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Procedia Technology 22 (2016) 535 – 542

Procedia Technology

9th International Conference Interdisciplinarity in Engineering, INTER-ENG 2015, 8-9 October 2015, Tirgu-Mures, Romania

# Numerical simulation of HVAC system functionality in a socio-cultural building

Cătălin-George Popovici[a], Valeriu Sebastian Hudișteanu[a,]*

[a]"Gheorghe Asachi" Technical University of Iasi, Faculty of Civil Engineering and Building Services, 1, D.Mangeron, Iasi-700050, Romania

**Abstract**

The study presents the functionality of the heating, ventilation and air conditioning (HVAC) system for an important and prestigious objective of Iasi, the "Vasile Alecsandri" National Theatre. A numerical model was created, for the indoor climate analysis, obtaining the main thermal comfort parameters, in different zones of the auditorium. The model carried out on the CFD tool ANSYS-Fluent, is based on the recently implemented HVAC system of the theatre. The results are presented comparatively in two distinct scenarios of the ventilation and conditioning system: when the theatre is occupied and during the breaks. Results from simulation showed that the system provides suitable conditions for occupants and decorative finishing.

Peer-review under responsibility of the "Petru Maior" University of Tirgu Mures, Faculty of Engineering

*Keywords:* numerical modeling; HVAC system; indoor climate; thermal comfort; social and cultural building

## 1. Introduction

The functionality of the HVAC system and other building services is a very important target for all type of buildings and even more for locations with high density of people, such as theatres. An important and prestigious objective of Iasi is the "Vasile Alecsandri" National Theatre, Fig. 1, one of the most representative historical monuments of the city, rehabilitated and consolidated until 2012.

The main technical requirements of this project were heating, cooling and ventilation installations re-dimensioning. The existing installations have never been dimensioned for cooling. Another important requirement was the control of indoor air parameters, especially temperature and humidity.

* Corresponding author. Tel.: +4-074-632-8149.

*E-mail address:* seby_hudisteanu@yahoo.com


Peer-review under responsibility of the "Petru Maior" University of Tirgu Mures, Faculty of Engineering
doi:10.1016/j.protcy.2016.01.113

The novelty element of the project was brought by the humidity control extremely important for the preservation of paintings and architectural elements.

**Nomenclature**

| | |
|---|---|
| p | Pressure (Pa) |
| v | Overall velocity vector (m/s) |
| t | Time (s) |
| ρ | Density (kg/m$^3$) |
| τ | Shear stress (Pa) |
| g | Gravitational acceleration (m/s$^2$) |
| F | Force vector (N) |
| E | Total energy (J) |
| h | Enthalpy (J/kg) |
| J | Mass flux; diffusion flux (kg/m$^2$-s) |

The main condition for HVAC installations re-dimensioning was highly limited by imposing the use of existing air channels, including dimensions and shape as well as grilles, all embedded in concrete walls, floors or ceilings.

Fig. 1. The “Vasile Alecsandri” National Theatre, Iasi

Initial project was designed in 1896 by Koerting brothers in Paris, Fig. 2. and solved only the problem of heating using natural circulation air combined with mechanical ventilation.


Fig. 2. Initial project from 1896 [1]

After careful examination and verifications of status of these elements the followings have been established: they had irregular shapes and some were even blocked. Moreover, intervention inside the channels for widening or rehabilitation of interior surfaces was not possible seeing that the resistance structure of the building could have been affected.

Under these circumstances and according to scientific literature specifications, the solution implemented for "Vasile Alecsandri" National Theatre Iasi consists in 4 HVAC integrated systems serving: Main Hall, stage, foyer and adjacent areas. It is a multi-zone solution which divides the building into 3 areas whose utilization is never simultaneous:

- Zone 1- stall, lodges and balcony;
- Zone 2 - stage and orchestra pit;
- Zone 3 - foyer and adjacent areas.

Most important decisions made were: the placement of 6 air handling units (AHU) respectively - 4 inside the technical room at semi-basement and 2 in the attic of the building, thermal insulation and usage of overpressure room from stall and balcony and keeping all inlet and outlet grilles with initial dimensions respectively all air channels impeded inside the walls. It was only allowed dimensioning of air channels in the basement and attic according with technical requirements.

The air circulation for the Main Hall, Fig. 3, is achieved through three systems for fresh air supply: stall, lodge and balcony, and one system for exhaust air: ceiling. For Zone 2-stage, inlet air is introduced trough grilles mounted at floor level and in Zone 3 -foyer trough inlet grilles mounted in the concrete floor.

