Comparison of the thermal comfort and air quality in two Belgrade theatres with different mechanical ventilation systems

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Abstract

Using a newly refurbished Belgrade theatres, Belgrade Drama Theatre and Terazije Theatre, this study investigates weather two different mechanical ventilation systems are able to provide adequate thermal comfort and air quality and which one of them performs more satisfactory.

In order to achieve the given objectives the four faze work was carried out. The first was the analysis of different ventilation strategies implemented in the theatres using the 'as installed' engineering drawings. Next step was the continuous monitoring of the following parameters such as: carbon dioxide levels (indoor and outdoor), air temperature, relative humidity, air velocity, and heat flux through the walls. Third was a detailed occupant survey. Finally, a detailed three dimensional CFD modeling of one of the theatres (Terazije Theatre) was carried out.

It was find out that the measured air temperatures, air velocities , relative humidity and carbon dioxide concentration (CO_2) ware within the limits of thermal comfort standards, although temperature and CO_2 concentration were located at the extreme of the limits. Furthermore, the predicted results of Terazije Theatre showed good distribution of airflow characteristics and temperature gradients. Moreover, these were in agreement with the empirical measurements. In addition, recommendations were made to improve the thermal comfort, air quality and reduce the build-up of CO_2 concentration in the investigated theatres.

KEY WORDS – field surveys, thermal comfort, theatres, neutral and preferred temperature, ventilation

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CHAPTER 5: Data Analysis

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CHAPTER 1: Introduction

1.1 Background to the Dissertation

"Human comfort is conceived as a mental state of ease or well-beings, a state of balance or equilibrium that exists between a person and the environment" (Sontag, 1985). Moreover, the term "comfort" might be used to describe a feeling of contentment or a state of mental well-being. Comfort is a cognitive process involving many inputs influenced by physiologists, biologists, anthropologists, historians, sociologists, epidemiologists, geographers, urban planners and other processes.

The human being reaches conclusion about thermal comfort and discomfort from direct temperature and moisture sensations from the skin, deep body temperature, and the efforts necessary to regulate body temperatures (Hansel 1973; Hansel 1981; Hardy et al. 1971; Gagge 1937; Berglund 1995). In general people feel comfortable when body temperature is held within narrow ranges, skin moisture is low and the physiological effort of a human body to maintain thermal comfort is minimised. Guided by thermal and moisture sensation human mind undertakes some behaviour actions in order to reduce thermal discomfort such as changing the way of dressing, activity, posture or location, thermostat setting or opening a window, complaining or leaving the space. Although regional climate conditions, living conditions, and cultures differ widely throughout the world, the temperatures that people choose for comfort under like conditions of clothing, activity, humidity, and air movement has been found to be very similar (Fanger 1972; de Dear et al. 1991; Busch 1992).

However, as definition given in ISO 7730 (ISO 1994) implies, thermal comfort is subjective sensation. Thus, satisfying all persons in a given environment may provide to be difficult or even impossible in practice. For this reason, the realistic aim is to create a thermal e nvironment, which satisfies the maximum possible percentage of people in a given room taken as a group. The term "thermal neutrality" can be defined as the condition in

which a person would prefer neither warmer nor cooler surrounding (Detelin Markov 2002).

Nowadays, p eople s pend more a nd m ore t ime in doors. F or t his r eason indoor air quality (IAQ) and thermal comfort become the most important characteristics of the indoor environment. The heating, ventilation and air-conditioning systems, which can offer high IAQ and thermal comfort, become significant. Therefore, ventilation systems should provide the sufficient amount of fresh or conditioned air to the occupied zone while effectively removing the contaminants and extra heat (Wang Qiu-Wang and Zhao Zhen 2006).

Theatres are the most complex of the auditoriums structures, since more than one performance occurs in a day. Moreover, they operate frequently at high occupancy level, and tend to have higher sensible heat factors. Additionally, the stage present the great problem since it consist of loads such as: a heavy; mobile light load, delicate stage scenery, which varies from scene to scene and presents difficult air distribution requirements; actors, who may perform tasks that requires exertion. Therefore, low air velocities are essential and air must be distributed over a wide area with numerous supply and return registers. Finally, for all these reasons, careful coordination is required to achieve an affective and flexible layout (ASHREA Applications Handbook 2003).

In this dissertation both indoor air quality (IAQ) and thermal comfort have been analysed and compared in two theatres with different ventilation strategies:

a) a full mechanical ventilation strategy with an old masonry supplying duct system (Belgrade Drama Theatre).
b) a displacement ventilation strategy (Terazije Theatre).

Both theatres are located in urban areas of Belgrade, Serbia.

The main objectives of this dissertation could be summarized as follow:

a) to assess the occupational performance of two different ventilation systems in relation to IAQ and thermal comfort

b) to examine the relationships between the thermal comfort achieved and architectural design of the theatres

c) to analyze the suitability of different ventilation strategies to provide the adequate thermal comfort and IAQ

d) to investigate the relationships between the occupant perception of IAQ and thermal comfort and monitored/modeled IAQ and thermal comfort parameters

To achieve the given objectives the following work was carried out:

a) the analysis of different ventilation strategies implemented in the theatres using the 'as installed' engineering drawings

b) continuous monitoring of the following parameters:
  - carbon dioxide levels (indoor and outdoor)
  - air temperature
  - relative humidity
  - air velocity
  - heat flux through the walls

c) a detailed three dimensional CFD modeling of one of the theatres (due to lack of needed input parameters it was not possible to develop the CFD models of both auditoriums)

d) a detailed occupant survey

1.2 Structure of Dissertation

CHAPTER ONE clearly states the aims and objectives of the dissertation and includes a brief overview of the work which was carried out to accomplish the set objectives.

CHAPTER TWO gives an extensive literature review on thermal comfort and IAQ in theatres and other spaces of similar use, such as lecture theatres.

CHAPTER THREE defines the methodology used in this study.

CHAPTER FOUR describes surroundings of the two theatres and their interior. Furthermore, it gives a more detailed explanation of the two mechanical systems installed, and highlights the fundamental differences between two of them.

CHAPTER FIVE is aimed at presenting and discussing the obtained monitoring results such as: temperature (T), relative humidity (RH) and CO2 concentration. Furthermore, it gives calculations of air ventilation rates, which enables comparison of two mechanical ventilation system designed and their compliance with the established international standards. Finally, the chapter five also gives and explains results of the questionnaire surveys.

CHAPTER SIX presents, discusses and evaluates results obtained by CFD modeling of Terazije Theatre. This chapter begins with the model set-up, where basic building, HVAC and loads object had to be defined. Next is presentation of numerical results organized in five paragraphs, such as: verification of the designed displacement ventilation, where obtained pictures present the flow pattern by velocity vectors and air movement of both ground and gallery level; model verification, where comparison of measured and numerical data is presented as well as the evaluation of the thermal comfort and IAQ of the simulated theatre; thermal comfort indices presentation of the variables such as: air temperature, *PMV, PPD, DR* and relative humidity at two horizontal planes located at the ground and gallery levels; indoor air quality indices presentation, where the mean age of air (*AGE*) index and CO_2 mass fraction are presented at the same horizontal planes as the thermal comfort indices; and finally neutral thermal sensation, where the neutral conditions of the thermal comfort, defined by T, PMV, PPD, DR of relative humidity as well as indoor air quality AGE and ventilation effectiveness Ev are presented as iso-surfaces.

CHAPTER SEVEN summarizes obtained results and reaches the final conclusions.

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CHAPTER 2: Literature Survey

"In the historical accounts of engineers, comfort generally presumed to be definable human condition or attribute, with each new innovation bringing society closer to the achievement of ideal indoor conditions" (Heather Chappells and Elizabeth Shove 2004).

Historians represent comfort as the end point of a technical quest, driven by advances in engineering (Roberts 1997). Innovations in air conditioning and other forms of heating, cooling or ventilation are mainly viewed as technological solution to the problem of producing and maintaining environmental conditions that are beneficial for human health, comfort and productivity.

Nagengast (1999), writing about the development of air-conditioning in the early 20th Century in the United States, has described how mechanical systems were perfected such that a once expensive and problematic curiosity evolved into "comfort air-conditioning" for all. Further studies show how mechanical systems of cooling came to transform expectations of comfort in all sectors of daily life-including factories, cinemas, schools, offices, cars and homes (Arnold 1999, Donaldson and Nagengast 1994, Janssen 1999, Pauken 1999).

The main aim of conditioning the interior environments is to provide a comfortable and healthy indoor environment. There is increasing concern over the quality of the indoor environment as the standard of living improves in society. Epidemiologists and medical scientist have examined the relationship between extreme thermal conditions and patterns of heat or cold related deaths. Semenza et al conducted a study of health-related deaths during a record-breaking hot spell in Chicago in 1995 (Semenza and Rubin 1996). Their study shows that those most at risk of dying were people with pre-existing medical conditions, who were socially isolated and did not have access to air-conditioning.

Kroeling (1988) compares a number of surveys of "disorders" and complaints regarding comfort, well-being and health in air-conditioned buildings. The result shows that, compared to a control study of a conventional non-conditioned buildings, those in air-conditioned environments complained significantly more frequently of a tendency to colds, dry throats, headaches and irritability. W argocki et al (2002) reviewed scientific material on the effects of ventilation on human health, comfort and productivity in non-industrial indoor environments (e.g. offices, schools and homes). Moreover, they suggest that ventilation and air quality requirements embodied in many existing building standards are inadequate and may increase the risk of sick-building syndrome symptoms. Furthermore, this is a d isputable f ield, f or there are different views about what sorts of conditions are healthy for human beings and whether perceptions of "bad" environment relate to the actual conditions recorded indoor.

Even though, numerous studies have been conducted to explore the conditions of residential and commercial buildings such as lecture theatres, offices, schools, etc, in which occupants spend a large amount of their everyday time, just a few of them explore the conditions in theatres.

Because of the large occupancy and lighting loads, the sedentary nature of its occupants and high air change rates theatre environment poses a series of problems to designers. Theatres, unlike other building types, cannot in general use opening windows for air intake and extract, and therefore require a different approach. For this reason, ventilation strategies for these densely occupied spaces should be developed and tested using salt-bath experiments and real-building case studies, while taking into account the acoustic sensitivity of the theatre environment (ASHREA Applications Handbook 2003).

In addition to the studies focusing on IAQ and ventilation in theatres, the literature review includes the existing studies looking at the same problems in building with similar use such as lecture theatres, and concert halls. However, performance theatres differ from cinemas and lecture theatres in the following ways (ASHRE Applications Handbook 2003):

- Performances are seldom continuous. Where more than one performance occurs in a day, performances are usually separated by a period of 2 to 4 h accordingly; pre-cooling techniques are applicable, particularly for afternoon performances.

- Performance theatres generally play to a full or near-full house.

- Performance theatres usually have intermissions, and the lobby areas are used for drinking and socializing. The intermissions are usually relatively short, seldom exceeding 15 to 20 min; however, the loads may be as dense as one person per 0, 5 m2.

- Because sound amplification is less used than in cinemas, background noise control is more important.

- Stage lighting contributes considerably to the total cooling load in performance theatres. Lighting loads can vary from performance to performance

In recent years, thermal comfort studies have been guided with the help of CFD tools. Detailed simulations allow a far greater degree of flexibility in the design, making it easier to meet the aspiration of architects and clients. What is more, since building regulation relating to sustainability have become more stringent, detailed simulation makes designing easier to meet compliance requirements. Specialists are now able to predict potential problems in the design so that structural engineers can 'tweak' the building to achieve the desired outcome. Nowadays, modeling allows us to test both, the year-round thermal and environmental performance of the building as a whole, and the airflow in a single space within the building.

In order to conduct prediction of air movement and thermal comfort in a mechanically ventilated office module and naturally ventilated office Awbi and Gan (1994) used CFD modeling. Moreover, the study showed that CFD could be used to predict air flow and thermal comfort in mechanically and naturally ventilated spaces with enough accuracy.

In 1999, Cheong et al. used CFD tools to predict air flow in an air-conditioned seminar room for a tertiary institution, and simulated results were in close correlation with the measured one.

In 2001 K.W.D Cheong et al. employed objective measurements, CFD modeling and subjective assessments to evaluate the thermal comfort in a lecture theatre. The study was conducted on a lecture theatre in an institutional building in Singapore, where warm and humid climate dominates. Objective measurements of physical parameters were limited to air temperature, relative humidity, air velocity and concentration of carbon dioxide (CO_2). Thermal comfort was sifted, with the examination of various factors which affect thermal comfort, the conditions for thermal comfort, the predicted mean vote (PMV) index and predicted percentage dissatisfied (PPD) index. A questionnaire survey was administered to the occupants to determine their comfort impression and investigate their perception of the level of comfort in the lecture theatre. The simulated model had the same geometrical configuration as the lecture theatre and details such as furniture and heat sources were then inserted into the geometry. Measurements of thermal comfort parameters included: air temperature, air velocity relative humidity and CO_2 concentration were carried out for a 4-h period on 2 days at several locations in the occupied zone within the lecture theatre, at 1.0 m above the floor level. The air temperature was measured at the supply diffuser outlets and extract grille inlets using thermocouples connected to a data logger. Air velocity was measured over 3-min period using a hot –wire anemometer. Relative humidity was taken at 1-h interval using hand-held humidity meter. The indoor CO_2 concentration was measured continuously using a multi-gas monitor. Finally, they concluded that the physical conditions of temperature, air velocity and humidity were within the limits set by the ISO Standard 7730. However, the carbon dioxide concentration profile indicated that air-conditioning system was unable to cope with the peak occupancy load.

In 2001 K.A. Papakonstantinou et al. conducted a study entitled" Numerical Simulation of CO_2 Dispersion in an Auditorium". A CFD tool was used for the numerical simulation of CO_2 dispersion caused by breathing of the occupants inside an auditorium. Flow field description concerning air velocity and temperature inside the auditorium is also discussed.' The study examines two different ventilation systems, air induction and abduction flow rate, the number of the people and the lighting equipment. The ventilation

system is placed on t he ceiling of the auditorium. T he induction of t he ventilation system in the first case have dimensions 5m in x-direction and 2.25m in the z-direction, while in the second case the respective dimensions are 1 and 12m. The simulated model has the same geometrical configuration as the lecture theatre and turbulence phenomena are also accounted for. Obtained results are examined and compared to results which a re g iven in t he in ternational l iterature. T he c onclusion h as b een reached that obtained results are reasonable and correspond to the compared international literature.

In 2002 K.W.D Cheong and H.Y.T.Lau assessed IAQ status in lecture theaters with different occupancy patterns and internal loads in a tertiary institution. The IAQ assessment consisted of monitoring of thermal comfort, concentrations of carbon dioxide, carbon monoxide, formaldehyde, total volatile organic compounds, microbial counts and dust particles. Ventilation effectiveness, air exchange and age of air were also investigated. In order to provide a subjective assessment of the indoor air quality, questionnaires were completed by the staff and students. A studied lecture theatre has a seating capacity of 120 and is served by an AHU that is retrofitted in 1998. Four sampling points were selected in the occupied space and two sampling points were selected in the return duct and outdoor location, respectively. Local air effectiveness evaluation included measurements of local age of air at the three selected locations at the occupant level in the premise and an average age of air at the system exhaust. The questionnaire was divided into several sections concerning occupants' work, occupants' health, environmental conditions, individual control of the office environment and other aspects such as cleanliness and odour. Obtained results were analysed and compared with ANSI/ASHREA Standard 62-1989. The revealed problems were lack of fresh air and higher level of CO2. The recommended strategy to overcome those problems was to increase the ventilation rate.

In 2005 Kwang- Chul Noh et al. wrote a study on the subject "Thermal comfort and indoor air quality in the lecture room with 4-way cassette air-conditioner and mixing ventilation system". A lecture room had a seating capacity of 30. The ventilation system is composed of 4 supply diffusers, 4

exhaust ones, and a heating exchanger. The paper consists of experimental and the numerical studies on thermal comfort and indoor air quality in the lecture room with cooling loads when the operating conditions are changed. In addition, CO_2 concentration of the lecture room and predicted mean vote (PMV) value are measured in order to estimate thermal comfort and indoor air quality. Experiments were carried out for three cases, and CO_2 and PMV were measured two or three times for each case. Three sampling points were selected and placed at 1.1 m high from the bottom, and measuring time w as s et o n e very 5 m in. B oth P MV a nd CO 2 s howed r easonable agreement with each other and then numerical model to analyze thermal comfort and indoor air quality for a couple of different operation conditions were applied. From results it has been found that the increment of the discharged angle of 4-way cassette air-conditioner makes uniformity of thermal comfort worse but seldom affects indoor air quality. Thermal comfort and indoor air quality are hardly affected by the variation of the discharge airflow, and thermal c omfort is merely affected by the increment of the ventilation rate however, CO_2 concentration satisfies Japanese standards when the ventilation rate is more than 220 l/s.

In 2004, Amanda Gali Kenton et al. conducted a study entitled "Theory and Practice of Natural Ventilation in a theatre". This paper suggests established guidelines for natural ventilation in theatres as an alternative to mechanical ventilation. In order to demonstrate the importance of internal temperature and seating design as predictors of audience comfort, field surveys have been carried out in four naturally and mechanically ventilated case-study theatres. Monitored data have shown increases between 2-3°C during a typical performance.

According to analysis of mean sensation (ASHRAE scale) and preference vote results, an audience is most sensitive to maximum temperature during the course of a performance. The theatre environment can be pre-conditioned in such a way that the peak of the temperature curve occurs towards the end of a performance. In this way it is possible to account for the lag in thermal sensation and acceptability caused by slowing of audience

metabolic rate. Moreover, theatre seating is found to be the strongest predictor of overall comfort.

In 2005 C.A. Short and M.J. Cook in Design guidance for naturally ventilated theatres consider the reconstruction and redesign for natural ventilation of the UK's stock of performing arts buildings from the 1960sand 1970s. Many of these buildings are regarded as hardly fit for service because of badly maintained and noisy mechanical ventilation systems. The paper reviews interventions by the lead author in three such buildings: The Queens Building auditoria, The Contact Theatre (University of Manchester) and The Lichfield Garrick, intended to reduce their dependence on mechanical systems and improve their thermal comfort. After refurbishment, monitoring data suggested that these buildings perform well, but require high quality components and good controls. However, the crucial matter is an understanding on the part of the building owners of how the building management system is implemented, operated and maintained through the whole buildings' life.

In the conference paper entitled "Engineering and Ingenuity –Towards Environmental Design", Thomas R (2000) suggests that the chosen subject of the conference – "a global review of state of the Art HVAC" - is too narrow. Choosing the art HVAC as starting point is wrong. Instead, the beginning for designs which contribute to our environment and ensure the comfort of occupants should be the building form. Importance needs to be given to site, orientation, facade and section design, and materials. The applications of this approach have been illustrated by three varying U.K. case studies: The BRE Environmental Building, The Contact Theatre and Snape Maltings Concert Hall. These buildings cover a full range of HVAC issues in both new and refurbished buildings and in settings from city centers to rural land.

