AN INVESTIGATION TO OPTIMIZE THE MECHANICAL SYSTEMS TO MEET COMFORT CRITERIA IN A LARGE ATRIUM

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ABSTRACT

A large office building has a 140 m atrium which is split into four sections: atriums 1, 2, and 3 and a "sky garden" which is the upper most atrium with trees and shrubs. The atrium was simulated first in EnergyPlus to obtain the correct surface conditions for the critical days and then in Star CCM+.

The first CFD analysis showed uncomfortable temperatures on the upper balconies in each section in the summer months. The optimization of the jet nozzles angles, the additional components and the supply temperature adjustment has shown a promising improvement in the thermal comfort on the balconies.

INTRODUCTION

Building Performance Simulation (BPS) has a key role for better design and improvement of new residential and commercial buildings (Mahdavi and Reis 1998, Malkawi and Augenbroe 2003, Hensen et al. 2004). It can help the designers to compare different scenarios for the buildings by changing the temperatures, flow rates and locations for installing HVAC systems to obtain thermal comfort.

The BPS tools contain Building Energy Simulations (BES) tools and Computational Fluid Dynamics (CFD) tools. The BES tools are widely used at the academic level and include e.g. Energy Plus (EnergyPlus 2005) and ESP-r (Clarke 2001, Strachan et al. 2008), etc. The widely used CFD tools are Fluent (Fluent 2006), Star-CCM+ (Star-CCM+ 2011), OpenFOAM (OpenFOAM 2004), etc.

BES tools are based on yearly simulations to find the most critical days of the year from a thermal comfort point of view. Most of the BPS simulations start by investigating the buildings with BES tools and later CFD. CFD deals with a set of non-linear partial differential equations for predicting some variables such as temperature, velocity, pressure, etc. (Anderson 1995, Ferziger and Peric 2002). It is capable of higher resolution modeling of flow patterns and temperature ditributions than the BES tools.

The current study deals with a 140 m atrium that is situated in Azerbaijan; here the climate is cold in the winter and hot in the summer. The atrium has a glass façade on its north and south sides. The atrium is divided into four smaller atriums and the results for Atrium 1 are presented in this paper. The atrium was simulated first in EnergyPlus to obtain the correct surface conditions for the critical days to be studied and then in Star CCM+ to help the design team stay within the comfort criteria of 18°C to 27°C. The aim of this paper is first to present the CFD analysis for the summer months. Then, the design will be optimized using the results from this analysis in order to fullfill the thermal comfort criteria.

SIMULATIONS

Building Description

The building has a height of 140m with an atrium that runs up through the center of the building. The specifications of this atrium are shown in Figure 1. The atrium is split into four parts. This paper focuses on atrium 1, the first of these four parts. Here there are balconies on both sides of the atrium at every floor level from floor 3 to floor 9. Each balcony has a fresh air outlet, as well as chilled floors and fan coil units designed to provide a comfort zone of between 18-27°C. These balconies can be accessed by the people from each side of the building. There are two bridges spanning the width of the atrium allowing people to cross one side to the other side. These bridges are at floor levels 5 and 7. The bridges are conditioned to meet the comfort criteria of 18 to 27°C using chilled floors. The ground floor is conditioned using a chilled floor and jet nozzles which direct streams of fresh air 15m into the space.