All 229 inlet grilles in stall zone are mounted in the floor, under the seats. At lodges, the inlet grilles are placed in the vertical air channels, while the balcony is connected through channels with the overpressure room, and the inlet grilles are in the tiers. The exhaust air from Main Hall is realized through twelve circular outlet grilles, symmetrically placed in the circular ceiling. The total airflow of the auditorium zone is of 21000 $m^3/h$, while the amount of the fresh air equals the exhaust air.

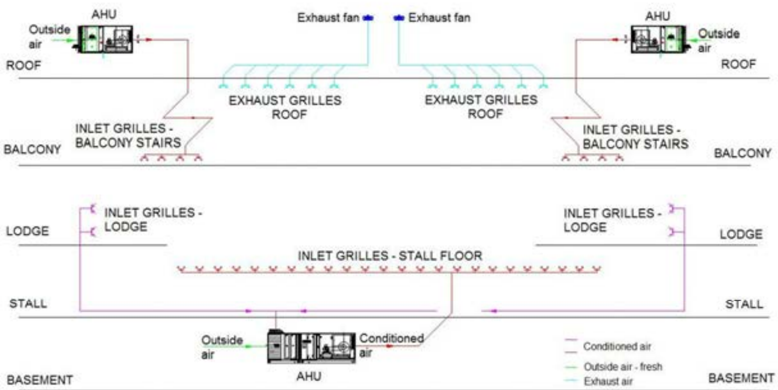



Fig. 3. Functional scheme of the HVAC system for Zone 1-Main Hall

The capacity of the theatre is about 800 places, which are often occupied during spectacles.

The purpose of this paper is to check if the recently implemented ventilation and air conditioning system is satisfying all technical requirements, taking into consideration all technical constraints on ventilation channel dimensioning as well as grilles number, shape and positioning due to architectural reasons. Thus resulted the need of simulation using specific software in the designing phase of the project and as well as understanding and interpretation of the results. This task was achieved by using the specialized software ANSYS-Fluent.

## 2. Problem description

The main problem in case of these types of buildings consists of high level of heat and vapor emission, when the entire auditorium is occupied. For modeling the phenomenon, a 2D model was created. The emissions were quantified properly for this type of approach by imposing heat and water mass fluxes, corresponding to maximum capacity of the objective. In literature there are many attempts to simulate air flow inside buildings and its effects over indoor climate [2] and also for the influence of the outside air circulation over interior climate [3]. This type of approach is also widely used in medical field, most of the time for obtaining preliminary information on the surgery or emergency ward climate [4, 5].

The thermal indoor climate, investigated in present study, is defined by the following parameters: air temperature, surface temperatures, air movements and relative humidity [6]. The HVAC system and the position of inlet and outlet grilles have an important role in order to provide these values.

## 3. Numerical approach

The numerical model was created for the indoor climate analysis, obtaining the main thermal comfort parameters, in different zones of the auditorium. In literature there are many attempts of using CFD software Fluent for simulating the airflow inside buildings [7, 8] or the impact of relative humidity [9]. The present model is carried out on the ANSYS-Fluent tool, which is appropriate for qualitative and quantitative evaluation of airflow and heat transfer inside closed domains [10]. The model is based on the real HVAC system. The 2D geometry, was created using ANSYS-Design Modeler with small control volumes, with refinements near the walls and near important areas, while the mesh was realized using ANSYS-Meshing. The geometrical dimensions used in model were those of the real building, Fig. 4. The resulting mesh consists of 5638 mixed cells, 12018 faces and 5884 nodes.