The Contact Theatre:

The existing mechanical ventilation system which had no function adequately for years has been replaced with a stack effect system with assistance from extract fans in the stacks. Air conditioning was considered

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but not chosen because of the high capital costs, ongoing maintenance and energy costs. The main design target was to ensure that the temperature in seated areas did not exceed the outside summer peak temperature by more than 3C°, the development of the design was assisted by extensive computer modeling. Air is led through attenuators and past concrete walls of high thermal mass for cooling. In the theatre air is introduced underneath the rear seats, then out through the chimneys which are equipped with three-bladed axial fans (for use in peak conditions) and attenuators.

Results from a heat load test showed that the 3C maximum temperature uplift criterion was satisfied. Further evidence that the building performs as anticipated is provided by monitoring actual performances during the summer.

Snape Maltings Concert Hall:

Conversion from redundant Maltings a short summer concert season was carried out in the late 1960s. Success and a full calendar of events led to improvement of summer internal conditions beyond what had been first considered. Venue had capacity for about 850 people. Refurbishment work included cooling for the hall; the existing heating and ventilation system installed consisted of a two-speed-supply fan, filter, heater and attenuators. The supply ductwork was sized to keep noise down and provide air velocity of 1.7m/s at low speed.

Cooling for the auditorium is provided by passing air over a heat exchanger that is chilled by ground water from a nearby 10m deep 200mm diameter borehole. Cooled air is pumped out of the ground at a temperature of about 10°C. Heating, ventilation and cooling are under the control of a building management system.

Monitored results show that on days with peak temperatures of approximately 28°C, internal conditions during full concerts are in the range of 24 to 27°C.

CHAPTER 3: Methodology

In view of the vital role played by perceptual and cognitive factors in the adaptive hypothesis, the preference should be given to data obtained from **field** rather than climate-chamber research. The reductionist, laboratory approach to comfort research runs the risk of stripping away those very aspects of thermal perception that are the focus of the adaptive hypothesis (McIntyre, 1982). The adaptive hypothesis indicates that one's satisfaction with an indoor climate is achieved by a correct matching between the actual thermal environmental conditions prevailing at that point in time and space, and one's thermal expectations of what the indoor climate *should* be like. Thermal expectations result from a confluence of current and past thermal experiences, cultural and technical practices (Auliciems 1981, 1989, de Dear 1993, Nicol 1993)

The approach in dissertation has, therefore, been to focus on research conducted in "real" buildings, occupied by "real" subjects going about their expected activities, which in this case are sedentary. In order to distinguish and identify various adaptive processes from the data, it has become evident in the research design strategy of dissertation that the field data need to be of a high standard. The purpose of this research is to investigate differences in the thermal comforts of two differently mechanically ventilated theatres by employing both objective measurements and subjective assessments. Therefore, the methodology proposed in this dissertation has been based on a few studies focusing on thermal comfort and indoor air quality in buildings of the similar use (K.W.D Cheong et al. 2001, K.W.D Cheong and H.Y.T.Lau 2002, Kwang- Chul Noh et al. 2005). These methodologies have been adapted according to the specific objectives of this study.

3.1 Feedback from occupants

The thermal comfort and IAQ revision will start with a discussion with the theatre facility management team that is responsible for the daily operation and maintenance of the air-conditioning and mechanical ventilation (ACMV) systems in the building. The feedback from the occupants, background of

the building and ACMV systems will support the thermal comfort and IAQ auditors to better understand the condition of the air quality in the occupied space qualitatively and to formulate preliminary scope of the revision for the occupied space.

Contacts with the facility managers of both theatres, Belgrade Drama Theatre and Terazije Theatre, will provide helpful information about daily operation an d s ome existing p roblems c oncerning (ACMV) s ystems an d audience complaints regarding thermal comfort and IAQ. Since both theatres have temperature and relative humidity monitoring, and Terazije Theatre in addition has automatic control of the (ACMV) systems, facility managers will provide access to these data as well. Furthermore, these contacts will help in making measuring strategy, since some of the used instruments needed electrical power supply.

3.2 Review of Mechanical drawings

A review of mechanical drawing will enable a better understanding of the relationship between ACMV design and other factors pertaining space layout, such as locations of supply and return grilles, fresh air intake and location of air handling units (AHUs).

The company Partner Engineering, which performed refurbishment of both theatres, has provided detailed AutoCAD drawings of theatre auditoriums. AutoCAD Drawing will enable planning of research methodology and choosing the location of the sampling points. Moreover, AutoCAD drawings will provide better insight and understanding of the ACMV systems and their performances.

3.3 Walkthrough

A walkthrough of the buildings is suitable for detecting any existing or potential pollutant sources, occupant's activities and the most important location of fresh air intakes, exhaust and air handling units. After the assortment of this information, it will be possible to decide about quantity

and location of the sampling points within the monitored space. After the collation of this information, main auditoriums of both theatres will be selected.

Belgrade Drama Theatre auditorium has one sloped ground level with capacity of 400 people, while Terazije Theatre auditorium, besides the ground level, has a balcony and total capacity of 500 people. Since Terazije Theatre is a music hall as well, capacity varies from performance to performance and is in range between 250 and 500 people. Both theatres are usually occupied between 19h and 22h, Monday to Friday. Three sampling points, 1-3, are selected in the occupied space with point 4 in the outdoor location.

3.4 Objective Measurements

Measuring methods and used instruments are in accordance with International Standard ISO 7726: Ergonomics of the thermal environment - Instruments for measuring physical quantities. According to this standard, any m easuring in strument w hich a chieves t he a ccuracy in dicated in t his International Standard, or even better, may be used.

Measurements will include monitoring of gases such as carbon dioxide (CO_2), and thermal comfort parameters such as air temperature (T), relative humidity (RH) and air velocity. These measurements will be conducted two times in each of the selected theatres at several carefully selected locations in order to ensure a good representation of human exposure to thermal comfort and air quality. The location of the indoor measurement locations will be based on the representative sample and on the layout of seats in the theatres.

In the Belgrade Drama Theatre, sampling points 1 and 2 were located near the outlets while sampling point 3 was placed in the corner of the auditorium in order to measure comfort parameters in the blind spot as shown in the Fig.1.

In Terazije Theatre, sampling point 1 was located at the balcony near the outlet while sampling points 2 and 3 were placed also at the balcony near the sockets, since used equipment needs power supply (Fig.2). All parameters were measured over a 5-min period. A 5-min period was chosen in order to find out how audience vacating the auditoriums at the breaks influenced the measured parameters. Especially, was interesting to see how the breaks will affect carbon dioxide concentration profile, since the pertinent source of CO_2 is human beings.
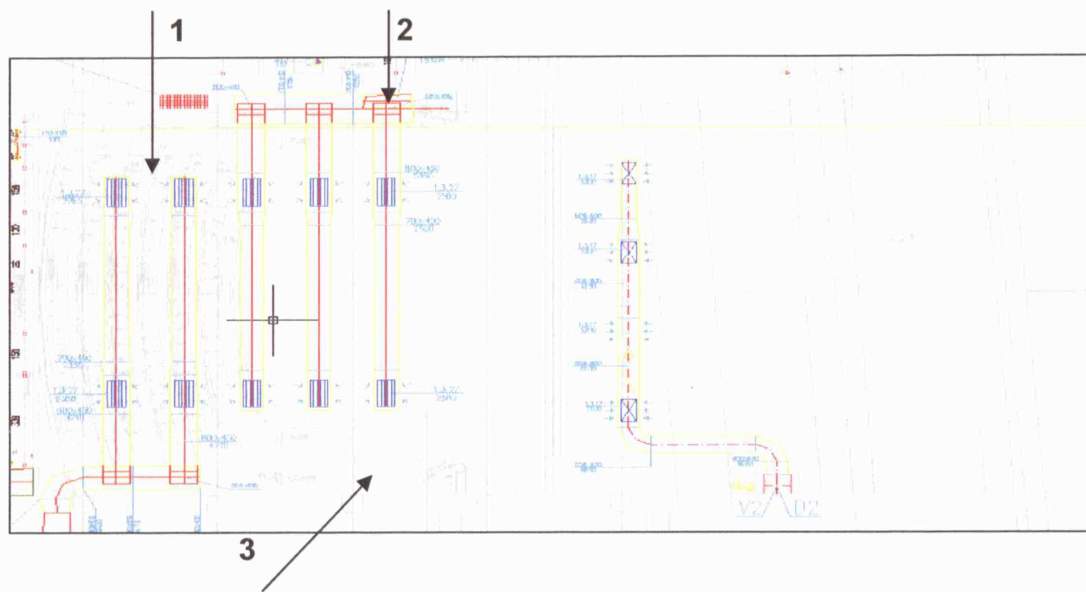
LOCATION OF THE SAMPLING POINTS

BELGRADE DRAMA THEATRE
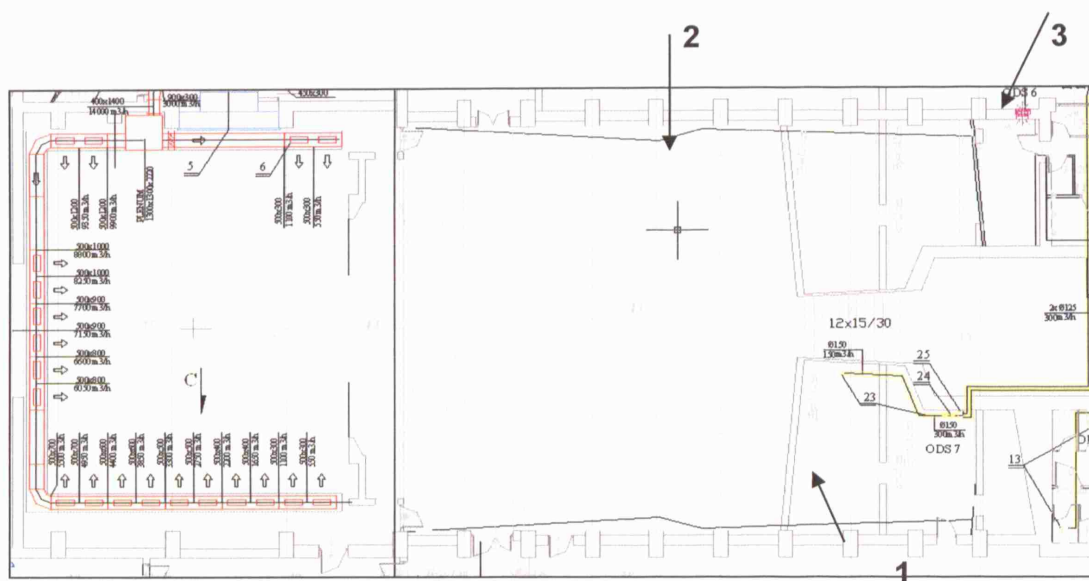
Fig.1.-Location of the sampling points

TERAZIJE THEATRE

Fig.2.-Location of the sampling points

3.5 Thermal Comfort Measurements and Carbon Dioxide Monitoring

The measured air velocities values were not exceeded 0.1 m/s at the head level of the occupants. Unfortunately, since the air velocity inside the occupied zone was below 0.1 m/s, available instrument Testo 400 with blade probe was not able to detect such a small value. Furthermore, it has to be noted that for CFD purposes, the air velocity was measured at the supply grilles in both theatres. The values recorded were as follows:

1. Belgrade Drama Theatre 0.4 m/s
2. Terazije Theatre 0.5 m/s

Two different sets of instruments were used for these measurements. Testo, Type 400 was used for measurement of relative humidity (RH), temperature (T) and carbon dioxide (CO2) in the sampling points near the outlets and measurement of outdoor parameters. Relative humidity (RH) was measured with capacity sensor, a pluck which works as condenser, while temperature (T) was measured with so called NTC sensor. NTC sensors are the best for temperature range between 20 and 50 ºC with accuracy of +/- 0.1ºC. Carbon

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dioxide (CO2) was measured with infrared sensor. Two HOBO instruments (attached to MY CO2) were used for measurement of RH, T and CO2 in the two other sampling points. The MYCO2 infrared gas sensor range offers high quality detection and measurement of CO2, using diffusion aspiration technology, to provide accurate and reliable determination of gas concentrations. Instrument operating temperature ranges from 0-45°C with an accuracy of +/- 0.2 of range.

In Belgrade Drama Theatre (Fig.1.), Testo 400 probes were attached to the outlet grille located on the left side of second half of the auditorium viewed from the sedentary position. The location of the two other instruments was conditioned by the position of the available sockets. One HOBO instrument (attached to MY CO2 instrument) was also located near the outlet grille, on the right side of the first half of the auditorium viewed from the sedentary position. Other HOBO instrument (attached to MY CO2 instrument) was placed in the top right corner of the auditorium viewed from the sedentary position in order to measure comfort parameters in the blind spot.

In Terazije Theatre (Fig.2.), Testo 400 probes measured T, RH and CO2. These probes were attached to the outlet grille imbedded in the ceiling at the balcony of the auditorium. Two other HOBO instruments (attached to MY CO2 instrument) were placed on the right and left sides of the balcony. These locations were conditioned by the position of the existing sockets. HOBO and Testo 400 instruments, measured all parameters over a 5-min period. Moreover, to provide a good representation of the examined thermal comforts and air qualities, all measurements were conducted two times in each theatre in the above described locations.

All parameters were measured shortly before the performance, during the performance and shortly after the performance. Regrettably, some CO2 data measured with MY CO2 have been lost since HOBO failed to record them.

3.6 Subjective assessment

In subjective assessments, a questionnaire surveys were conducted during the break of each play, twice in each theatre. Audiences of these auditoriums were requested to complete the questionnaire pertaining to thermal comfort.

The questionnaire was divided into sections, namely users' sex, users' health, environmental conditions, and other aspects of the auditorium environment such as cleanliness and odour. This was to assess the users' observation on the indoor air quality and investigate how people with some health problems, such as sinusitis or asthma, react to existing indoor environment. A sample of the questionnaire is shown in the Appendix A. The assessment of the thermal comfort and air quality was based on the audiences' vote on the thermal sensation, humidity and air movement in the auditoriums. A 3-point scale was used to evaluate thermal impression and sensation of comfort regarding humidity, air temperature, and air velocity. Unfortunately, in Belgrade Drama Theatre monitored performances did not have a brake. For this reason, only a few people managed to fill in the questionnaire. However, in Terazije Theatre both performances had a brake, and the response to the questionnaire was satisfactory.

3.7 CFD Modeling

3.7.1. Boundary Conditions and Related Sources

The unique solution of the coupled partial differential equations of the set of governing equations and turbulence transport equations can be obtained by specifying boundary conditions and related sources. There are some different classes of boundary conditions and related sources:

- Wall boundary conditions.
- Inlet boundary conditions.
- Outlet boundary conditions.
- Internal heat sources (persons, lightning, etc.).
- Internal water vapor sources (persons).
- Internal carbon dioxide sources (persons).

The most common practice of wall boundary conditions is well known logarithmic wall functions. The main idea of this practice is to bridge the first layer of numerical cells at the walls, not to be solved by differential equations, but empirically resolved by the logarithmic wall functions for all

dependent variables. Specific details about the logarithmic wall functions can be found in the broad literature on fluid mechanics.

3.7.2. Thermal Comfort Index Calculation

Important purpose of every indoor environment is to provide sensation of thermal comfort air quality for the occupants. Sensation of thermal comfort is related to environmental parameters, such as air temperature and air velocity, and to personal factors, such as metabolic heat production. The balance between the heat production by the body and the body heat loss, at a comfortable skin and body core temperature, depends on a set of environmental and personal parameters that result in a neutral thermal sensation.

In practice, the indoor environmental parameters are rarely optimal for achievement of thermal neutrality. In such case the thermal environment puts a strain on the thermoregulatory mechanisms of the body. The measure of this strain is provided by the *PMV* index, which is the Predicted Mean Vote of a large group of people subject to certain combination of environmental parameters. The vote is represented on the seven-point thermal sensation scale (ISO 7730-1994, ASHRAE 55-1992, CIBSE Guide A), which ranges from -3 (cold) to +3 (hot). The dissatisfaction with the thermal sensation is estimated using the *PPD* index (Predicted Percentage of Dissatisfied), which is calculated as a function of the *PMV* index. This is known as *PMV/PPD* approach of thermal comfort quantification.

-PMV determination

A person's sensation of warmth is influenced by the following main physical parameters, which constitute the thermal environment:

- air temperature (T_{ai})
- mean radiant temperature (T_r)
- relative air speed (V_{rel})

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- humidity (P_s).

Besides these environmental factors there are personal factors that affect thermal comfort:

- metabolic heat production (M)
- clothing (I_{cl}).

It is also required that there is no local discomfort (either warm or cold) at any part of the human body due to, for example, asymmetric thermal radiation, draughts, warm or cold floors, or vertical air temperature differences. The predicted mean vote (*PMV*) is given by the equation (ISO 7730-1994):

$$
\begin{aligned}
PMV = \left(0.303\,e^{-0.36M} + 0.028\right)\{&(M - W) \\
&- 0.00305[5733 - 6.99(M - W) - P_s] \\
&- 0.42(M - W - 58.15) \\
&- \left(1.7 \cdot 10^{-5}\right)M\left(5867 - P_s\right) \\
&- 0.0014\,M\left(34 - T_{ai}\right) \\
&- \left(3.96 \cdot 10^{-8}\right)f_{cl}\left[\left(T_{cl} + 273\right)^4 - \left(T_c + 273\right)^4\right] \\
&- \left[f_{cl}h_c\left(T_{cl} - T_{ai}\right)\right]\}
\end{aligned}
\tag{3.1}
$$

Where *PMV* is the predicted mean vote, *M* is metabolic rate (W/m² of body surface), *W* is external work (W/m² of body surface, 0.0 for most activities), f_{cl} is the ratio of the area of the clothed human body to that of the unclothed human body, T_{ai} is the local air temperature surrounding the body (°C), T_c is the operative temperature (°C), P_s is the local partial water vapor pressure in the air surrounding the body (Pa), h_c is the convective heat transfer coefficient at the body surface (W/m²K) and T_{cl} is the surface temperature of clothing (°C). The surface temperature of clothing (T_{cl}) is given by:

$$
\begin{aligned}
T_{cl} = 35.7 - 0.028&(M - W) - I_{cl}\left(3.96 \cdot 10^8\right) \\
&\cdot f_{cl}\left[\left(T_{cl} + 273\right)^4 - \left(T_c + 273\right)^4\right] \\
&+ f_{cl}h_c\left(T_{cl} - T_{ai}\right)
\end{aligned}
\tag{3.2}
$$

Where I_{cl} is the thermal resistance of clothing (m^{2}K/W). The ratio of the area of the clothed human body f_{cl} and the convective heat transfer coefficient at the body surface h_c are deduced by the following conditions:

$$\text{For } \left\{2.38\left(T_{cl} - T_{ai}\right)^{0.25}\right\} > 12.1\sqrt{V_{rel}}: \qquad h_c = 2.38\left(T_{cl} - T_{ai}\right)^{0.25} \qquad (3.3)$$

$$\text{For } \left\{2.38\left(T_{cl} - T_{ai}\right)^{0.25}\right\} > 12.1\sqrt{V_{rel}}: \qquad h_c = 12.1\sqrt{V_{rel}} \qquad (3.4)$$

$$\text{For } I_{cl} < 0.078 \text{ m}^2\text{K/W}: \qquad h_c = 1 + 1.29\,I_{cl} \qquad (3.5)$$

$$\text{For } I_{cl} < 0.078 \text{ m}^2\text{K/W}: \qquad h_c = 1.05 + 0.645\,I_{cl} \qquad (3.6)$$

It is very important to emphasize that in the case of CFD calculation, air temperature T_{ai}, relative velocity of body and surrounding air V_{rel} and the partial water vapor pressure in the air surrounding the body P_s are related to space coordinate. In other words, *PMV* is not constant value, it is the scalar field.