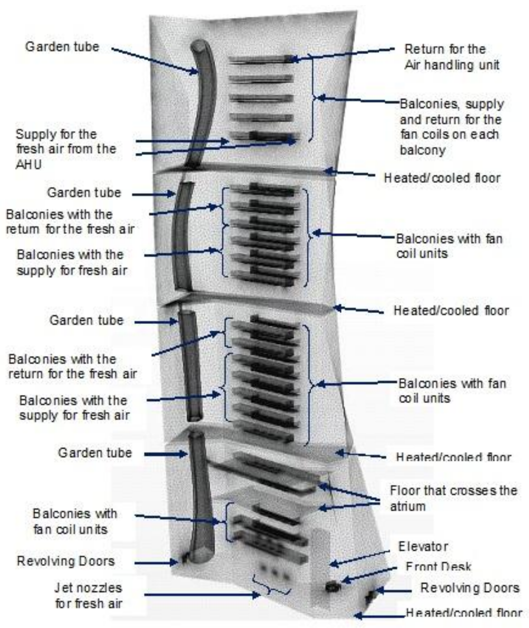


Figure 1 The building specification

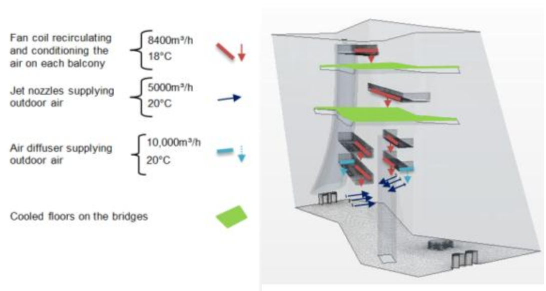


Figure 2 Conditioning in the first quarter of the atrium

The current study focuses on Atrium 1. It has a height of 38.7 m. The StarCCM+ CFD software is used for modeling the Atrium. After building the three dimentional geometry, the next step is to mesh the atrium. The mesh density needs to be checked to ensure that the quality of the mesh will provide us with a reasonable result. REHAVA (Nielsen et al. 2007) suggests that the number of good cells can be calculated by the following equation.

$$N = 44.4 \times 10^{3} V^{0.38} \quad \text{Eq. (1)}$$

Where N is the number of cells and V is the room volume [m].

The atrium volume is substituted into Eq. (1) and the calculation shows that the number of mesh should be at least 1.1 million. In the current study the number of mesh is about 2 million and it fulfills the criteria to have a fine mesh in the atrium. The models used for meshing the geometry are Polyhedral Mesher, Prism Layer Mesher and Surface Remesher. The base size mesh is 1 m, the number of the prism layer is 3 and the prism layer stretching and surface growth rate cell are 1.1. The mesh is considered to be denser close to the supply outlets, returns and the walls. The mesh is checked and has a low mesh skewness angle.

Boundary Conditions

Atrium1 uses jet nozzles to supply its spaces with fresh air. These have a high velocity which throws the air far into the atrium to place fresh air into the central region of the atrium. 5,000 m /h of fresh air is supplied by the jet nozzles. The remaining 10,000 m /h of fresh air is delivered through air handling unit diffusers. These are located on the underside of the balconies in the atrium. The top balconies contain the returns for the fresh air. All supply air is conditioned to 20°C.

Each balcony has a fan coil unit on the underside. There is one supply and four returns for each fan coil unit. The air is supplied at 18°C with 1,400 m /h for each balcony. A balcony with supply outlet and returns is shown in Figure 3.

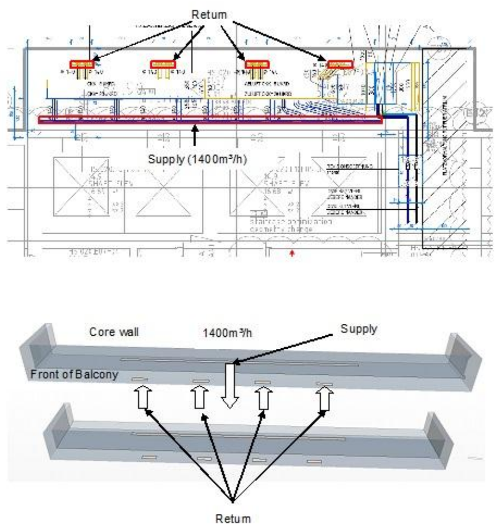


Figure 3 The balcony returns and supply outlets and their location

The balconies all have cooled floors, which help to keep the temperature on and around them between 18°C and 27°C. There are two revolving doors in both sides of the atrium. It is assumed that each revolving door has an inlet and outlet which allows the air to go in and out of the building.

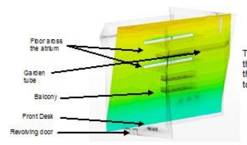
The physical models used for the simulations are the k-ε turbulence model, segregated flow, three dimensional, ideal gas and steady state conditions for solving the Navier Stokes and energy equations.

A performance model was run to obtain the boundary conditions for the wall and façade temperatures for the model. The simulation program used to run this model was EnergyPlus v6. The model was run for a year and the hottest and coldest days of the year were chosen from this model to be applied to the CFD model for the summer variations. The hottest day was July 21st with the hottest hour at 4pm, the outside dry bulb temperature at this time was 40°C (wet bulb temperature was 25°C). Based on the yearly results, surface temperatures of the core wall and different wall orientations of the atrium were obtained and used as inputs for the CFD model.