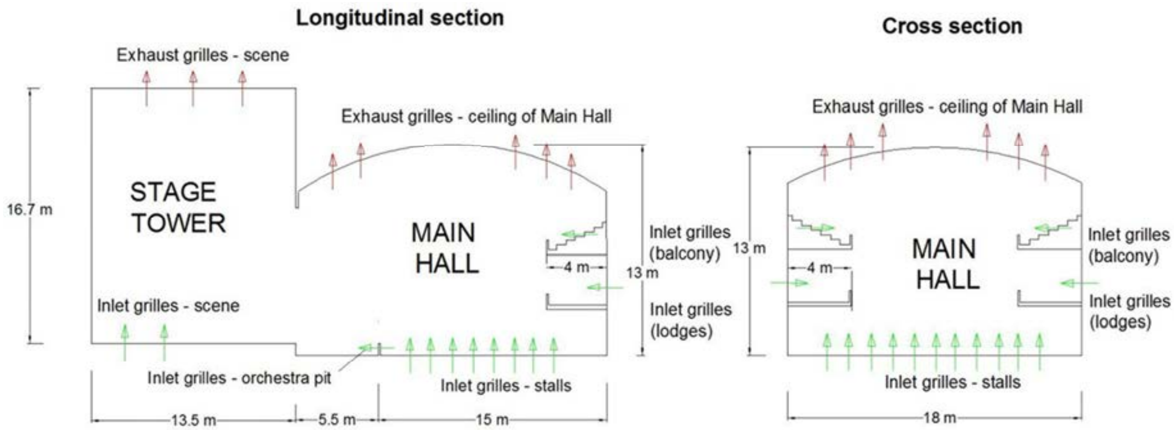



Fig. 4. Longitudinal section and cross section of the building

Applying the differential equations of heat transfer and fluid mechanics, the temperature, velocity and relative humidity data inside the main hall of the theatre were obtained. The CFD tool, ANSYS-Fluent, uses the finite-volume method to solve the following conservation equations [11]:

- Momentum equation:

$$\frac{\delta}{\delta t}(\rho\vec{v})+\nabla\cdot(\rho\vec{v}\vec{v})=-\nabla p+\nabla(\bar{\bar{\tau}})+\rho\vec{g}+\vec{F} \qquad (1)$$

- Energy conservation equation:

$$\frac{\delta}{\delta t}(\rho E)+\nabla\cdot(\vec{v}(\rho E+p))=-\nabla\cdot(\sum_{j}h_{j}J_{j})+S_{h} \quad (2)$$

- Continuity equation (conservation of mass):

$$\frac{\delta p}{\delta t}+\nabla\cdot(\rho\vec{v})=S_{m} \quad (3)$$

As boundary conditions, at the inlet sections, the conditioned fresh air temperature of 20 °C was imposed and the mass flow inlet, as an equivalent velocity for each grille, taking into account the 2D simplified geometry. The outlet sections were set as outflow zones. The external conditions imposed to the walls and windows in simulations were the air temperature of -18 °C and the convective heat transfer coefficient of 24 $W/m^2K$, typical for Iasi.

The Reynolds number resulted for the imposed velocities lays between 4310 and 13100, therefore, the flow regime considered is the turbulent one. There is no universal appropriate turbulence model that can be used for all types of flows. Therefore, an important task consists of choosing the appropriate turbulence model. In this numerical approach, the k-ε RNG model was used, which is considered the most realistic for air flow inside large domains [11]. The semi-empirical model k-ε is based on the transport equations model for the turbulence kinetic energy (k) and the dissipation rate (ε) [4].

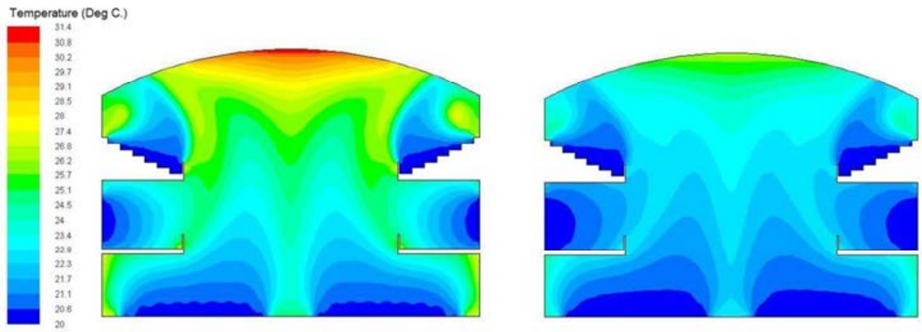
For modeling humidity inside building, the species model was activated. The two volumetric species used are air and water-vapors. The moisture sources were calculated taking into account that a group of people can be modeled as a mass flow inlet of water, with a mass flux proportional to the number of occupants and considering the 2D model similarity. According to [12], a sitting person produces around 70 g $H_20$/h. Applying heat generation rate under the circumstance of full occupancy, a constant source of energy of 100 $W/m^3$ was imposed.