- Operative temperature determination

The operative temperature T_c combines the air temperature and the mean radiant temperature into a single value to express their joint effect. It is a weighted average of the two, the weights depending on the heat transfer coefficients by convection h_c and by radiation h_r at the clothed surface of the occupant. The operative temperature is defined as (CIBSE Guide A):

$$T_c = HT_{ai} + \left(1 - H\right)T_{ai} \qquad (3.7)$$

Where T_r is the mean radiant temperature (°C), H is the ratio of $h_c / (h_c - h_r)$. Researchers have differed in their estimates of the values of these heat transfer coefficients, and hence of the value of H. In CIBSE Guide the value of $(10v)^{0.5}$, where v is the air resultant velocity (m/s) is retained for the ratio of h_c to h_r, and so:

$$T_c = \frac{T_r + T_{ai}(10 \cdot v)^{0.5}}{1 + (10 \cdot v)^{0.5}}$$
(3.8)

Where T_r mean radiant temperature that can be determined either by analytical methods or by solving the included radiation model into the governing equations.

At indoor air speeds below 0.1 m/s, natural convection is assumed to be equivalent to the $v = 0.1$ m/s, and equation (3.7) becomes:

$$T_c = 0.5(T_{ai} + T_r)$$
(3.9)

- PPD determination

People are thermally dissimilar. Where a group of people is subject to the same environment, it will normally not be possible to satisfy everyone at the same time. The aim, therefore, is to create optimum thermal comfort for the whole group, i.e. a condition in which the highest possible percentage of the group is thermally comfortable.

As the individual thermal sensation votes will be scattered around the mean predicted value (i.e. *PMV*), it is useful also to predict the percentage of people who would be dissatisfied, taken as those who would vote >+1 or <−1 on the sensation scale. The Predicted Percentage Dissatisfied index (*PPD*) attempts to do this and is obtained from the *PMV* using the following equation:

$$PPD = 100 - 95\exp\left(0.03353 \cdot PMV^4 + 0.2179 \cdot PMV^2\right)$$
(3.10)

The *PMV/PPD* index is a mathematical model of human thermal physiology, calibrated against the warmth sensations reported by people during experiments in climate-controlled spaces. The index has not always been found to agree with the sensations reported by people in the circumstances of daily life. Reasons for these differences are diverse and not fully understood. In general, people are found to be more tolerant to diversity in

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ordinary circumstances than would have been predicted from the *PMV/PPD* model. The greatest systematic discrepancies occur when indoor temperature is warm and outdoor temperatures are high, when *PMV* predicts that people would be warmer than has been found in practice and in this circumstance empirical results from CFD studies should be preferred.

- Draught Rate (DR) determination

Although a person may feel thermally neutral as a whole, parts of his or her body could be subject to local cooling or heating, which may be rendered as unpleasant. This is an additional indication for the presence of local thermal discomfort. The most common local thermal discomfort encountered in ventilated spaces is draught. Draught is defined by ISO 7730-1994 and ASHRAE 55-1992 as unwanted local cooling of the body, caused by air movement. A measure of the discomfort due to draught is the Draught Rate index (*DR*) which expresses the percentage of people dissatisfied due to draught. It is dependant on both the resultant velocity and temperature of air, as well as on the level of turbulence intensity:

$$DR = (34 - T_{ai})(v - 0.05)^{0.62}(0.37 \cdot v \cdot In + 3.14)$$ (3.11)

Where *In* is turbulence intensity (%). In the case of CFD calculations, the turbulence intensity is defined as the ratio of the standard deviation of velocity fluctuations to the averaged value of resultant velocity by formula:

$$In = 100 \cdot \frac{\sqrt{k}}{v}$$ (3.12)

Based on the *PMV/PPD* and *DR* model, standard CEN CR 1752 (1998) defines three categories of thermal environment, which are listed in Table 4.

Table 1-Three categories of thermal environment (CEN CR 1752-1998)

CATEGORY	THERMAL STATE OF THE BODY AS A WHOLE		LOCAL DISCOMFORT
	PPD (%)	PMV	DR (%)
A	< 6	$-0.2 < PMV < +0.2$	< 15
B	< 10	$-0.5 < PMV < +0.5$	< 20
C	< 15	$-0.7 < PMV < +0.7$	< 25

Category A refers to high expectations, category B to medium and category C to mediocre expectations. To achieve certain category rating, a given thermal environment should satisfy all criteria listed in the table, along with the criteria for the rest of the local discomfort parameters, not included in Table 4.

3.8 The Prediction of Ventilation Rates

Carbon dioxide is an un-reactive gas and remains unchanged on entering the building and then adds to the carbon dioxide generated by the breathing of the occupants within the building. Because carbon dioxide is emitted as part of the metabolic process, the resultant increase in CO_2 concentration above the ambient outdoor value can be used as an estimate of the adequacy of ventilation. In this respect, CO_2 is considered as a tracer gas and, even at concentrations associated with unacceptably low ventilation, is rarely regarded as harmful. The rate of emission of CO_2 is dependent on the degrees of physical activity. Guidelines related to CO_2 concentrations almost always refer to sedentary environments and do not apply to areas of substantial physical activity (e.g. manual labor and sports activities). Also, it takes a finite period for CO_2 to reach a steady state level thus monitoring a space shortly after occupancy commences may give an erroneously low result.

This method was chosen for following reasons: there is no need for use of an artificial tracer gas; it gives the true ventilation rates in that it automatically accounts for the ingress of air from other parts of the building and it can be used during occupied periods to give time-varying results. Moreover, this method requires accurate information about the rate of CO2 production within the space, which sometimes could be a problem. However,

this matter did not affect measurements since number of people during the performances was constant (Coley D.A and Beisteiner A. 2002).

3.8.1 Occupied Periods

The rate of change in concentration of the monitored gas depends on the concentration of the in-flowing air, the concentration of the out-flowing air and the internal generation rate of the gas in question. The time derivative of the monitored concentration is given by:

$$V \, dC_{(t)} / dt = G + QC_{ex} - QC_{(t)} \qquad (3.13)$$

Solving (3.13) by integration leads to:

$$C_{(t)} = C_{ex} + G/Q + (C_{in} - C_{ex} - G/Q) \, e^{-Q t/V} \qquad (3.14)$$

Where:

$C_{(t)}$= internal concentration of tracer gas at time t (ppm)

C_{ex}= external concentration of the tracer gas (ppm)

G = generation rate of tracer gas in the space (cm3/s)

Q = internal-external exchange rate (m3/s)

C_{in} = initial concentration of the tracer gas (ppm),

V = room volume (m3),

Q/V = v = air supply rate (ac/s) and

t = time (s)

After examining the CO2 record, it was decided to apply equation (3.14). Furthermore, G, the production rate is assumed to be 20l/h, for grown up person what makes 5.5cm3/s.

CHAPTER 4: Installed Mechanical Ventilation Systems

4.1 Belgrade Drama Theatre

4.1.1 Location

Belgrade Drama Theatre is located at the Red Cross Square, one mile south-east of the city centre. Front façade, shown in the Fig. 3 and Fig.4, is facing the street of high traffic frequency causing air pollution, while side and back façades are facing the streets of lower intensity. In September 2002, the Municipal Government of the City of Belgrade entrusted company Partner Engineering with the task of drawing up plans and carrying-out a complete reconstruction of the Belgrade Drama Theatre. This 6500 m2 building - a former culture club, was built in 1948 and was not renovated or maintained ever since. Venue has finally been transformed into a real theater with a magnificent lobby, comfortable main auditorium (Fig.6), an exclusive convention hall, vast cloakroom and a fully equipped small auditorium.

Fig.3. -Front façade before reconstruction

Fig.4. -Front façade after reconstruction

Fig.5. –Side façade

Fig.6. -Main auditorium

4.1.2 Ventilation System

Mixing mechanical ventilation strategy is applied. In mixing ventilation the supply zone is usually above the breathing zone, and the best conditions are achieved when mixing is sufficiently effective so that the two zones merge to form a single zone (CIBSE Guide A). Photos of both the plate supply diffusers, imbedded into the ceiling, and square air extracting grilles, imbedded into the lower half of the side walls, are shown in the Fig.7 and Fig. 8. Enlargement of the outlet grilles was conditioned by the original building design. The previously constructed old masonry supplying and extracting ducts have been preserved.

Fig.7. –Inlet grilles

Fig.8. -Outlet grille

The installed air handling units/heat pump is made by "RHOSS", type: CWR/E 166. The air handling unit consists of supply and return chambers (Fig.9). Heat pump feeds three air handling units, which constitute four independent systems:

- System KL-1- air-conditioning of the small auditorium, the exclusive convention hall and the technical space on the second floor

- System KL-2 – air-conditioning of the main auditorium, the lobby, the technical space of the main auditorium and the lobby of the small auditorium
- System KL-3 – air-conditioning of the stage of the main auditorium and the first floor
- System KL-4 – air-conditioning of the acting club with buffet

All systems work with air recirculation, except system KL-4 which works with 100 % of fresh air. In the main auditorium the amount of air supply per one plate diffuser is 391l/s, while the total air supply is 3888l/s.

The heat pump is planned for heating during the transient periods, as well as during the night periods, when Belgrade power plant stops with energy delivery. Capacity of the heat pump covers 100% of systems' need when outside temperature is above -5°C. The devices work with a mixture of water and glycol which represents 35%. There is an automatic control of the ventilation system, as well as of the regulation of parameters at the central system level, which is made by "SIEMENS"-Landis & Staefa.
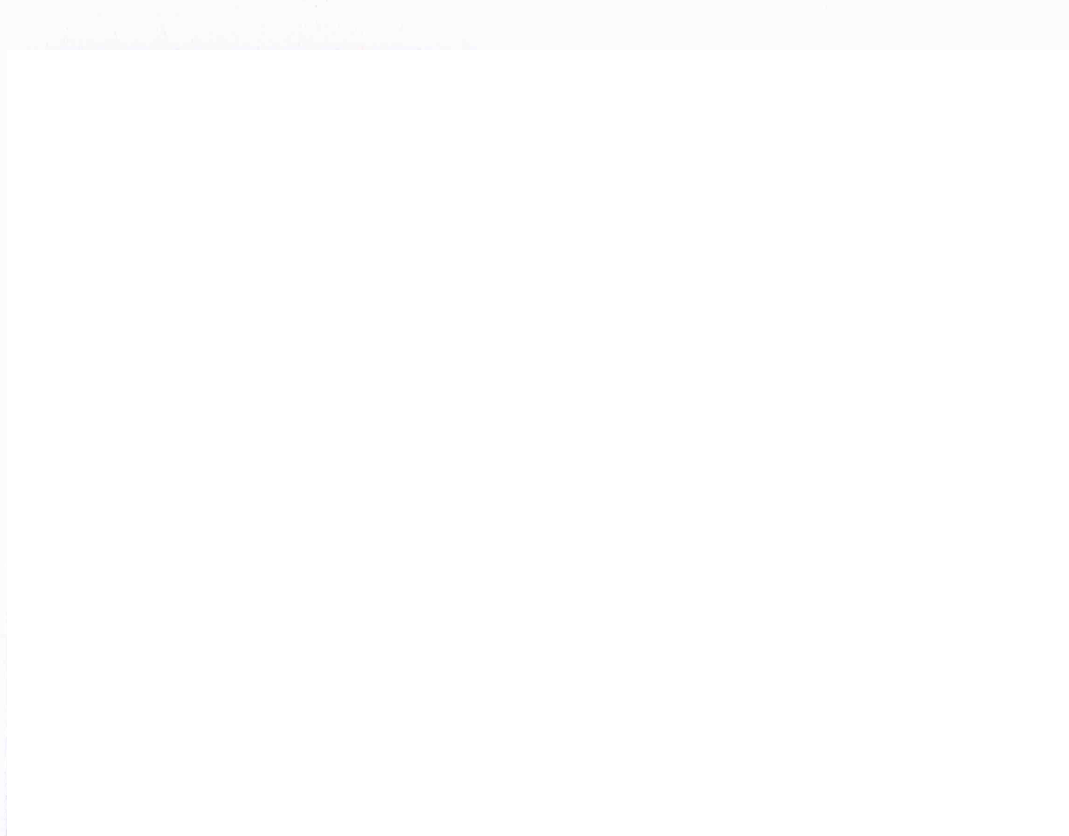
Fig.9.-Air handling unit of the main auditorium and lobby located in the basement

The following drawing 1 presents the principal scheme of the mechanical ventilation system designed in the auditorium. Since the drawing is protected by the company who carried out the work, the table in the lower right corner is not translated completely and some words remained in Serbian.

4.2 Terazije Theatre

4.2.1 Location

Terazije Theatre is located at the Belgrade central square which bears the same name. Theater capacity is nearly 500 persons depending on ground level seats arrangement. Traffic around the theatre building is very intensive; therefore it is reasonable to have a higher value of outdoor pollutant volume fraction, e.g. 460 ppm of carbon dioxide (averaged value during the measurement campaign). The main entrance façade (Fig.10.) is facing the street of high traffic frequencies causing air pollution. Side façade is facing Terazije Square, surrounded by two also very busy streets (Fig.11.), while back façade is facing the internal yard where air pollution is somewhat less intensive (Fig.12.). The reconstruction of the whole theatre building was finished last year. Photos of theatre interior are shown in the Fig.13 and Fig.14.

Fig.10. -Main entrance

Fig.11. -Side façade

Fig.12. -Backyard

Fig.13. - Terazije Theatre interior


Fig.14. - Terazije Theatre interior

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4.2.2 Ventilation System

From the HVAC point of view, a concept of displacement ventilation was introduced. In displacement ventilation the supply zone is usually at low level where the occupants are, and the exhaust zone is at a higher level. The best conditions are achieved when there is minimal mixing between the two zones.

Photos of both vortex air supply diffuser, mounted at ground and gallery floors directly under the seats, and round air supply diffuser imbedded into the ceiling above the lodges are shown in the Fig.15. Technical details of these diffusers are specified in Table 1 (Chapter: 6). Rectangular outlet grilles are imbedded into the ceiling at ground and gallery level (Fig.16.).
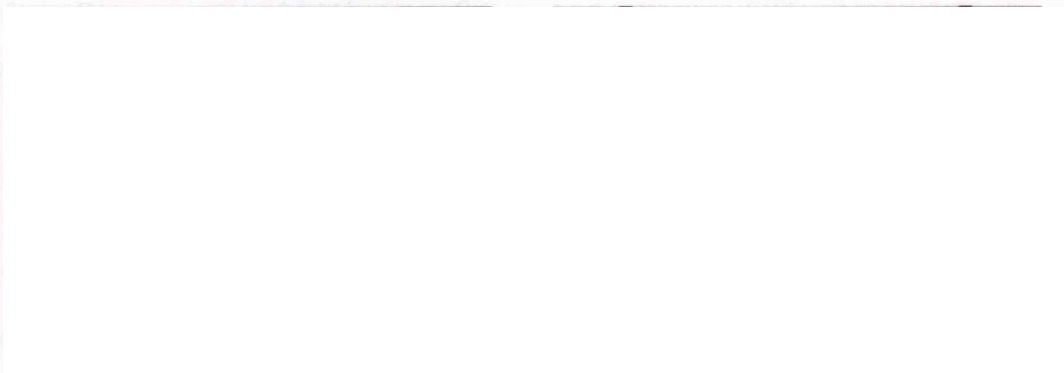
Fig.15. -Supply air diffusers (left-vortex at the floor, right-round at the lodge ceiling)
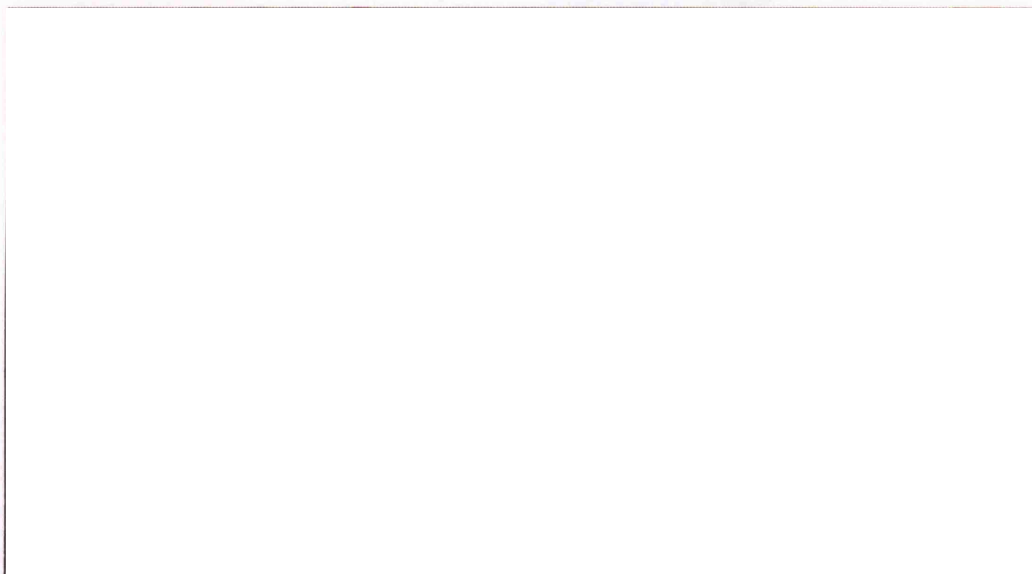
Fig.16. -Outlet grilles

The following systems of mechanical ventilation are designed:

- System V1 – air-conditioning of the auditorium
- System V2 – air-conditioning of the stage
- System V3 – air-conditioning of the lobby at ground level
- System V4 – air-conditioning of the theatre club
- System V5 – air-conditioning of the lobby at gallery level
- System V6 – air-conditioning of the rehearsal and ballet premises
- System V7 – air-conditioning of the rehearsal choir premises and of the cloakroom
- System V8 – air-conditioning of the rehearsal orchestra premises

All systems work with 100% of fresh air, except V1, which has recirculation of air. The amount of fresh air is 8l/s/p, and presents 60% of total air supply per person which is 13l/s/p.

The installed air handling unit/heat pump is low noise version made by "Mc Quay" type: MHP 171.2 (Fig. 17.). The device works with cooling agent FHFC 407C. There is an automatic control of the ventilation system, as well as of the regulation of parameters at the central system level, which is made by "SIEMENS".

Fig.17. -Air handling unit of the auditorium located on the roof

The following drawing 2 presents the cross-section of the mechanical ventilation system installed in the auditorium.

CHAPTER 5: Data Analysis

5.1 Thermal Comfort Parameters

This chapter presents, discusses and compares thermal comfort parameters temperature (T), relative humidity (RH) and air velocity obtained from monitored auditoriums of both theatres, Belgrade Drama Theatre and Terazije Theatre.