RESULTS

Temperature and Velocity Variations within the Atrium

The atrium has an average temperature of 31°C. According to Figure 4, the temperature on the ground floor is around 25°C and this slowly rises until it reaches around 36°C at the ceiling. The temperatures for summer comfort in the atrium are between 18°C – 27°C for any floor crossing the atrium and also for the balconies. The rest of the atrium should be at or below outside air temperature (40°C on the hottest day which is the situation the model simulated).



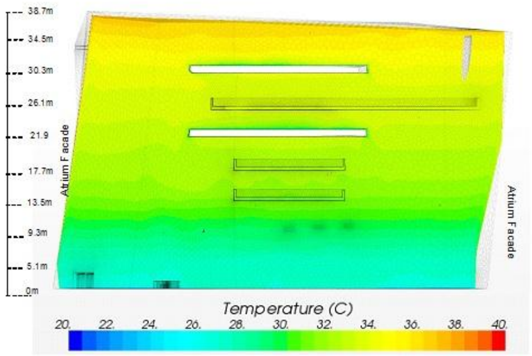


Figure 4 Temperature distribution in the middle of the atrium

Figure 5 is a graphical representation of the results seen in the slice. The height and temperature of each of the cells within this slice has been taken and plotted on the graph. The graph shows a fairly linear pattern; the higher in the atrium, the higher the temperature. The fourth and sixth floors that cross the atrium are cooled and as a result show a much lower temperature than the surrounding area. There are a couple of lines that show a higher temperature at the same height. These are the temperatures at the façade.

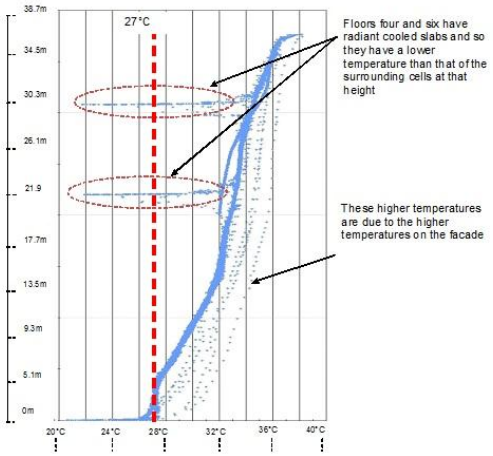


Figure 5 Temperature of the atrium at different heights

Figure 6 shows the velocity vector within the atrium. The velocity flow rates are between 0 m/s and 0.5 m/s. The facades see a greater velocity than the center of the atrium. This is because the facades have a hotter temperature than the interior so the air rises up faster. The air above is hotter and so when the cool and the hot air meet they move faster. The velocity here is still very low, at around 0.2 m/s.

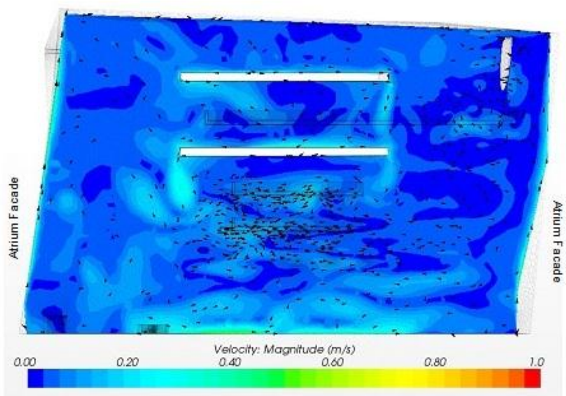


Figure 6 Velocity distribution in the middle of the atrium

Figure 7 shows the temperature distribution through the balconies. Overall the entrance hall (atrium1) shows stratification in temperature from 26°C on the bottom to

36°C at the top. The facades have a slightly higher temperature than the rest of the atrium.