## 4. Results

The results are presented comparatively in two distinct scenarios for the ventilation system: when the theatre is occupied - system is functioning at maximum capacity and during the breaks - emissions are lower and the ventilation system works at reduced load.

The extracted data are presented as contours, vectors and charts for different plans, at variable cross section heights. The numerical results show that the system provides suitable conditions for occupants and also for decorative finishing.

Fig. 5 and Fig. 6 show the important gradient of temperature in the investigated zone. Despite this, in the main areas where spectators are present, stall, lodge and balcony respectively, temperature measures between 20 °C and 23 °C. The temperatures are lower during breaks, when most of the people are outside the Main Hall. This is the favorable moment when the HVAC system can adjust the controlled values to the nominal ones.




(a) (b)

Fig. 5. Temperature contours in cross section (a) during spectacles; (b) during breaks

Fig. 6 presents more accurate quantitative values for vertical plans of 1m height – stall zone, 4m height – lodge zone and 7.5 m height – balcony zone, which are the most occupied areas. As expected, the temperatures have similar distributions in both moments, but with smaller amplitude during breaks, Fig. 6.

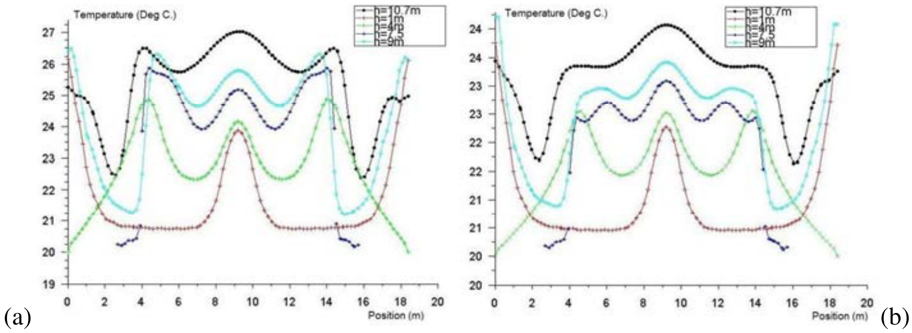



Fig. 6. Temperature chart (a) during spectacles; (b) during breaks

The contours of velocities, Fig. 7, show the main circulation zones of the fresh air. The inlet zones are supplying a proper ventilation of the occupied zones.

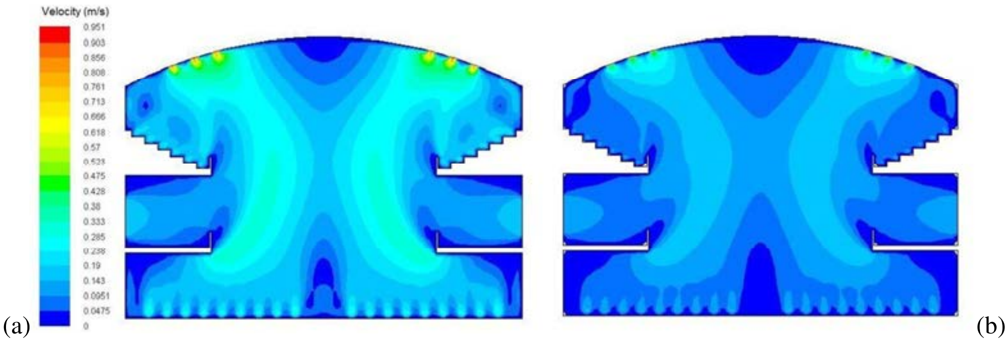



Fig. 7. Velocity contours (a) during spectacles; (b) during breaks

The average velocities are about 0.2 m/s and the peak values are recorded in the outlet and inlet zones, due to 2D simplified assumptions of the ventilation airflow. During breaks, when the HVAC system is at most half loaded, the air circulation is tempered. The same aspects are underlined by velocity profiles in the occupational zone, Fig. 8.