5.1.1 Belgrade Drama Theatre

AIR TEMPERATURE COMPARISON FOR DAY 1 AND DAY 2

Graphs below (Fig.18, 19 and 20) compare the measured temperatures in the auditorium during the monitoring period. During the both days the location of the instruments and the performance duration were the same.

The monitoring started 50 min before the beginning of the performances and ended 30 min after performances en ded. T o p repare the au ditorium for audience entering, space was cooled down to 22.1°C and 21.8 °C, respectively. However, when audience started entering the auditorium, air dry-bulb temperature rose for couple of degrees. On the first day around 60% of the auditorium was occupied, while on the second day the occupation percentage was 95%. This enabled evaluation of thermal comfort under almost the full occupancy. Air temperature curves in the Fig.18 and Fig. 19 reach similar peak values, while curves in the Fig. 20 follow the same pattern but without such abrupt temperature rises. This was expected since curves in the Fig.20 present the air temperatures recorded in the blind spot, where density of people was lower. Fig.18 and Fig.19 are recordings from the locations at the outlet grille and 1.5 m from the outlet grille, respectively (as shown in the Chapter 3: Methodology).

According to the curves plotted on the graph, Fig.18 that the air temperatures corresponded closely. Matching is especially noticeable for the period before and first 15min after the beginning of performances. This was expected as during the day 2 the auditorium was fully occupied. Furthermore, on the day 1 power delivery problems occurred and air-

handling units stopped working around 21h, while the performance was still going on. Immediately after that, temperature started to rise gradually. Till the end, the monitoring black curve, day 1, reached red curve, day 2, again.
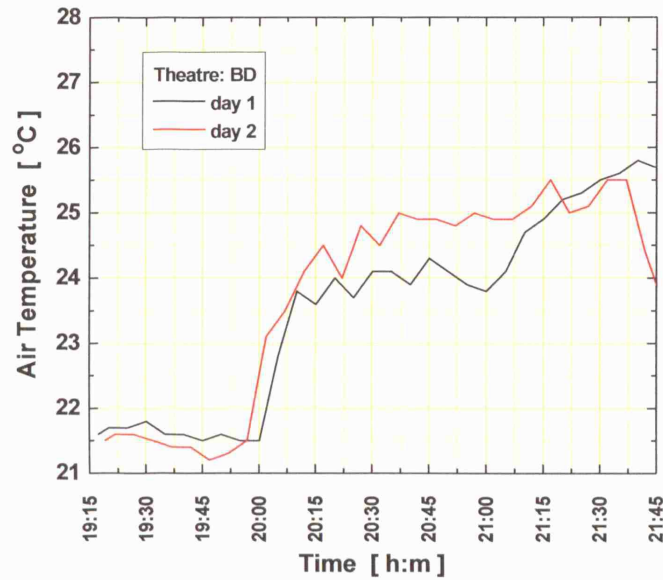

Fig.18. T (ºC) Graph -Location 1, Testo 400

Similarly to Fig.18, temperature curves in the Fig.19 correspond very closely for the first 50 min of the monitored time. Subsequently, the air temperature curve of the second day starts rising until the end of the measuring, when two temperature curves merge. However, overall temperature deviation of 1 ºC is negligible.
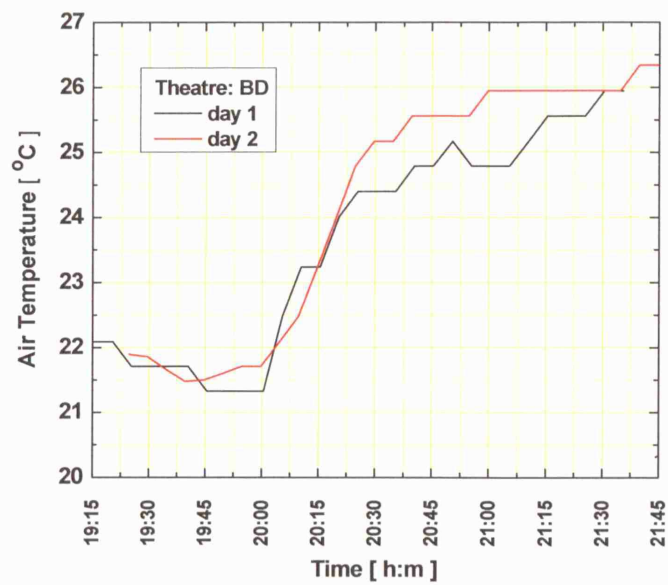
Fig.19. T (ºC) Graph -Location 2, HOBO

On the graph below, (Fig.20.), which presents data obtained in the blind spot, matching of two air temperature curves is also evident. Deviation of day 1 temperature curve, from day 2 temperature curve is less than 1 ºC.

Fig.20. T (ºC) Graph -Location 3, HOBO

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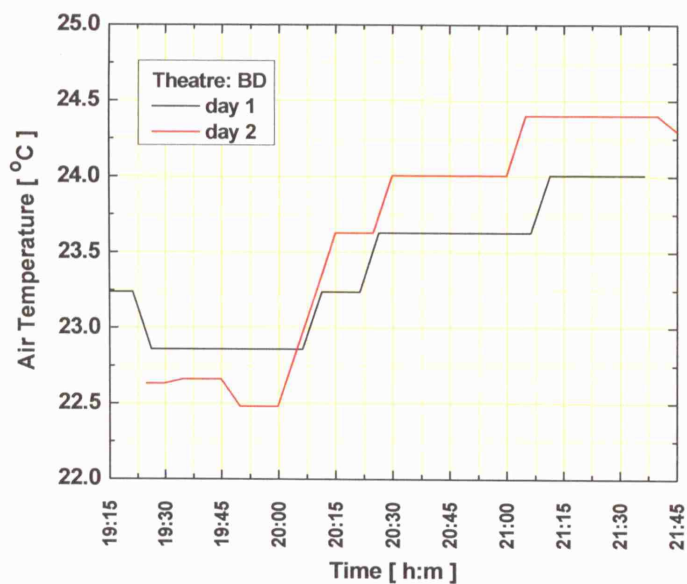
From the graphs above, it can be concluded that air temperatures for this auditorium correspond closely with a standard deviation of 1 °C. The mean air temperature for day 1 and 2 were 23.6 °C and 23.9 °C, respectively. Apart from the last peak probably due to the breathing while instrument was being taken off (Fig.18.), on day 1 air temperature ranged between 21.3°C and 25.9 °C, while on day 2 it reached values between 21.2 °C and 26.7 °C. On both days, temperature values exceeded lower limit of the acceptable range recommended by the ISO Standard 7730.

However, the facility manager explained that because of the noise which the mechanical system produces, it works in the lower regime during the performances. For this reason, the auditorium is cooled down below the recommended limits for a short period before the performance, in order to provide the adequate thermal comfort. The Tables 2 and Table 3 below present the outdoor air temperatures and minimum, maximum and mean air temperatures for each location for both days.

Table 2-Outdoor air temperatures

| OUTDOOR AIR TEMPERATURE T (°C)					
Date/Time	18h	19h	20h	21h	22h	23h
19.06.2006.	30.7	28.9	26.7	25.0	24.4	23.3
20.06.2006.	24.3	24.5	24.0	23.7	23.3	22.3

Table 3-Measurements of air temperatures for Belgrade Drama Theatre

Locations	Minimum Air Temperature(°C) Day1/Day2	Maximum Air Temperature(°C) Day1/Day2	Mean Air Temperature (°C) Day1/Day2
1	21.3 / 21.2	26.2 / 26.8	23.6 / 23.8
2	21.3 / 21.7	25.95 / 25.9	23.6 / 23.6
3	22.8 / 22.5	24.0 / 24.7	23.4 / 23.7

Graphs below (Fig. 21, 22 and 23), show that relative humidity fluctuates relative to the recorded locations much more than the air temperatures do. This difference is the most evident at the beginning of the monitoring when auditorium was still empty. Moreover, relative humidity like the air temperatures was somewhat higher on the second than on the first day. This could be explained by the full auditorium and higher outdoor humidity on the second day. Especially high outdoor humidity affected rise of indoor relative humidity since the both doors, from the theatre and the auditorium, were open while audience was entering. Yet, all three graphs follow the occupancy pattern, their entering, applause at the end of the performance and their vacating.

Relative humidity curves in the Fig.21 correspond closely. Deviation of day 1 curve, from day 2 curve is not more than 2%. Higher relative humidity at the beginning of the measuring is due to the run of the mechanical ventilation system just before instruments were set up. Moreover, since Testo 400 probe was attached to the outlet grille, for the first 45 min instrument was recording relative humidity of the stale air. After audience sat down around 20h, relative humidity started to decrease drastically until the end of the performance at 21:20h when it rose again to 63.4%. The main cause of humidity increase at 21h on the first day was power delivery failure. Last peaks on both curves are due to the audience vacating and breathing while instrument was taken down. Relative humidity at this location on day 1 and day 2 ranged between 58.7% and 65.9% and between 60.1% and 67.9%, respectively.
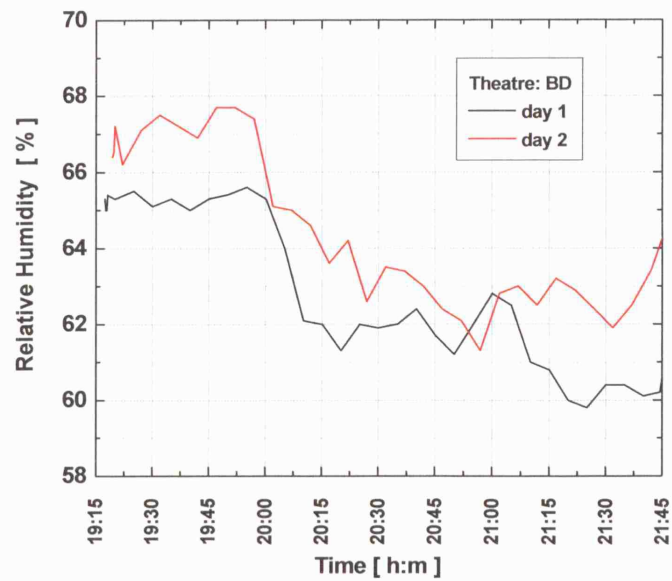
Fig.21. RH (%) Graph -Location 1, Testo 400

Once more correspondence of two curves in the Fig.22 shows that relative humidity recorded at the location 2 was similar on both days, with a standard deviation of 2%. Moreover, both curves reach peak values soon after 20h, when audience enters the auditorium and takes their seats. Second, but less abrupt humidity rise happens in the end of the performance while audience is applauding and vacating the auditorium.

Similar to the air temperature, relative humidity on the second day was somewhat higher than on the first day. Humidity at this location on day 1 and day 2 ranged between 52.2% and 65.5% and between 54.4% and 68.6%, respectively.
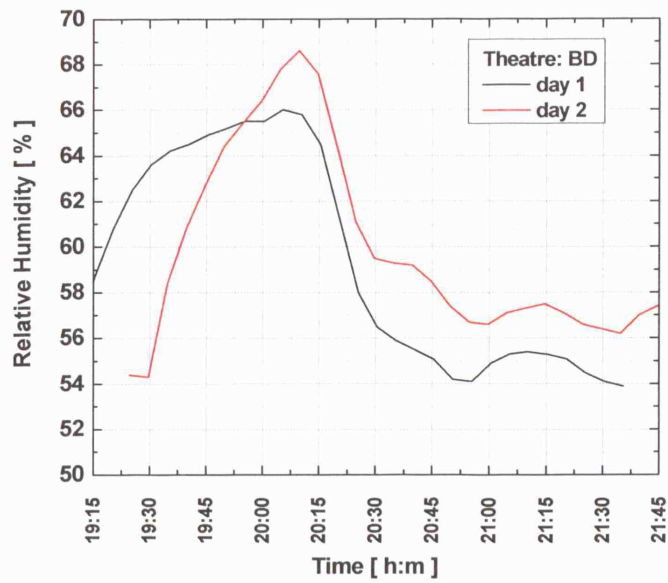
Fig.22. RH (%) Graph -Location 2, HOBO

Relative humidity curves given in the Fig.23 follow the same occupancy pattern. Similar to Fig.22, humidity curves correspond closely, with a standard deviation of 2%. Moreover, Fig. 23 presents the lowest recorded relative humidity values. This was expected since instrument was located in the corner of the auditorium where the density of people was lower. Relative humidity at this location was within 42.7% and 50.1% on the first day and within 42.3% and 51% on the second day.
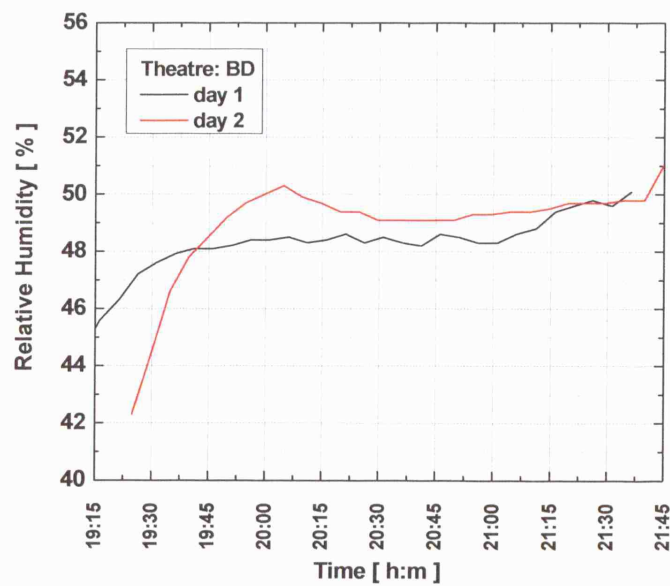
Fig.23. RH (%) Graph -Location 3, HOBO

The mean relative humidity was, 56.5% on day 1 and 57.7% on day 2. All recorded values between 42.3% and 67.9% are within recommended range for acceptable indoor quality of 30%-70% from the ISO Standard 7730. The Table 4 and Table 5 below present outdoor relative humidity and minimum, maximum, and mean relative humidity for each location for both days.

Table 4-Outdoor relative humidity RH (%)

OUTDOOR RELATIVE HUMIDITY RH (%)						
Date/Time	18h	19h	20h	21h	22h	23h
19.06.2006.	34	40	45	48	57	59
20.06.2006.	65	63	64	65	71	74

Table 5-Measurements of relative humidity for Belgrade Drama Theatre

| Locations	Minimal Relative Humidity (%) Day1/Day2	Maximal Relative Humidity (%) Day1/Day2	Mean Relative Humidity (%) Day1/Day2
1	58.7 / 60.1	65.9/ 67.9	62.6 / 64.2
2	52.4 / 54.3	66.0 / 68.6	58.9 / 59.9
3	42.76 / 42.3	49.8 / 51.0	48.0 / 48.9

CO2 CONCENTRATION COMPARISON FOR DAY 1 AND DAY 2

The exposure period was between 8h time –weighted average (TWA) and short-term exposure limit of 15 min (STEL). Moreover, there is no recommended threshold value from established standards of guidelines for this period of time. However, it is noted that occupants in these situations were allowed to have a much higher level of exposure. In the theatre, the main source of CO_2 was human beings. Therefore, CO_2 profile followed the occupancy pattern. Furthermore, it is observed that CO_2 build-up rapidly from the moment audience entered the space.

From the Fig.24 it is perceived that CO_2 concentration curves correspond closely. Full auditorium on the second day caused higher CO_2 concentration during the most of the time. However, after air-handling units stopped working at 21h on the first day, CO_2 concentration increased so rapidly that at the end outstripped the red curve (day 2). Thus, it can be concluded that CO_2 concentration was the most affected by the power delivery failure.
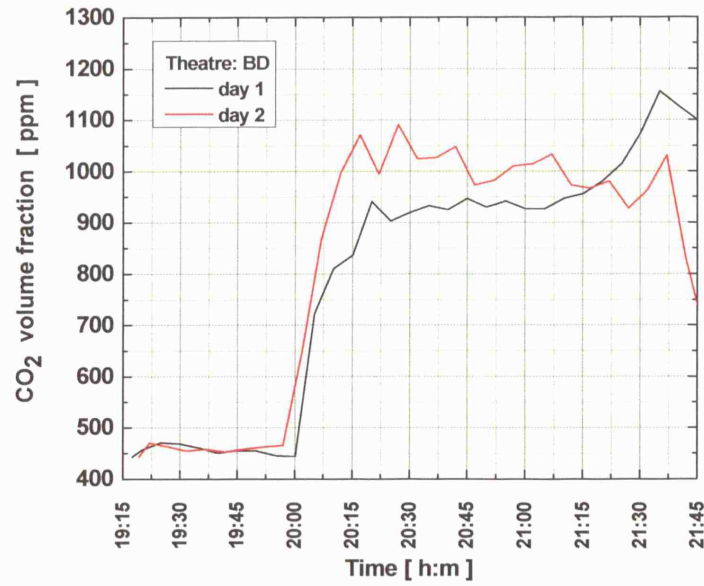
Fig.24. CO2 (ppm) Graph -Location 1, Testo 400

It is observed that the CO2 concentration in the Fig.25 also follows occupancy pattern. The concentration of CO2 increased as audience entered the auditorium and reached a peak of 1170 ppm at the end of the performance. However, once the audience vacated the space, the concentration decreased drastically.
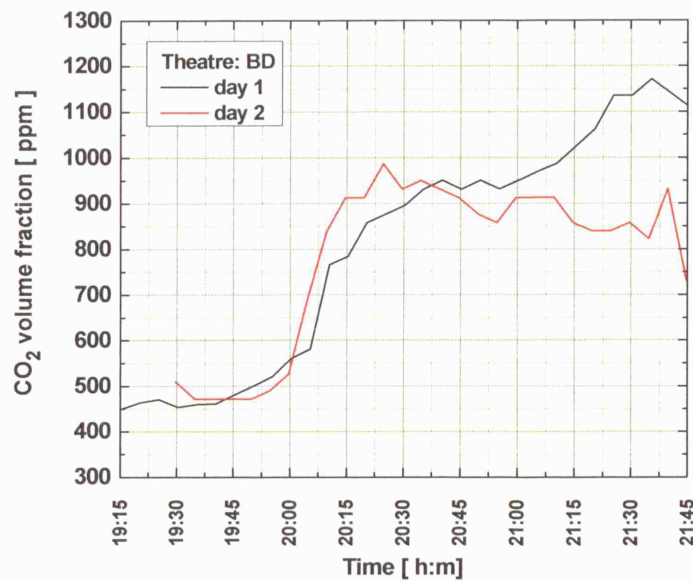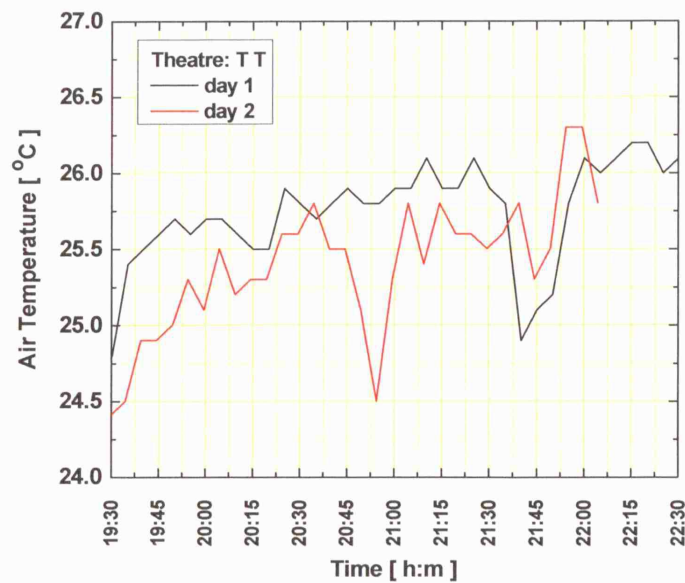
Fig.25. CO2 (ppm) Graph -Location 2, HOBO

The concentration measured over the period of monitoring ranges between 450 and 1179ppm with an average concentration of 871 ppm and 803 ppm, respectively. Mean concentrations are below the 8-h recommended threshold value of 1000 ppm. Even though CO2 concentration was occasionally above 1000 ppm, this may not present the issue of concern as the recommended threshold values should be more than 1000 ppm for 2h exposure. Nevertheless, this may cause some discomfort for the audience due to the relatively rapid build up of carbon dioxide level. In addition, it can be concluded that mechanical ventilation system which worked in the lower regime was unable to provide sufficient fresh air to dilute the build-up of concentration of CO2 during the peak load. However, the mean values of all parameters are within the limits recommended by ISO Standard 7730.