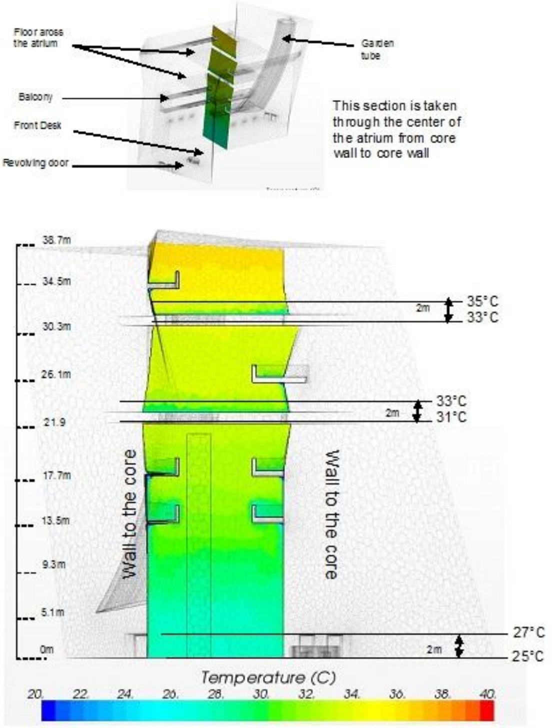


Figure 7 Temperature distribution through the balconies

Figure 8 shows the velocity distribution through the balcony. The fan coil units have air coming straight down from the balconies. The lower balcony has fresh air as well as the fan coil units; this is why the velocity is greater in this area.

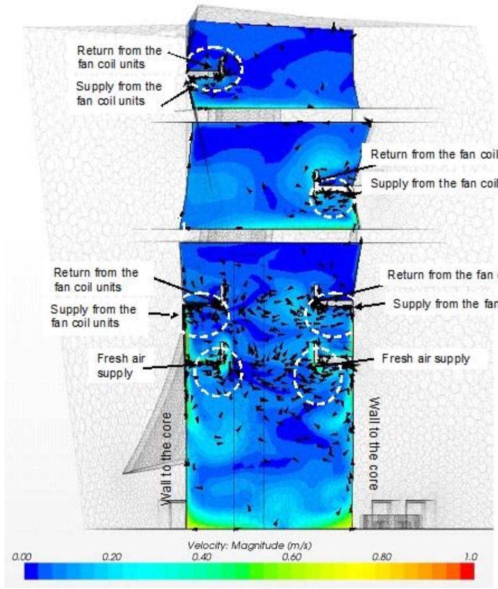


Figure 8 Velocity distribution through the balconies

The temperature on the ground floor is around 25°C to 26°C. This is within the temperature bounds required for the comfort of both the front desk and the people entering the atrium. The temperature on the fourth floor connection between the cores is around 31°C – 33°C. This is fairly hot and might be uncomfortable if there is a desk area here. The connection floor on floor 6 is very hot between 34°C and 36°C, which is likely very uncomfortable for anyone who might work there. The fresh air in the summer flows straight down from the diffusers under the balconies and the air from the fan coil flows straight down the core wall. The fresh air reaches the people by flowing under the balcony floor, joining with the supply air from the fan coil and moving down on to the balcony.

Optimizations, e.g. raising the air flow rates, lowering the supply air temperature and changing air injection angles are considered in the next step.

Variant 1 for Atrium 1

Technical details concerning the heating and equipment change in the new design procedure are as follows:

- Increased air flow was added to the Atrium 1 bridges in order to make the bridge floor more comfortable in the summer. 4 cooling outlets have been added to the lower part of the bridge balustrade with a 15 m length and a 0.49 m height from the bridge floor, considering that the maximum velocity coming out of the outlets is below 0.15 m/s with a combined flow rate of 16,000 m /h.
- Cooling unit on each balustrade of the bridge: 4,000 m /h each

- Outlet temperature of 18°C
- Two 3m×3m returns added beneath the upper bridge floor and on the ceiling

Figure 9 shows the new equipment with changes in the geometry.

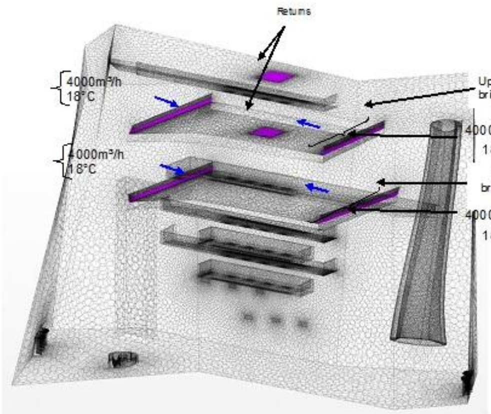


Figure 9 Variant 1 geometry

According to Figure 10, the temperature on the ground floor is around 24°C and this slowly rises until it reaches around 35°C at the ceiling. The atrium has a volume average temperature of 29.6°C.

