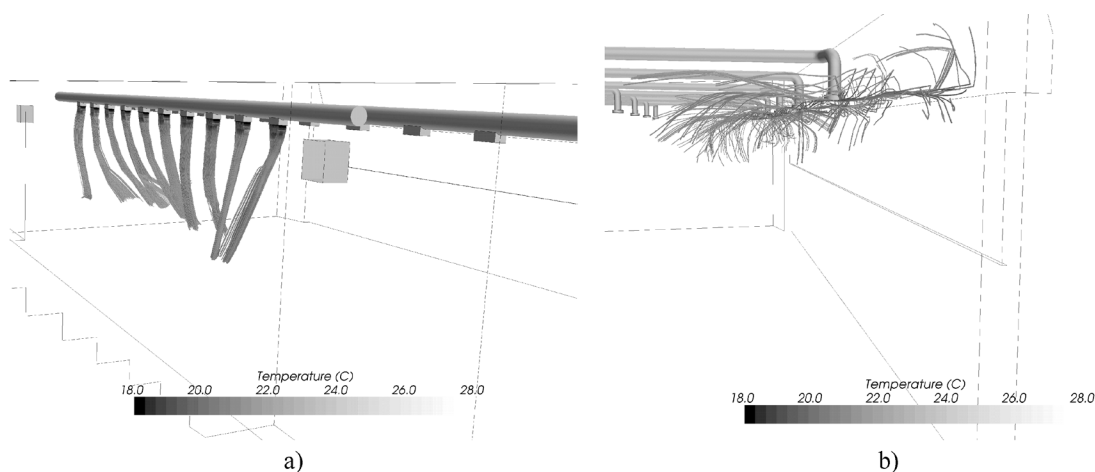

Figure 9. Streamlines for the cooling mode of the existing (a) and redesigned (b) sports hall ventilation system.
Slika 9. Strujnice pri hlađenju sportske dvorane postojećim (a) i redizajniranim ventilacijskim sustavom

6. Conclusion

An analysis of air distribution was presented for the sports hall in the heating and cooling regimes of both the existing and redesigned ventilation system. The redesign comprised changing the number, position and make of the

conditions for both the summer and winter regimes when using the special adjustable diffusers. The application of computational fluid dynamics in air distribution analysis has been proven as a very useful tool in designing modern air conditioning systems.

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