5.1.2 Terazije Theatre

AIR TEMPERATURE COMPARISON FOR DAY 1 AND DAY 2

Graphs below present the air temperature differentiation for two monitored days conditioned to the occupancy pattern. In order to compare thermal comforts for both days, curves from the same location are plotted on the same graph. Instrument locations are the same for both days. Yet, performances duration differ for two monitored days. Since it was not possible to enter the theatre much earlier, measurements started 10 min before the beginning of the performances and ended 10 min after performances were over. On the first day auditorium was occupied approximately 95%, w hile on the second day the o ccupation w as 80%. Almost full auditorium enabled evaluation of thermal comfort under peak load.

According to the curves plotted in the Fig.26 shows that the air temperatures correspond closely. Due to a greater attendance, air temperatures on the first day were slightly higher than on the second day. Main temperature peaks occurred when audience was entering somewhat before 19:30h, when it was cheering and applauding during the performance, and while vacating the auditorium. Moreover, since Terazije Theatre is a cabaret theatre, audience was much more involved in cheering, which influenced the increase of air temperature. The temperature recorded in this location ranged between 24.6°C and 26.6 °C and between 24.2 °C and 26.7 °C, respectively.

Fig.26. T (ºC) Graph -Location 2, Testo 400

As it is observed in the Fig.27, two temperature curves are closely related. The air temperature in this location was within 25.1ºC and 25.9ºC and within 24.5ºC and 25.9ºC, respectively.
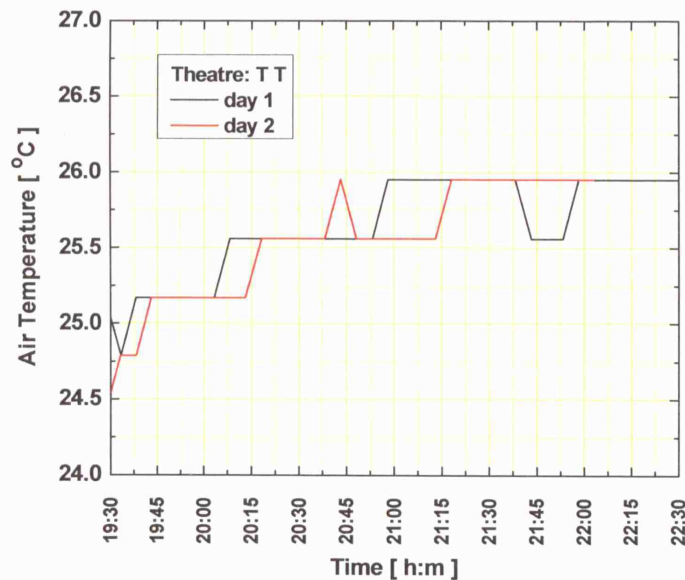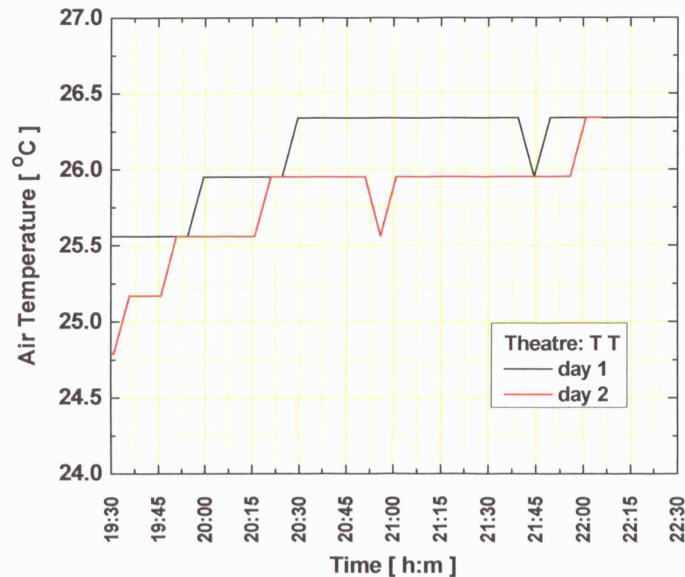

Fig.27. T (ºC) Graph -Location 2, HOBO

Two temperature curves plotted on the graph below (Fig.28) also correspond closely although the black curve is slightly translated upwards. However,

both curves follow the same occupancy pattern. The air temperature ranges between 25.6ºC and 26.3ºC and between 24.8 ºC and 25.9ºC.

Fig.28. T (ºC) Graph -Location 3, HOBO

Mean air temperatures for monitored days are 25.9ºC and 25.5 ºC, respectively. This is within the recommended range for acceptable indoor air quality of 22 ºC-26 ºC from the ISO Standard 7730. However, overall measured air temperature ranged between 24.2 ºC and 26.7 ºC, and exceeded the higher limit of acceptable air quality recommended by ISO Standard 7730. Explanation for this could be compromising location of two HOBO instruments attached to MY CO_2 instruments, conditioned by accessible sockets. The third instrument, Testo 400 probe was attached to a ceiling imbedded outlet grille, where all wasted air from the auditorium was depositing. Moreover, a sharp increase of air temperature could also be due to existence of side lifted lights and upward movement of the hotter air masses toward the ceiling. Despite the high temperature values, the thermal comfort of the people who were present in the auditorium was not so influenced, since the warm and polluted air was above their seats. The Tables 6 and Table 7 below, present outdoor air temperatures and minimum, maximum, and mean air temperatures for each location for both days.

Table 6-Outdor air temperature t (°C)

| OUTDOOR AIR TEMPERATURE T (°C)						
Date/Time	18h	19h	20h	21h	22h	23h
30.06.2006.	23.4	21.3	20.2	20.3	20.1 '	20.0
01.07.2006.	22.5	21.6	20.8	20.4	19.8	18.6

Table 7-Measurements of air temperatures for Terazije Theatre

| Locations	Minimum Air Temperature (°C) Day1/Day2	Maximum Air Temperature (°C) Day1/Day2	Mean Air Temperature (°C) Day1/Day2
1	24.6 / 24,2	26.6 / 26.7	25.8 / 25.4
2	25.1 / 24.5	25.9 / 25.9	25.6 / 25.4
3	25.6 / 24.8	26.3 / 25.9	26.1 / 25.7

RELATIVE HUMIDITY COMPARISON FOR DAY 1 AND DAY 2

Relative humidity, like the air temperatures, was somewhat higher on the first than on the second day. Reasons for this could be more people and much higher outdoor humidity, on the f irst day. Especially high outdoor humidity affected the rise of indoor relative humidity since in the end of performance, at 22h, indoor humidity reached 90%. Nevertheless, all three graphs follow the occupancy pattern, their entering, applauding at the end of the performance and their vacating.

It is observed in the Fig.29, that in the first 15 min two temperature curves correspond closely. However, after 15min period curves start to distance from each other so that in the end of the performance deviation exceeded 8%. Moreover, while red curve, day 2, had a descending tendency all the time, black curve, day 1, after first drop to 58.2%, had an increasing trend during the rest of the recorded time, and in the end of the performance when audience was exiting, reached 67.4%. After audience vacated the auditorium, humidity decreased again and approximated to the relative humidity of the second day. Relative humidity for this location ranged between 58.3% and 67.3%, and between 57.5% and 64.8%, respectively.
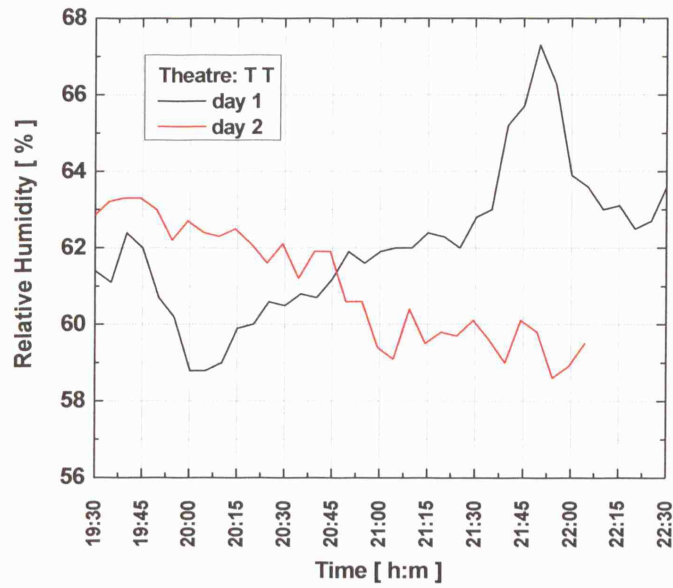
Fig.29. RH (%) Graph -Location 1, Testo 400

It is observed that relative humidity curves in the Fig.30 resemble to the humidity curves in the Fig.29. Even though, humidity curves follow the same pattern and even have increase and decrease concurrently, curves are placed in the lower relative humidity range between 45.1% and 48.9% and between 45.5% and 47.4%, respectively.
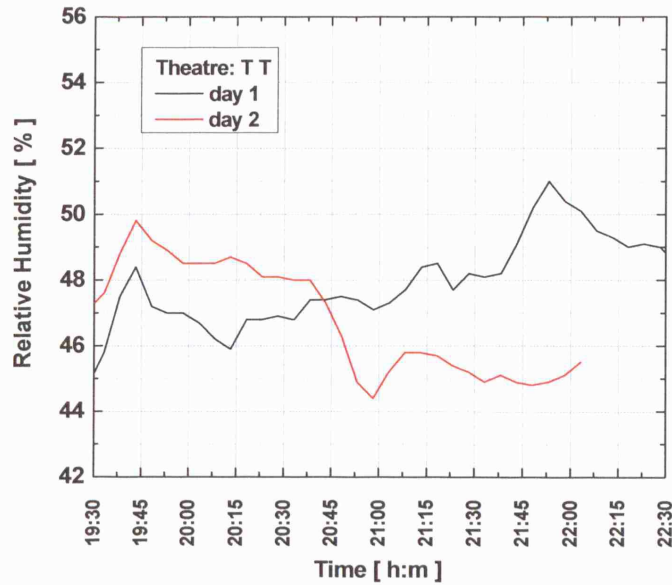
Fig.30. RH (%) Graph -Location 2, HOBO

Relative humidity curves in the Fig.31 differ a bit from humidity curves in the Fig.29and Fig.30. Moreover, while black curve, day 1, follows the same trend but without sharp peaks, red curve day 2, does not repeat such a drastic decrease as in the previous graphs. However, curves in the Fig.31 are in the field of higher relative humidity. Relative humidity in this location falls within 54.8% and 58.9% and within 56.5% and 57.8, respectively.
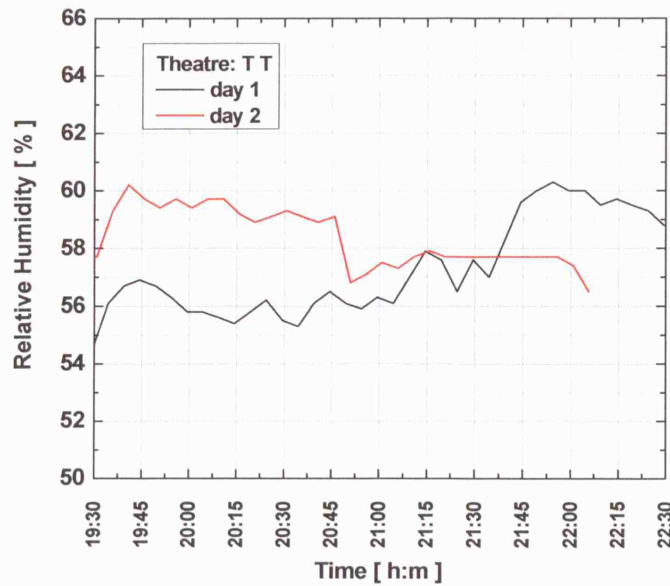
Fig.31. RH (%) Graph -Location 2, HOBO

Mean relative humidity for day 1 and day 2 were 55.7% and 55.3%, respectively. Relative humidity for the first and second day ranged between 45.1% and 67.3% and was within the recommended range for acceptable indoor air quality of 30-70% from ISO Standard 7730 guideline. The Table 8 and Table 9 present outdoor relative humidity and minimal, maximal, and main relative humidity for each location for both days.

Table 8-Outdoor relative humidity RH (%)

| OUTDOOR RELATIVE HUMIDITY RH (%)						
Date/Time	18h	19h	20h	21h	22h	23h
30.06.2006.	60	76	83	90	90	89
01.07.2006.	68	72	75	78	80	84

Table 9-Measurements of relative humidity for Terazije Theatre

Locations	Minimum Relative Humidity (%) Day1/Day2	Maximum Relative Humidity (%) Day1/Day2	Mean Relative Humidity (%) Day1/Day2
1	58.3 / 57.5	67.3/ 64.8	62.2 / 61.0
2	43.7 / 44.4	51.0/ 49.8	47.8 / 46.7
3	48.4 / 56.4	61.0 / 60.2	57.0 / 58.3

## CO2 CONCENTRATION COMPARISON FOR DAY 1 AND DAY 2

The rate of increase and the peak concentration are largely dependent on the human load. Likewise there is discernible concentration profile as the human load varies with time. Therefore, the build-up and decay of the carbon dioxide concentration followed the occupancy pattern.

Two CO_2 concentration curves In the Fig.32 correspond closely. Furthermore, as audience entered abrupt build-up of concentration was perceived, while there was a gradual decay as they settled. Other rapid decays and increases in the CO_2 concentration were due to the breaks, when most of the people moved to lobby. Finally, the third CO_2 peak happened in the end of the performance when audience was applauding, cheering and vacating. Measured CO_2 concentrations in this location ranged between 599ppm and 1041ppm and between 587ppm and 949ppm, respectively.
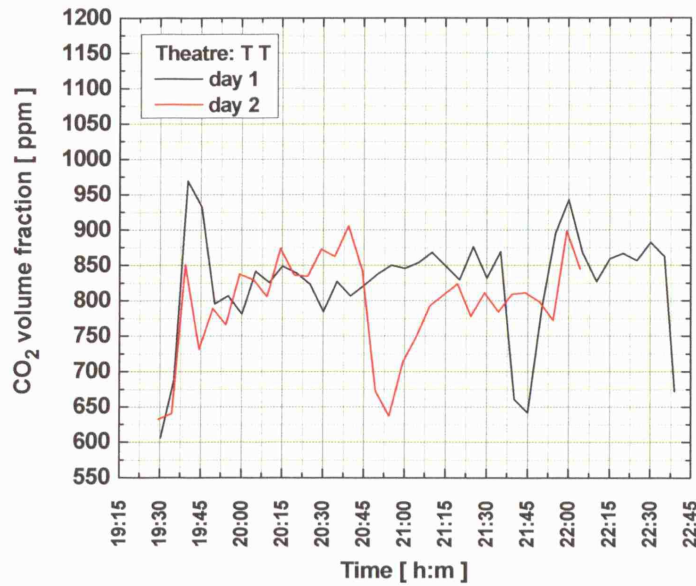
Fig.32. CO2 (ppm) Graph-Location 1, Testo 400

In the Fig.33 it is observed that two CO2 curves follow the same pattern as those in the Fig.32. Moreover, CO2 curves tend to have peaks and drops according to audience behavior. However, it is also noticed that black curve, day 1 is below red curve day 2, while in the Fig.32 it is vise versa. Moreover, since on the day 1 there were much more people than on the day 2, the only explanation for this could be instrument closeness to the scene and musical performance where actors were singing and dancing most of the time. CO2 concentrations in this location were within 475ppm and 637ppm and within 450ppm and 780ppm, respectively.
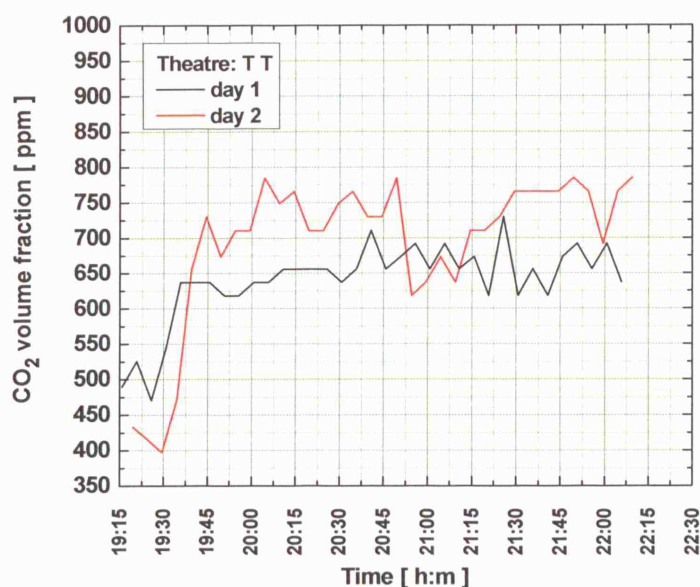
Fig.33. CO2 (ppm) Graph-Location 3, HOBO

The concentration measured over the period of monitoring ranged between 450 and 1041ppm with an average concentration of 744 ppm on the first day and 734 on the second day. Both mean concentrations are below the 8-h recommended threshold value of 1000 ppm. The only time when CO2 concentration exceeded 1000 ppm, was in the beginning of the performance and such a short period may not present the issue of concern as the recommended threshold values should be more than 1000 ppm for 2h exposure. Moreover, this concentration peak was probably due to higher outdoor CO2 concentration since doors were open while audience was entering the auditorium. Nevertheless, the mean values of all parameters are within the limits recommended by ISO Standard 7730.

5.2 IAQ and Ventilation Rates

This chapter presents and discusses ventilation parameters, CO2 concentration and ventilation rates l/s/p, obtained from monitored auditoriums of both theatres, Belgrade Drama Theatre and Terazije Theatre.