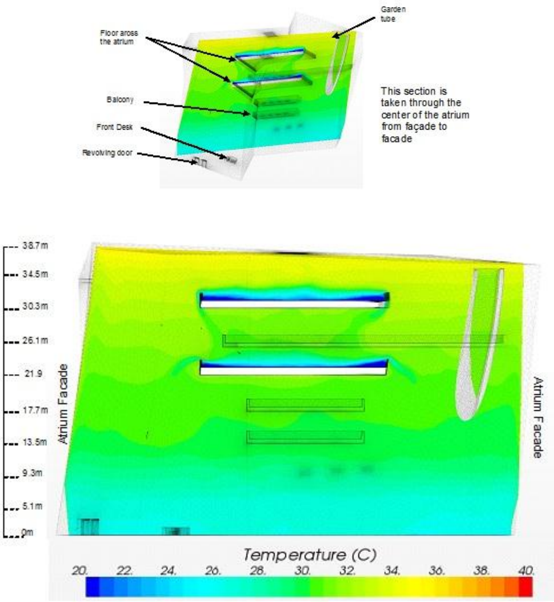


Figure 10 Temperature distribution in the middle of atrium

The cold air rises from the floor and flows over the balustrades which are 1m in height. This air flows down to the bridge underneath and then into the atrium as shown in Figure 11.

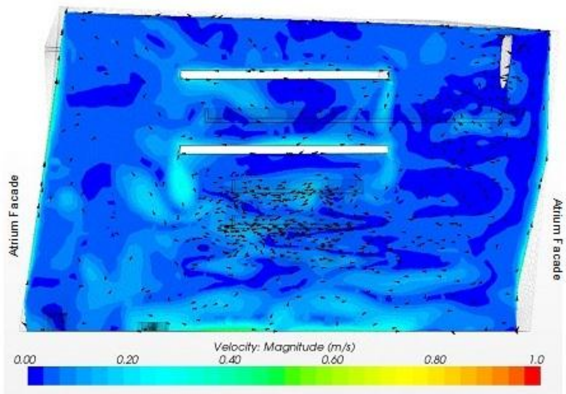


Figure 11 Velocity distribution in the middle of atrium

Figure 12 shows a section that is 0.25 m above the floor of the upper bridge. The temperature 0.25 m from the floor is fairly even at around 20 - 24°C. However, the temperature at the same level of the floor bridge and inside the atrium has higher temperature of about 32°C.

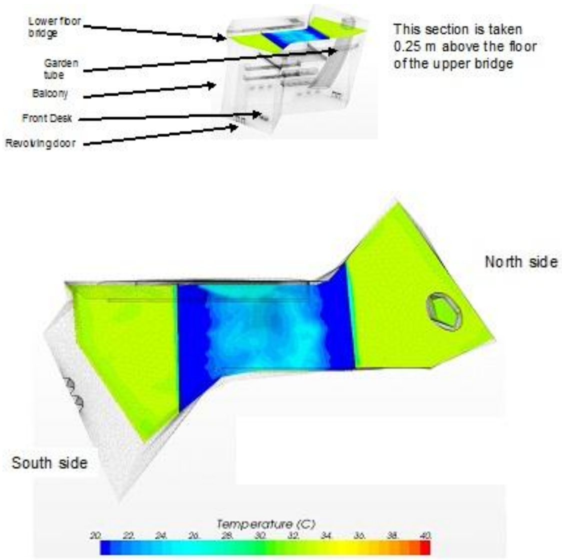


Figure 12 Temperature distribution in the middle of atrium

Figure 13 shows the velocity distribution 0.25 m above the floor of the upper bridge. The velocity above the floor is overall low between 0 and 0.2 m/s.

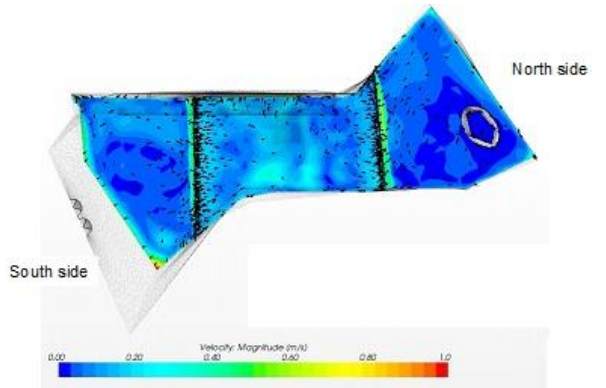


Figure 13 Velocity distribution in the middle of atrium

Overall the situation in Atrium 1 is improved in the summer. Atrium 1 has a lower average temperature (29.6°C) with a range of 24°C-35°C (deltaT of 11 K) between the ground floor and the top floor compared to the previous situation (31°C). The temperature on the bridges in Atrium 1 is improved and is in the range of the comfort level. The temperatures range from 20°C to 24°C.