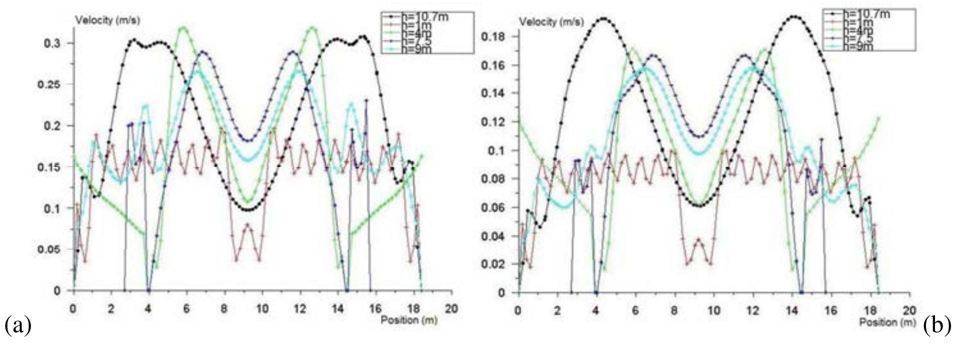
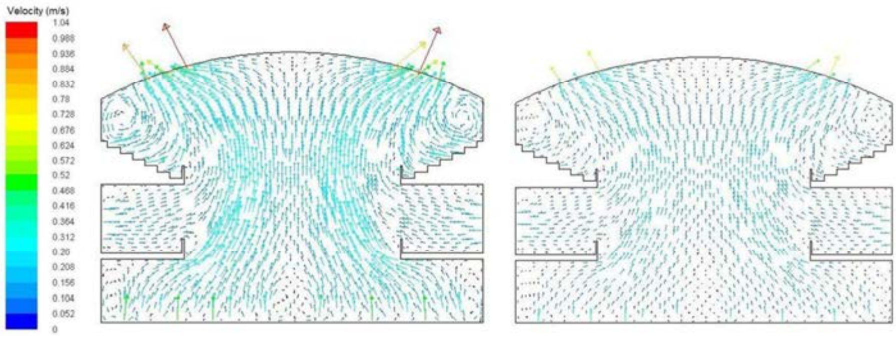



Fig. 8. Velocity chart (a) during spectacles; (b) during breaks

Fig. 9 shows the vectors of velocity in the study field. There are some differences between the studied cases, in terms of velocity magnitude, while the direction is almost identical. When seeking air velocity and direction, while the auditorium is occupied, we distinguish a very smooth air flow in the comfort zones. Some recirculation zones are recorded in the upper side of the hall, in the balcony zones, determined by the vicinity of the outlet grilles, but the velocities are below 0.3 m/s.




(b)

Fig. 9. Vectors of velocity (a) during spectacle; (b) during breaks

In terms of relative humidity, Fig. 10, values are placed into a relatively narrow range, between 50% and 65%.

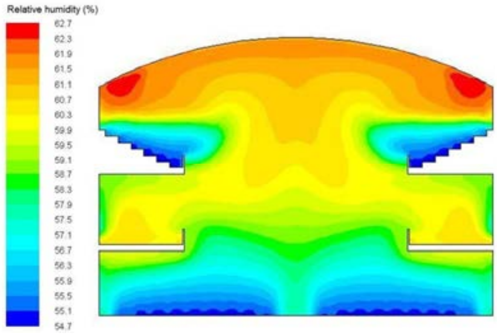



Fig. 10. Contours of relative humidity during spectacles

As expected, the highest values are recorded in the upper side of the room, but the amount of moisture of 65%, is not too high for determining condensation at ceiling and walls.

## 5. Conclusions

A 2D model was realized for the cross section of the building, taking into account the actual position of the inlet and outlet grilles of ventilation. The model was simulated using ANSYS-Fluent CFD package, considering the implemented HVAC system, and parameters like temperature, velocity and relative humidity were evaluated.

Considering the simultaneous effects of the results, the new installed HVAC system performed its contribution in maintaining the indoor parameters at optimum values in this historical, social and cultural edifice. Another effect consists of ensuring the comfort of people and integrity of paintings by humidity control.

This study shows that for this type of buildings, even during the winter season, when outside temperatures are very low, in particular moments, it could be necessary to cool the auditorium hall and evacuate the excess heat and moisture.

More general conclusions can also be drawn from the consolidation works analysis of the historical monument "Vasile Alecsandri" National Theatre. Interventions of such amplitude on objectives with cultural, religious or historical importance always have to take into account:

- Preservation of original architectural elements of the building;
- Adjustment of engineering design of specialized works with existent conditions;
- The limitation of air channels and grilles dimensions due to the initial architectural constraints; Close correlation between installations and construction works;
- Simulation with specific software, ANSYS-Fluent, in the designing phase and results interpretation;
- The importance of understanding and applying the simulations results by both engineering designers and architects.

This type of approach can be used for future projects in order to achieve functional systems that meet all the special requirements of buildings with national historical value.

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