5.2.1 Belgrade Drama Theatre

Values presented for Belgrade Drama Theatre are those obtained in the location 1, at the outlet grille and in the location 2, near the outlet grille in the occupied zone. The levels of CO_2 measured in the auditorium varied and are summarized in T ables 1 0 a nd Table 1 1 t ogether w ith t he e stimated a ir supply rates. These tables also show average values and air supply rates, in terms of liters per second per person (l/s/p).

Day: 1

Table 10 –Occupied period (Min: minimum; Max: maximum; Av: average; Stdev: standard deviation)

	Location 1	Location2
Max CO2 Measured (ppm)	1156	1136.00
Min C02 Measured (ppm)	925	858.00
Av CO2 Measured (ppm)	997	973.00
Stdev CO2 Measured (ppm)	83	83.98
Max ach	2.17	2.13
Min ach	1.44	1.50
Av ach	1.83	1.82
Stdev ach	0.24	0.20
Max l/s/p	10.74	10.56
Min l/s/p	7.12	7.40
Av l/s/p	9.08	9.03
Stdev l/s/p	1.19	0.98

In order to prove if the auditorium can be efficiently ventilated, experiments were carried out twice. The experiments show CO2 concentrations which in some moments were beyond the guideline value of 1000 ppm.

The following can be concluded:

• The average "occupied" ventilation rate was 1.82 ac/h (9.03 l/s/p for 300 occupants), with a minimum of 1.50 ac/h and a maximum of 2.13 ac/h (10.56 l/s/p for 300 occupants).

• The average CO2 concentration during the occupied period was 973 ppm, the maximum was 1136 ppm.

Day: 2

Table 11 –Occupied period (Min: minimum; Max: maximum; Av: average; Stdev: standard deviation)

	Location 1	Location 2
Max CO2 Measured (ppm)	1018.00	951.00
Min C02 Measured (ppm)	921.00	858.00
Av CO2 Measured (ppm)	958.29	906.00
Stdev CO2 Measured (ppm)	34.96	31.66
Max ach	2.79	3.22
Min ach	1.79	1.85
Av ach	2.32	2.61
Stdev ach	0.29	0.46
Max l/s/p	11.82	13.64
Min l/s/p	7.59	7.87
Av l/s/p	9.85	11.08
Stdev l/s/p	1.25	1.95

The following can be concluded:

• The average "occupied" ventilation rate was 2.61 ac/h (11.03 l/s/p for 350 occupants), with a minimum of 1.85 ac/h and a maximum of 3.22 ac/h (13.64 l/s/p for 350 occupants).

• The average CO2 concentration during the occupied period was 906 ppm, the maximum was 951 ppm.

• Adequate fresh air was being provided.

According to this CO2 trend, calculated average air supply rates on both days were within the recommended 10 l/s/p (category A), except in the location 2 on the second day, when the average ventilation rate reached 11.08 l/s/p (Table 11). Category A corresponds to a high level of expectation,

and leads to a highest percentage of satisfied occupants in respect of indoor environment (CEN/TC 156 2005).

5.2.2 Terazije Theatre

Values presented for Terazije Theatre are those obtained in the location 1, at the outlet grille. Unfortunately, due to a lack of sockets either near outlet grilles or in the occupied zone, results obtained with other instrument were not valid for calculation of ventilation rates. The levels of CO_2 measured in the auditorium varied and are summarized in Tables 12 and Table 13 together with the estimated air supply rates. These tables also show average values and air supply rates, in terms of liters per second per person (l/s/p).

Day: 1

Table 12 –Location 1, Occupied period (Min: minimum; Max: maximum; Av: average; Stdev: standard deviation)

Max CO_2 Measured (ppm)	903.00
Min CO_2 Measured (ppm)	797.00
Av CO_2 Measured (ppm)	846.76
Stdev CO_2 Measured (ppm)	29.86
Max ach	5.09
Min ach	3.85
Av ach	4.38
Stdev ach	0.31
Max l/s/p	16.79
Min l/s/p	12.70
Av l/s/p	14.46
Stdev l/s/p	1.03

The following conclusion can be made:

• The average "occupied" ventilation rate was 4.38 ac/h (14.46 l/s/p for 450 occupants), with a minimum of 3.85 ac/h and a maximum of 5.09 ac/h (16.79 l/s/p for 450 occupants).

• The average CO2 concentration during the occupied period was 846 ppm, the maximum was 903 ppm.

Day: 2

Table 13 –Location 1, Occupied period (Min: minimum; Max: maximum; Av: average; Stdev: standard deviation)

Max CO2 Measured (ppm)	874.00
Min CO2 Measured (ppm)	739.00
Average CO2 Measured (ppm)	813.12
Dev CO2 Measured (ppm)	38.01
Max ach	5.27
Min ach	3.04
Average ach	4.08
Dev ach	0.53
Max l/s/p	20.07
Min l/s/p	11.57
Average l/s/p	15.53
Dev l/s/p	2.01

The following conclusion can be made:

• The average "occupied" ventilation rate was 4.08 ac/h (15.53 l/s/p for 390 occupants), with a minimum of 3.04 ac/h and a maximum of 5.27 ac/h (20.07 l/s/p for 390 occupants).

• The average CO2 concentration during the occupied period was 813 ppm, the maximum was 874 ppm.

It can be concluded that in Terazije Theatre air ventilation rates were beyond the recommended 10 l/s/p (CEN/TC 156 2005). However, the available data indicate that occupant health and perceived IAQ will usually be improved by avoiding ventilation rates below (9 L/s) per occupant and indicate that further improvements in health and perceived IAQ will sometimes result from higher ventilation rates up to (18 L/s) per person (ASHRAE Journal, August 2002).

5.3 Subjective Assessments

In this occupant survey a total of 100 questionnaires were distributed to the audience in both theatres. Unfortunately, in Belgrade Drama Theatre monitored performances did not have a break, and only 20 and 15 of them were completed and returned during the day 1 and day 2, respectively. However, in Terazije Theatre performances on both monitored days had breaks, so 65 questionnaires on the first day and 75 of them on the second day 2 were completed and returned.

5.3.1 Belgrade Drama Theatre

A total of 67% (Fig.34) of the respondents claim that they suffer from one or more physiological symptoms. This enables investigating how people with some health problems react to the existing indoor environment. Dry or irritated throat (Fig.34 and Fig.36) is the most common symptom among the respondents, with 21% on the first day and 20% on the second day experiencing it. The next most prevalent symptoms in the Fig.34 are dry eyes (16%) and nasal related symptoms, with 10% and 5% suffering from blocked or stuffy nose and runny nose, respectively. Other also spread symptoms are watering eyes (5%), headaches (5%), chest tightness or breathing difficulties (5%) and sinusitis (5%).

Fig.35 and Fig.37 show the results of the physical parameters part of survey. Total of 64% and 69% of the respondents felt that thermal comfort and indoor air quality was satisfactory. Most of the respondents, 16% and 13% expressed that the air was warm. Furthermore, 10% and 6% felt that air was too humid and 10% and 6% felt that air was too still. Finally, in the Fig.37, 6% of respondents claim that during the performance air was rather stuffy.
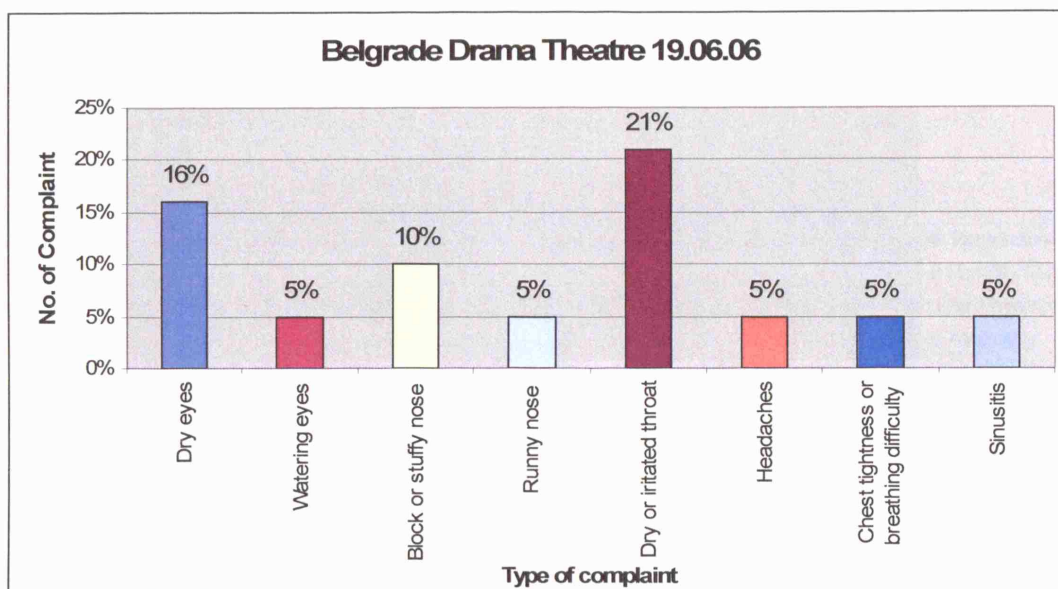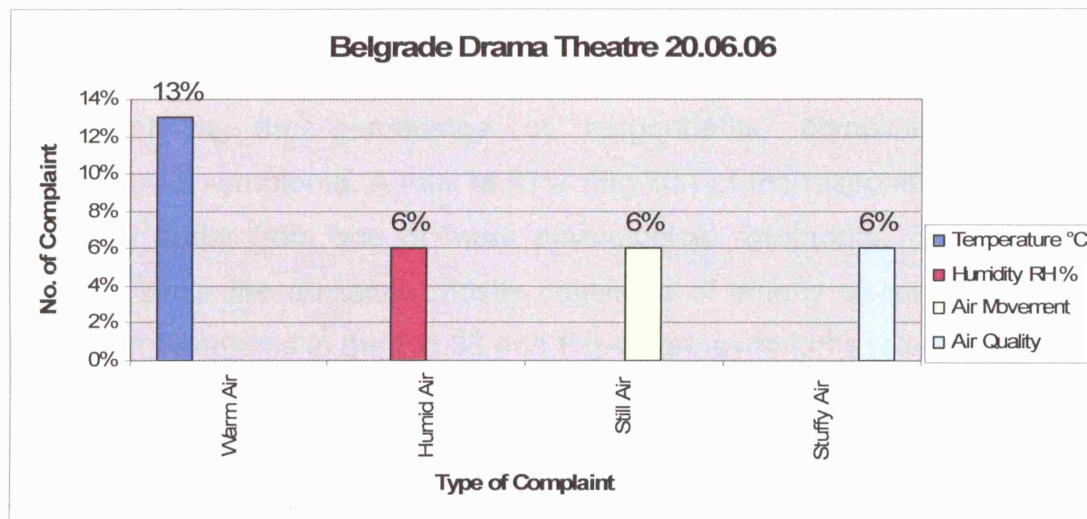
Fig.34.-Physiological parameters
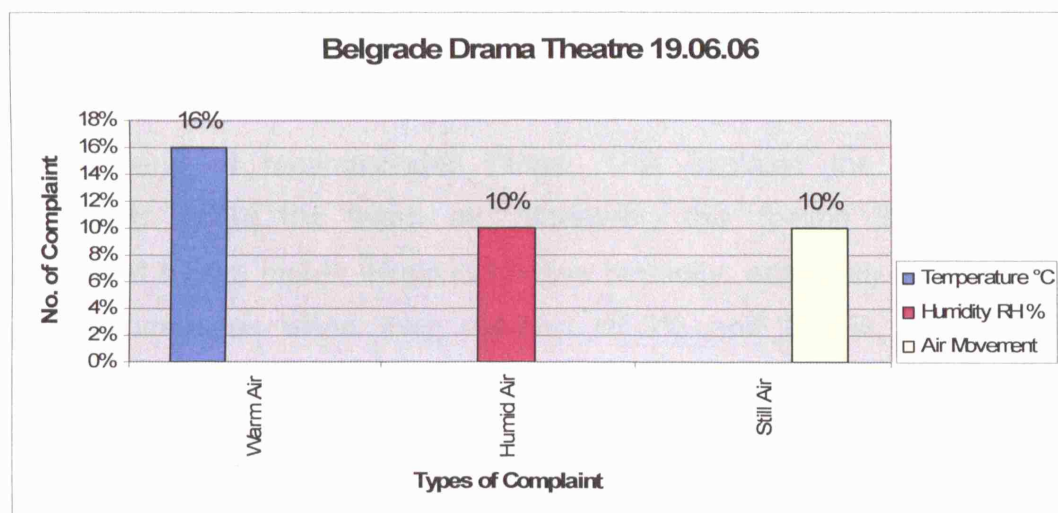
Fig.35.-Physical parameters
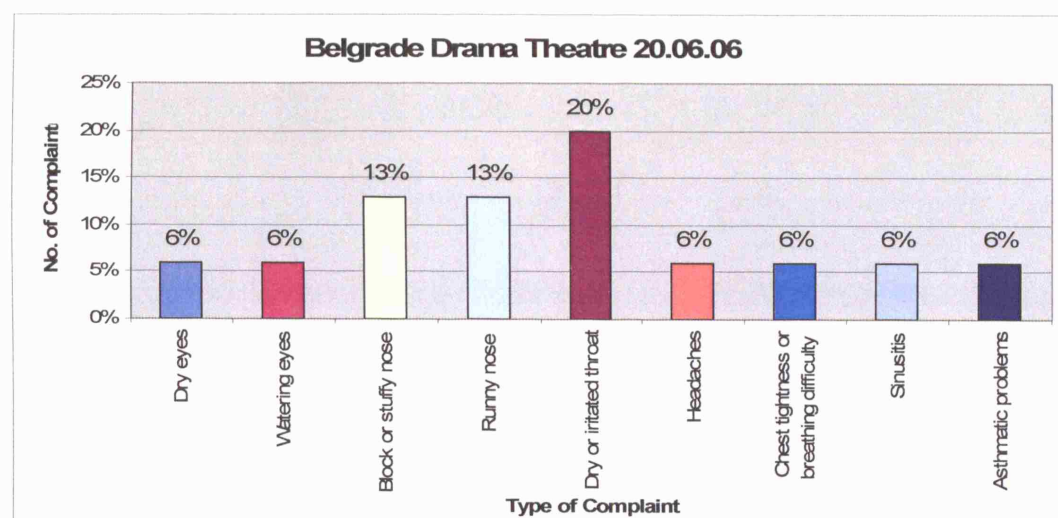
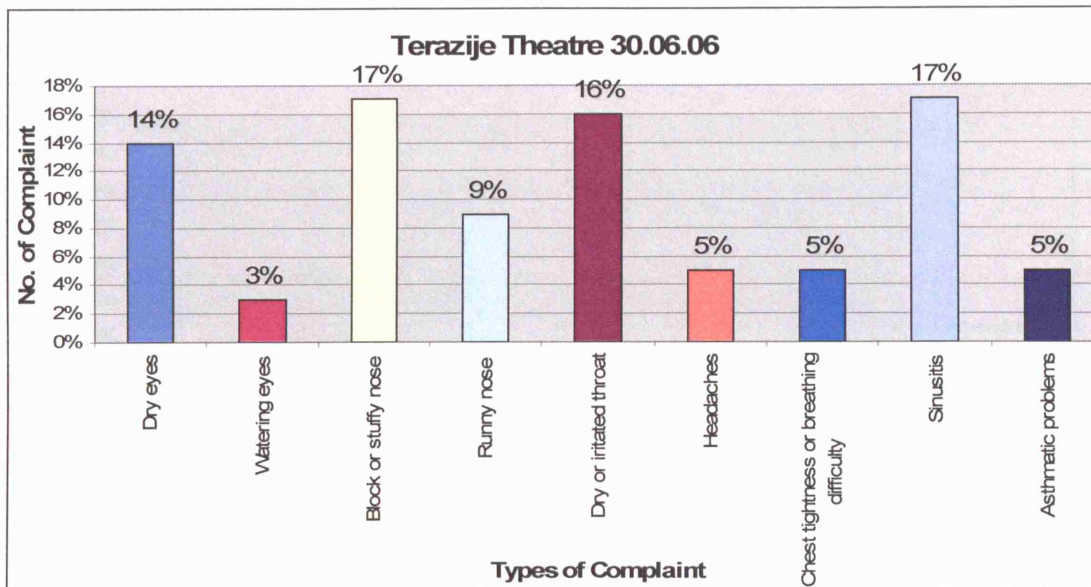**Fig.36.**-Physiological parameters

Fig.37.-Physical parameters

Even though the collected sample was too small compared to overall number of people attending the performance, the obtained responses enabled some conclusions to be reached. The air temperatures, of 25.9°C on day 1 and 26.7 °C in the end of the performances are inclined toward the warmer end of recommended range. This explains the respondents' complaints about the warm air. Moreover, this feeling is additionally influenced by the higher levels of relative humidity, especially in the end of the performances when they reached 67.9% and 68.6%, respectively. Respondents perceived higher humidity levels therefore, 10% and 6% complained on rather humid air, respectively. Furthermore, six per cent of people on the second day claimed that air was stuffy. This could also be due to higher humidity levels. Finally, 10% and 6%, respectively, complained about still air. However, calculations of air ventilation rates show that sufficient amounts of fresh air were provided.

5.3.2 Terazije Theatre

Fig.38 shows the percentage of respondents' complaints on the physiological symptoms. A total of 91% (Fig.38.) of the respondents claimed that they suffer from one or more physiological symptoms. This is not a surprise since the audience mostly consisted of elderly people. The most prevalent symptoms in the Fig.38 and Fig.40 are symptoms related to nasal, with 17% and 20% suffering from blocked or stuffy nose, 17% and 14 % from sinusitis and 9% and 11% from runny nose, respectively. Dry or irritated throat (Fig.38. and Fig.40.) is the next most common symptom among the respondents with 16% on the first day and 5% on the second day experiencing it. The next common symptoms in the Fig.38 and Fig.40 were dry eyes (14%) and (15%), watering eyes with 3% and 9%, respectively. Unexpectedly, even 5% on the first day and 9% on the second day of respondents claimed that they suffer from asthma. Other remaining symptoms were headaches and chest tightness or breathing difficulties both per 5% on the first day and 11% and 4% on the second day, respectively.