The fresh air from the outlets flows along the floor on the upper bridge, and creates a more comfortable cooler environment than in the previous situation. The flow from the upper floor flows over the balustrades and falls on to the lower bridge. On the lower bridge, the thermal requirements are met and the temperature is between 20°C-24°C. The velocity is low and is between 0-0.2 m/s. The temperature on the balcony in the upper floors has improved but is still higher than the previous simulation.

Variant 2 for Atrium 1

Technical details concerning the heating and equipment change in the new design procedure are as follows:

- Increased air flow was added to the Atrium 1 bridges in order to make the bridge floor more comfortable in the summer. 8 cooling radial outlets with nominal diameter of 400 mm have been added 6.8 m above the lower and upper bridges with 2,000 m /h flow rates each and 18°C.
- 13 jet nozzles were added in the lower left part each 400 m /h, 14°C, angle of 10° to the lower part of the bridge balustrade with the maximum velocity of 10 m/s. 11 jet nozzles were added in the lower right part. 18 jet nozzles were added in the upper left and right parts each 400m /h, 14°C, angle of 75°.
- Jet nozzle returns are located 6.8 m above the lower and upper bridges on the right and left sides.
- Three returns were added on each upper and lower bridge floor with two right and left side returns with -2,000 m /h and the middle return with -4,000 m /h.

Figure 14 shows the geometry for the variant 2 simulation.

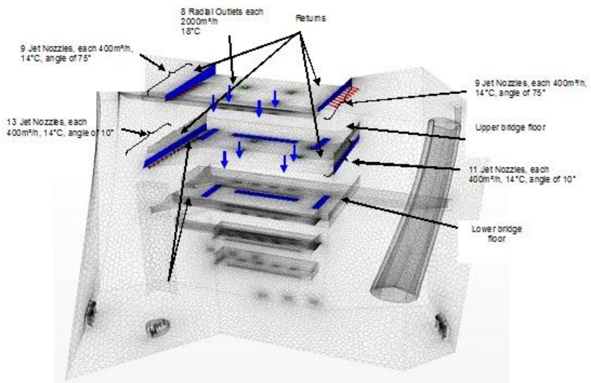


Figure 14 Variant 2 geometry

According to Figure 15, the temperature on the ground floor is around 24°C and this slowly rises until it reaches around 31°C at the ceiling. The atrium has a volume average temperature of 27.7°C.

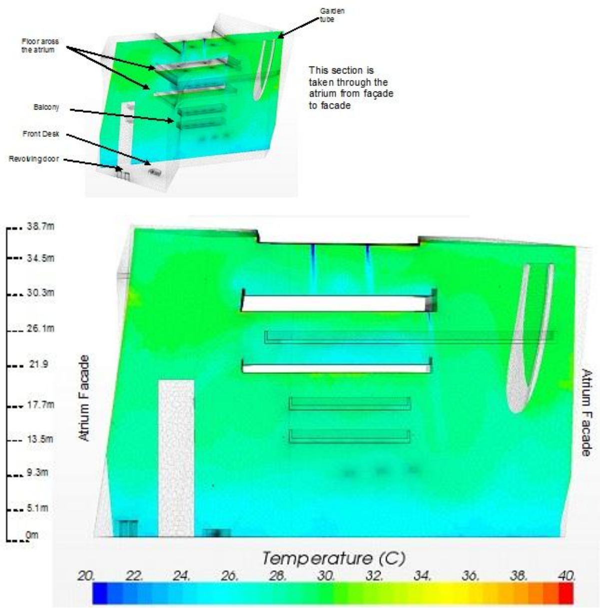


Figure 15 Temperature distribution in the middle of atrium

Figure 16 shows the velocity in the atrium. The cold air coming out of the radial outlets flows down onto the upper floor bridge and keeps the temperature comfortable on the bridge. The jet nozzles on the right and left hand sides act like an air curtain and separate the air in the atrium and the air above the floor bridges.

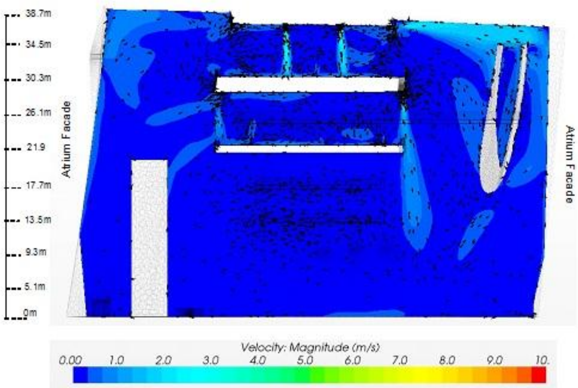


Figure 16 Velocity distribution in the middle of atrium

Figure 17 shows the temperature distribution 0.8 m above the floor of the upper bridge. The temperature 0.8 m from the floor is fairly even at around 20 - 24°C. However, the temperature around the floor bridge is about 30°C.

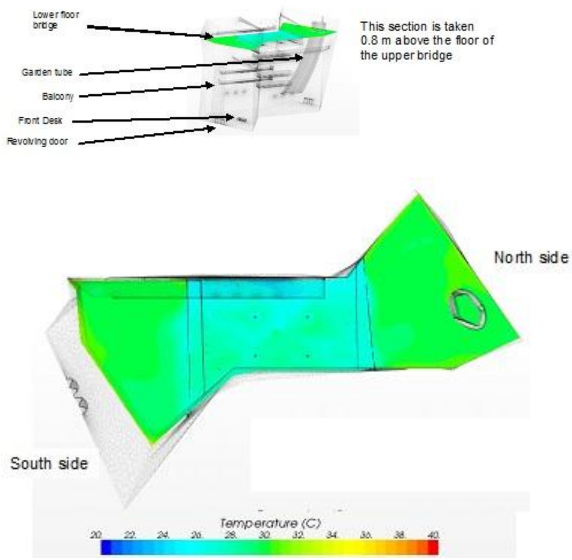


Figure 17 Temperature distribution in the middle of atrium

Figure 18 shows the velocity distribution 0.8 m above the floor of the upper bridge. The velocity above the floor is overall low between 0 and 0.2 m/s. however, the velocity is higher where the radial outlets push the air downwards.

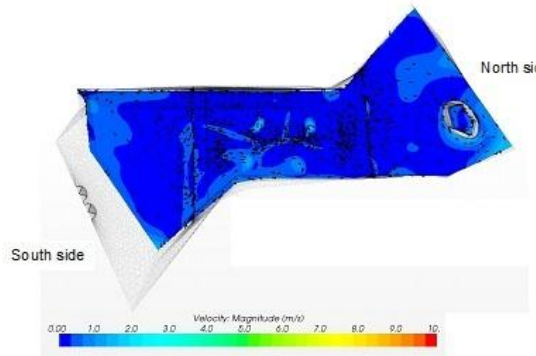


Figure 18 Velocity distribution in the middle of atrium

Overall the situation in Atrium 1 is improved in the summer. Atrium 1 has a lower average temperature (27.7°C) compared to the previous situations (31°C and 29.6°C). The temperature on the bridges in Atrium 1 is improved and is in the range of the comfort level. The temperatures range from 20°C to 24°C. The balcony also has a comfortable temperature compared to the previous simulations.

CONCLUSION

Atrium 1, with a height of 38.7 m was investigated in order to find the best mechanical design to have a comfort level of 18°C-27°C on the balconies and floors. The first simulation shows that the average temperature of the atrium is 31°C. The temepratures on the balconies and the floor bridges are not comfortable since they have a higher temeprature than 27°C. Therefore, the HVAC systems have been changed and the first new variant applied to the model. The avarege temeprature of 29.6°C is obtained with the new variant change, the floor bridge temeprature was improved and met the thermal comfort criteria. However, the temeprature on the balconies did not meet the criteria, therefore another modification was made to improve the model. Therefore the second new variant was designed and simulated. In the last simulation, the average temperature decreased to 27.7°C. Also the temeprature on the floor bridges and balconies met the thermal comfort criteria.

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