Fig.39 and Fig.41 show the results of the physical parameters part of survey. Total of 58% and 62% of the respondents felt that thermal comfort and indoor air quality was satisfactory. A certain number of respondents, 9% and 16% expressed that the air was too cold. Furthermore, 14% and 8% felt that air was too dry and 11% and 8% felt that air was too still. Complaints about other conditions presented in the Fig.39 and Fig.41 are not significant since they present a minor percentage.
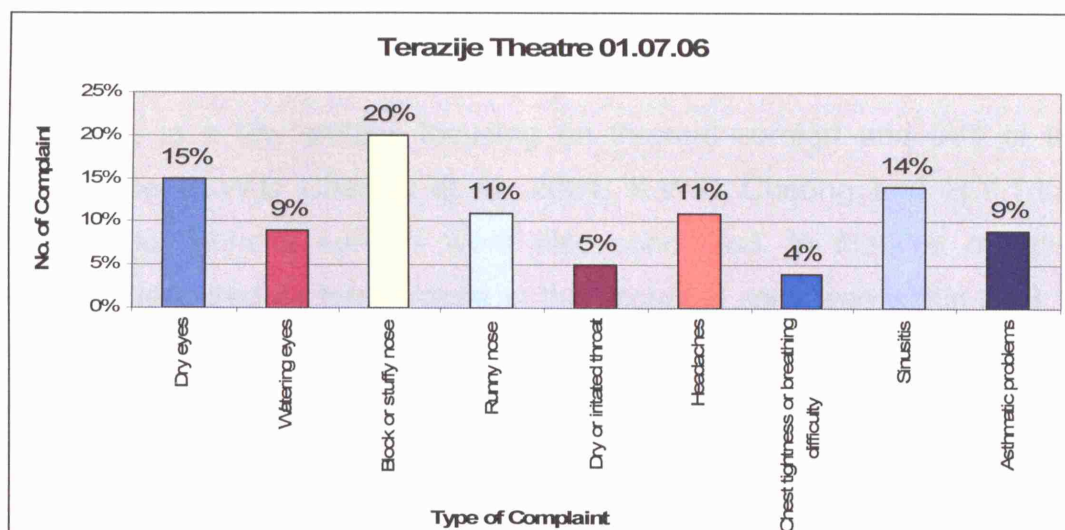
72
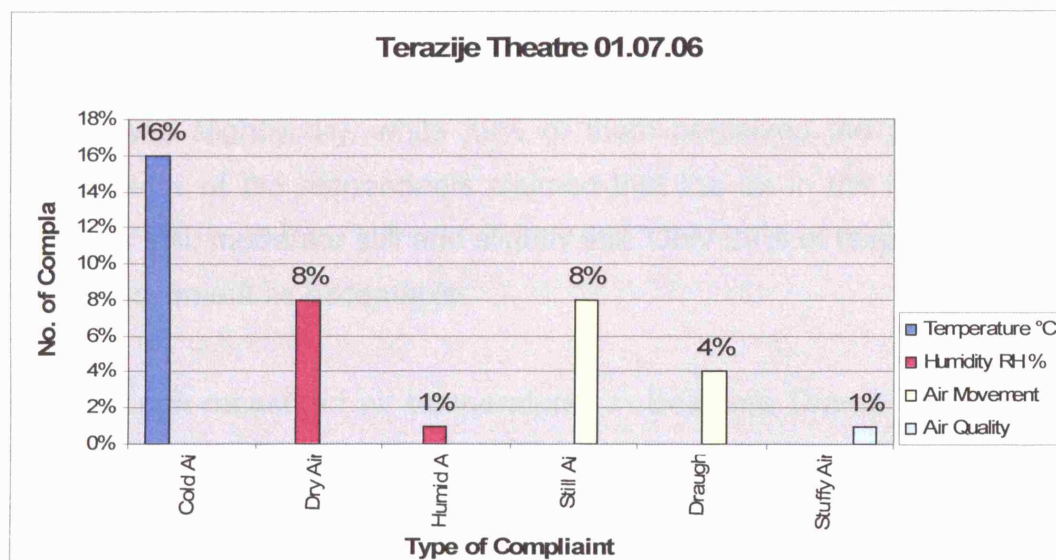
Fig.38.-Physiological parameters
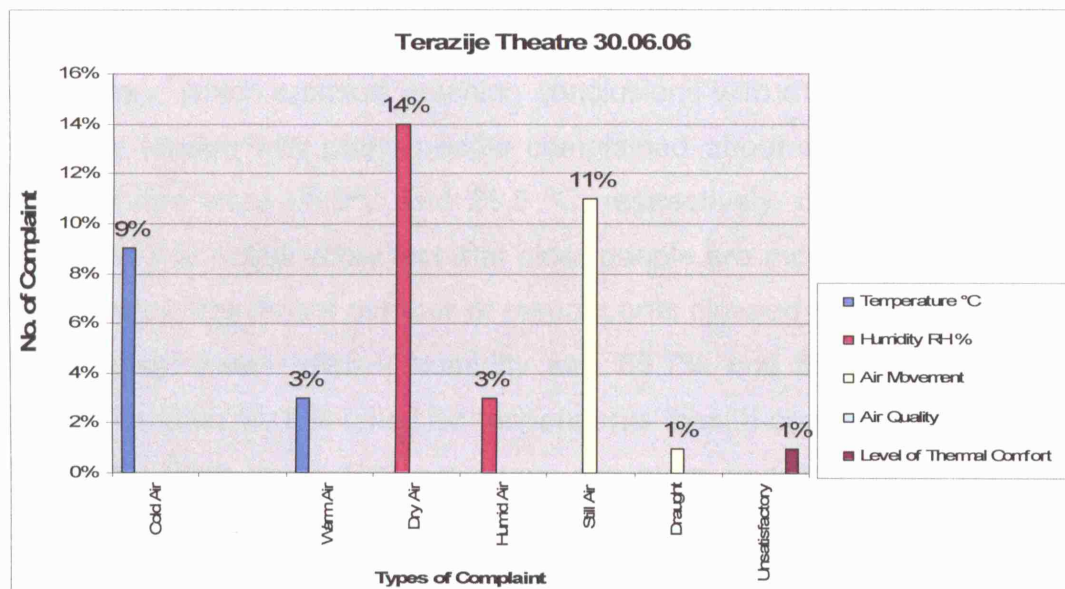
Fig.39. -Physical parameters

Fig.40. -Physiological parameters

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Fig.41.-Physical parameters

This time the number of completed and returned questionnaire was satisfactory, which enabled reaching conclusions with much more certainty. The only reason why many people complained about cold air, since main temperatures were 25.9°C and 25.5 °C, respectively, could be old-age of audience. It is a well know fact that older people are more sensitive to cold. Furthermore, significant number of respondents claimed that air was too dry even though mean relative humidity was 55.7% and 55.3%, respectively. The explanation for this could be respondents' health condition since people who suffer from respiratory symptoms are more sensitive to air humidity. Also, many people who complained about dry air were those with dry or irritated throat symptoms. Even though, 11% and 8%, respectively, claimed that air was too stale calculated ventilation rates indicate that it was not the case.

Moreover, in a few studies focusing on thermal comfort and IAQ of the similar use (K.W.D Cheong et al. 2001, K.W.D Cheong and H.Y.T.Lau 2002), questionnaire surveys were also conducted. In the first of these studies, measured air temperature in the occupied zone was within 21.3 °C and 25.6 °C, while relative humidity was within 61% and 77%. The mean air velocity was within 0.07m/s and 0.18m/s. Furthermore, CO_2 concentration increased as occupants entered lecture theatre and reached a peak of 1200ppm during the occupied period. Majority of the respondents

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(68%) complained about cold, cool, and slightly cool air, while 24% of respondents indicated neutral. Moreover, 41% of the respondents perceived the air was slightly dry, while 39% of them perceived the air as neutral. Finally, 44% of the respondents claimed that the air in the lecture theatre was very still, moderate still and slightly still. Only 29% of respondents rated the air movement as acceptable.

Even though measured air temperatures in Belgrade Drama Theatre (21.2 °C-26.7 °C) and Terazije Theatre (24.2 °C- 26.7 °C), were similar to the air temperatures in above mentioned lecture theatre, majority of the respondents were satisfied. Furthermore, measured relative humidity was even lower than in this lecture theatre, between 42.3% and 67.9% in Belgrade Drama Theatre and between 45.1% and 67.3% in Terazije Theatre. Yet, 10% and 6% of the respondents in Belgrade Drama Theatre claimed that air is too humid, while, 14% and 8% of the respondents in Terazije Theatre perceived the air too dry. Moreover, in Belgrade Drama Theatre 10% and 6% of the respondents complained about the still air, while in Terazije Theatre 11% and 8% of them perceived the air was too still. Finally, it could be concluded that even though some people were not satisfied with the indoor environment, majority of the respondents (more than 50%) in the both theatres were comfortable.

CHAPTER 6: CFD Modeling

The CF D m odeling is f requently u sed t o as sess t he t hermal c omfort in complex built environments such as theatres. This chapter focuses on a deeper analysis of the thermal comfort parameters in one of the two studied auditoriums. The auditorium in Terazije Theatre was selected for this CFD exercise for three reasons:

1. All parameters needed to define the model were known at the time when the work on this dissertation was carried out.
2. The 3D solid model of the auditorium was provided by the consulting company which carried out the project; this greatly reduced the time needed to carry out a CFD study of this complex environment
3. Unlike the mechanical ventilation system in the other theatre, Terazije Theatre has been equipped with the advanced mechanical ventilation system (described in the Chapter 4). The literature survey showed that this type of system has not been simulated using the CFD modeling (for academic purposes).

Terazije CFD case study was performed using FLAIR software (CHAM Ltd. London, UK). Usually, the CFD practice consists of three main phases:

- the model set up by pre-processing software module
- the run time processing, and
- the results presentation by post-processing software module

6.1 The Model Set-Up

There are several groups of input data that had to be specified by pre-processing software module, as follows:

- *geometry model set-up*
- *physical / mathematical model set-up*
- *boundary conditions and related sources set-up*
- *thermal comfort and indoor air quality indices set-up, and*
- *numerical model set-up*

In the following part of the chapter, the case study definition is shortly described.

Geometry model of Terazije Theatre Hall consists of three groups of objects, namely the building, HVAC and loads objects. Many of these objects are of regular shape, which is why they are introduced as FLAIR default objects. Obviously, it was needed to make some geometrical approximation such as bases of occupant seats. However, the shape of gallery was too complex. Therefore, different techniques were used in order to define the gallery solid object. Based on technical drawing, the 3D solid of gallery was made in the AutoCAD software package and imported into FLAIR. The HVAC objects were specified from the FLAIR library of HVAC as vortex diffusers on the ground and gallery, round diffusers on the lodge ceiling and grille/nozzle diffusers on the lateral stage walls. The under-seats round vortex diffusers were approximated as squared ones. This was possible since the grouped squared vortex diffusers by row are located above the real floor-position to the higher level where the uniformity of inlet velocity is reached. This location was determined by measurement, and it was approximately 0.16 m above the floor. The only reason for the approximated technique was saving the number of numerical cells. Linked building and HVAC objects are shown in the Fig.42.
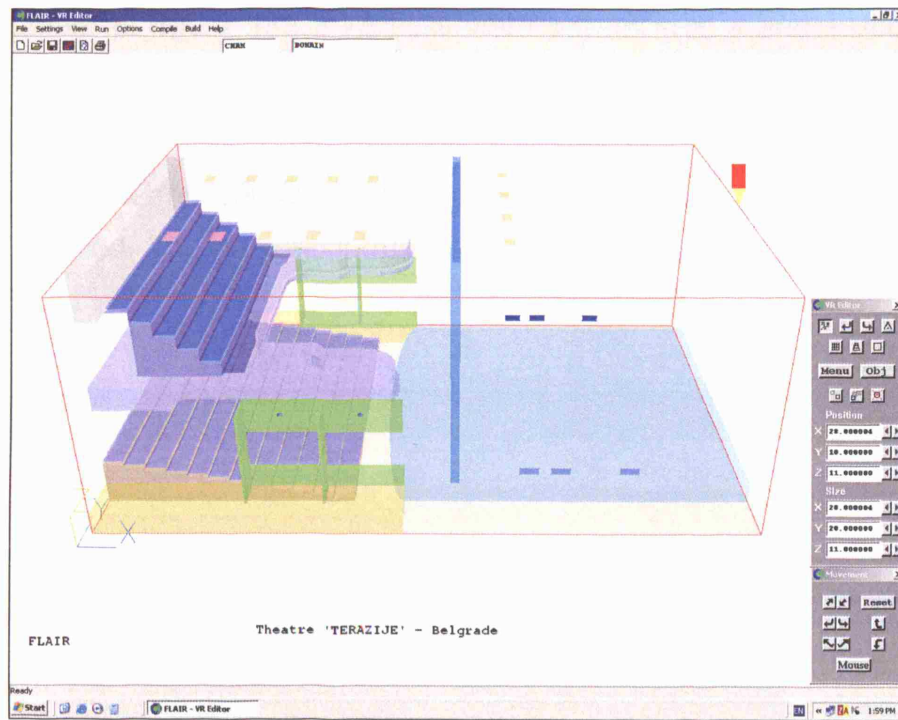
Fig.42. -Building and HVAC object set-up

The loads objects were specified as boxes of persons, defined as people objects filled by domain fluid with the specified heat, water vapor and carbon dioxide sources. Also, the lightning was set up as a heat source box. Load objects set up are shown in the Fig.43.
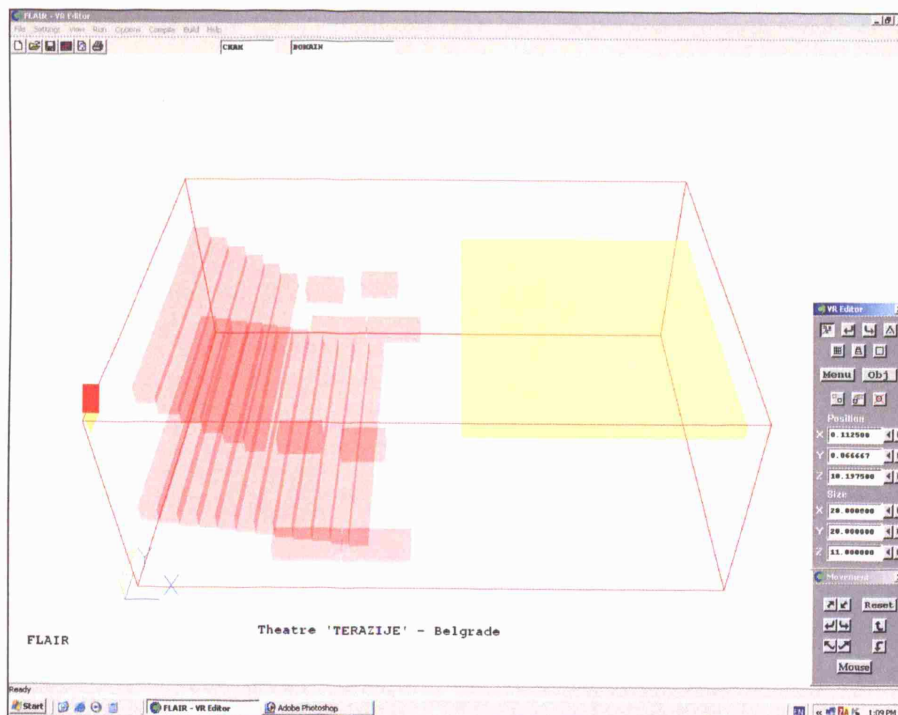

Fig.43. -Loads objects set-up

The number of 140 x 153 x 75 cells were set up in *x, y* and *z* directions, respectively. In other words, the whole theatre hall domain was discredited to approximately $1.6 \cdot 10^6$ finite volumes (cells). In every cell, all physical parameters, thermal comfort indices as well as indoor air quality parameters were deduced. The numerical grid resolution is shown on Fig. 44 and Fig. 45.
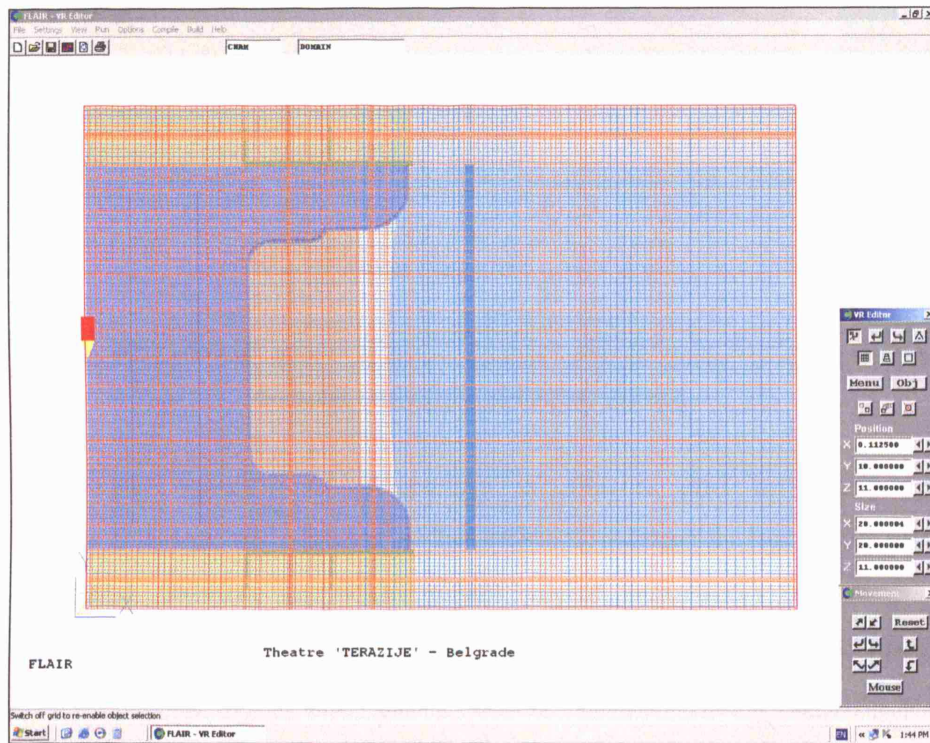
Fig.44. -Horizontal grid resolution
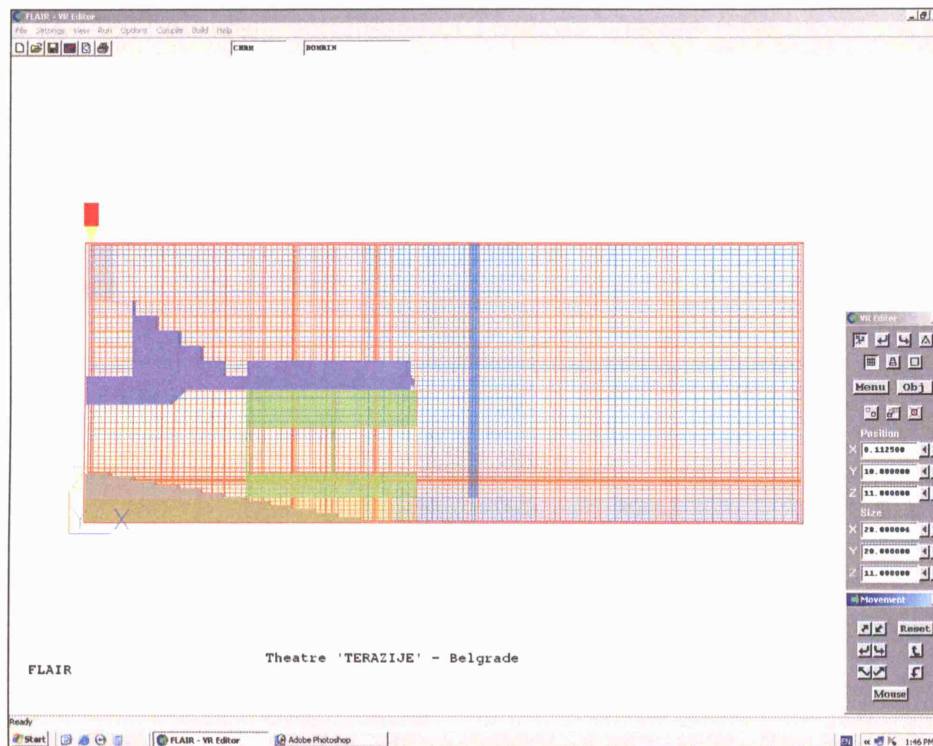
Fig.45. -Vertical grid resolution

The numerical solution of governing equations and turbulence model transport equations, as additional parameters related to humidity, such as, humidity ratio, relative humidity, water vapor saturation pressure, water vapor partial pressure and water vapor mole fraction, were set-up by the appropriate menus of FLAIR Virtual Reality Editor. Also, additional sources of buoyant force in the momentum equation of vertical velocity component, and transport equations of turbulence model, as well as equation of ideal gas low set up was done by the same technique.

The unique solution of the model was obtained by setting the boundary conditions and related sources. Data of measurement as well as data specified in *The Final Report of HVAC Reconstruction of Terazije Theatre* have been used to specify all necessary boundary conditions and the related sources.

The ceiling, floor and walls were modeled by using a material with the following properties; density: 1600 kg/m^3, specific heat: 840 J/kgK, thermal conductivity: 0.69 W/mK. The rest of needed parameters are summarized in Tables 14 to 16.

Table 14-Inlet boundary conditions of Terazije Theatre

HVAC AIR SUPPLY SYSTEM								
SUPPLY DIFFUSERS	DIMENSIONS (mm)	NUMBER OF ELEMENTS	EFFECTIVE AREA (m^2)	SUPLLY PRESSURE (Pa)	TEMPERATURE ($^{\circ}$C)	HUMIDITY (kg/kg)	TOTAL VOLUME FLOW RATE (m^3/ h)	CO_2 VOLUME FRACTION (ppm)
GROUND LEVEL								
Vortex (under seats)	$\varnothing$ 180	312	0.00354	14	20	0.008654	15650	460
Round (lodge ceiling)	$\varnothing$ 200	8	0.008	17	20	0.008654	1600	460
GALLERY LEVEL								
Vortex (under seats)	$\varnothing$ 180	120	0.00354	14	20	0.008654	6450	460
MEAN STAGE LEVEL								
Grille (lateral walls)	825 x 325	6	0.134	2	20	0.008654	6000	460

Table 15-Outlet boundary conditions of Terazije Theatre

HVAC RETURN AIR SYSTEM				
RETURN DIFFUSERS	DIMENSIONS (mm)	NUMBER OF ELEMENTS	EFFECTIVE AREA (m^2)	PRESSURE DROP (Pa)
GALLERY CEILING				
Grille	1025 x 525	10	0.269	2
MEAN STAGE CEILING				
Grille	825 x 425	4	0.175	2

Table 16-Internal sources of Terazije Theatre

PARAMETERS	HVAC LOAD SOURCES						
	NSITIVE HEAT (W / person)	LATENT HEAT (W / person)	TOTAL HEAT (W / person)	TOTAL NUMBER OF PERSONS	HUMIDITY SOURCE (g / h / person)	CO_2 SOURCE above outdoor air (ppm)	LIGHTNING (W)
	GROUND OCCUPANTS						
	60.5	55	115.5	332	55	450	0
	GALLERY OCCUPANTS						
	60.5	55	115.5	132	55	450	0
	MEAN STAGE						
	0	0	0	0	0	0	19600

The theatre external walls as well as floor and ceiling were assumed to be adiabatic isolated. It was a reasonable assumption regarding the fact that the theatre hall is located at the central part of building and all surrounding rooms are also air-conditioned. Setting the adiabatic option for immersed

solid object had a consequence due to which the equation of thermal transport by conduction has been used. As a result, the temperature distribution inside of the internal walls has been obtained.

6.2. Presentation of Numerical Results

In order to point out thermal comfort and air quality of Terazije Theatre, only one but the most significant part of the obtained numerical data has been chosen for the presentation. The presentation of numerical results is organized in five paragraphs, namely:

- *Displacement Ventilation Concept Verification*
- *Model Verification*
- *Thermal Comfort Indices Presentation*
- *Indoor Air Quality Indices Presentation, and*
- *Neutral Thermal Sensation*

In the following text, each of these topics is briefly discussed.

6.2.1. Displacement Ventilation Concept Verification

The thermal stratification and flow pattern indicate the typical concept of displacement ventilation. Cold and fresh air is located at the lower zones of both ground and gallery levels, while the hot air is moved to upper zones, shown in the Fig.46. The typical air movement from lower to upper zones could be seen in the Fig.47 where the flow pattern is presented by velocity vectors. Also, vertical temperature profiles at three middle cross-section locations (Fig.48.) are shown on Fig.49, indicating the typical vertical temperature profiles of stratified layers in displacement concept of indoor ventilation.
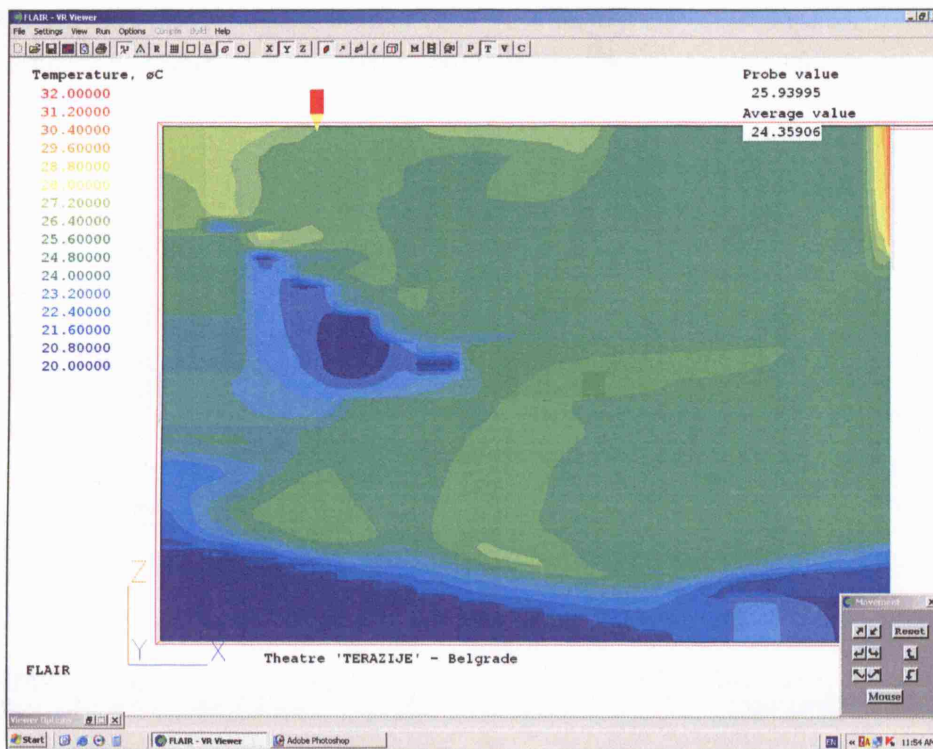
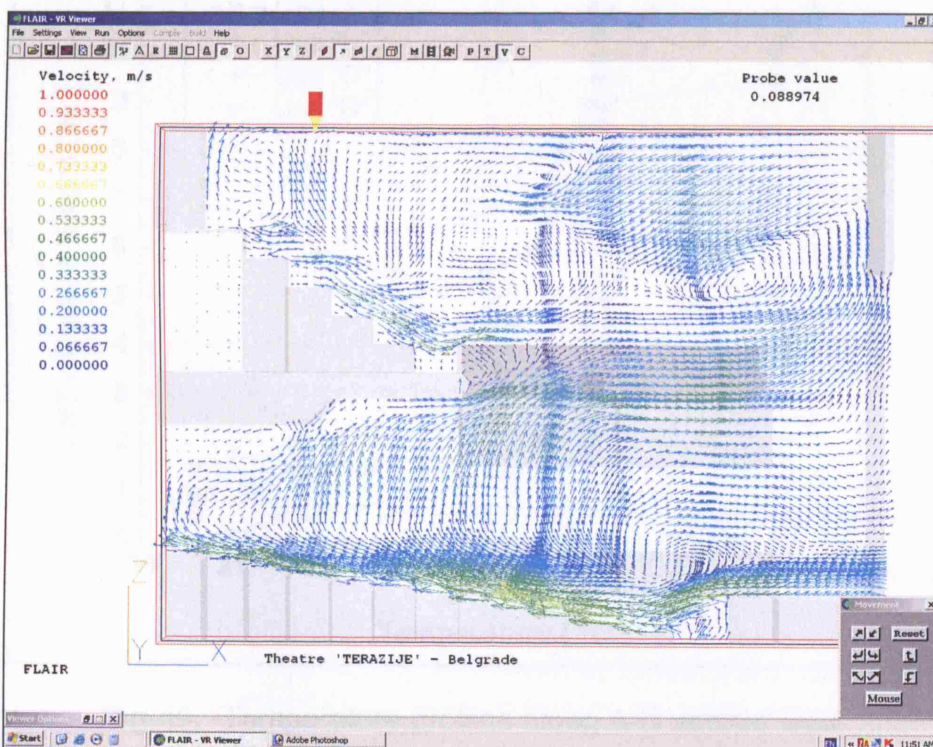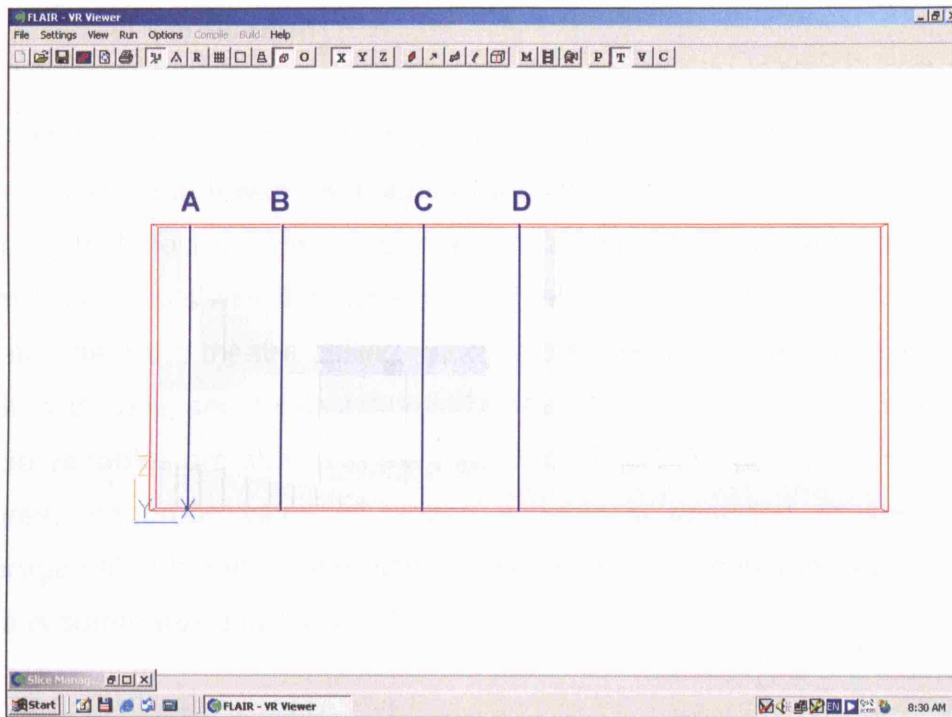**Fig.46.** -Thermal stratification in the middle-vertical cross-section
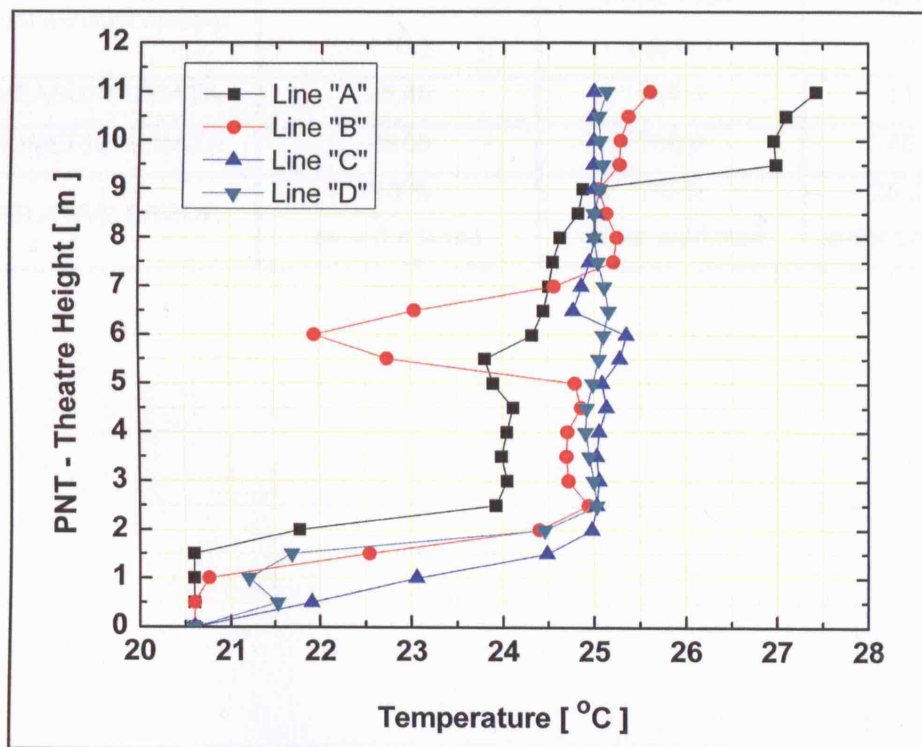

Fig.47. -Flow pattern in the middle-vertical cross-section

**Fig.48.** -Vertical middle cross-section lines for temperature vertical profiles

Fig.49. -Temperature profiles along A-D vertical lines

6.2.2. Model Verification

Numerical probe was located approximately at the same position as location of measurement. It was the center of the first exhaust diffuser located at the theatre hall ceiling. The proper view to compare the experimental and numerical results was the distribution of related variables in horizontal plane located near the theatre ceiling. Since the air temperature, mass fraction of carbon dioxide and relative humidity have been measured, distribution of these variables are shown in the Fig.50 to Fig.52. At the right-upper part of figures, the probe value of related variable is specified as well as the average value in the shown plane. Comparison of measured and numerical data is summarized in Table 17.

Table 17-Comparison of measured and numerical data

| PROBE LOCATION: First exhaust diffuser	AIR TEMPERATURE (°C)	CO_2 VOLUME FRACTION (ppm)	RELATIVE HUMIDITY (%)
MEASURED DATA	25.40	795.0	61.0
NUMERICAL DATA	25.65	738.8	45.4
RELATIVE ERROR	1.0 % over predicted	7.0 % under predicted	25.6 % under predicted
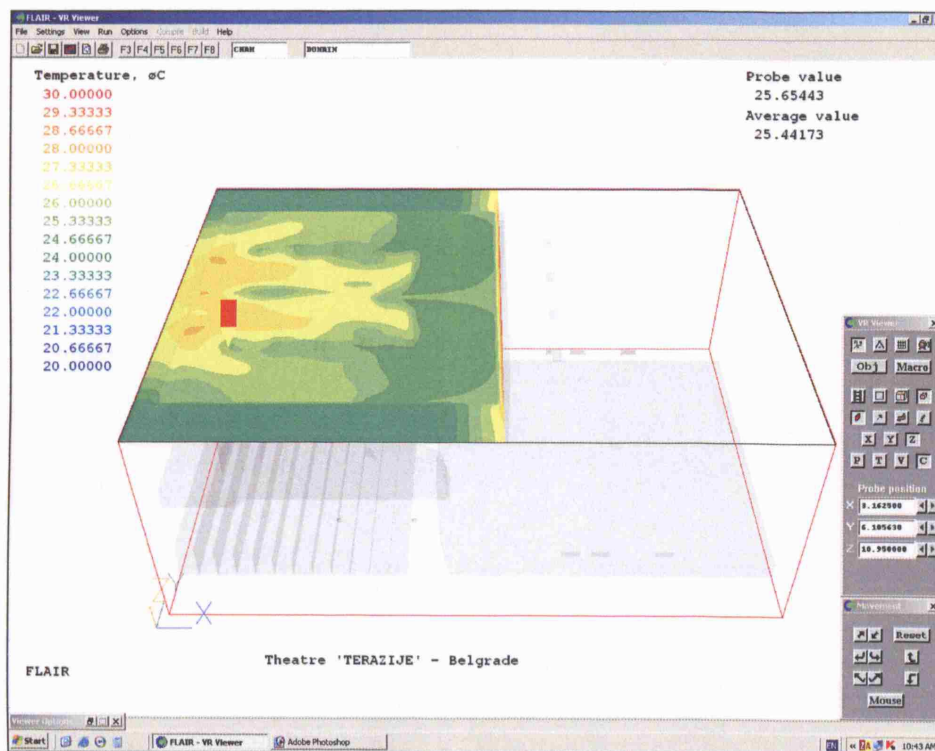
Fig.50. -Air temperature distribution in horizontal cross-section at the theatre ceiling
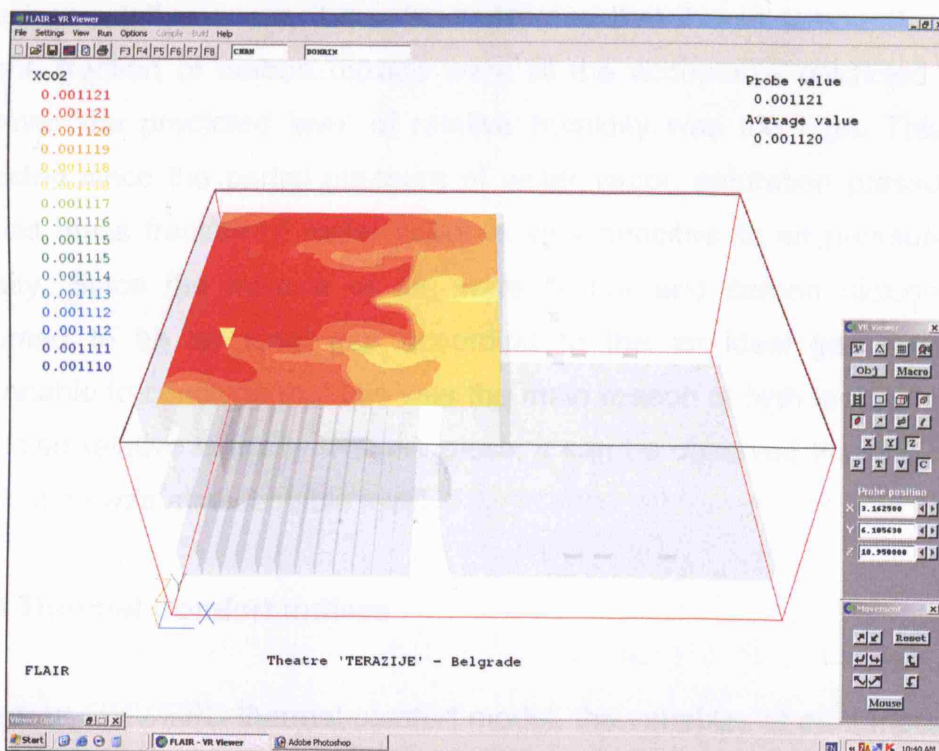
Fig.51. -CO$_2$ mass fraction distribution in horizontal cross-section at the theatre ceiling
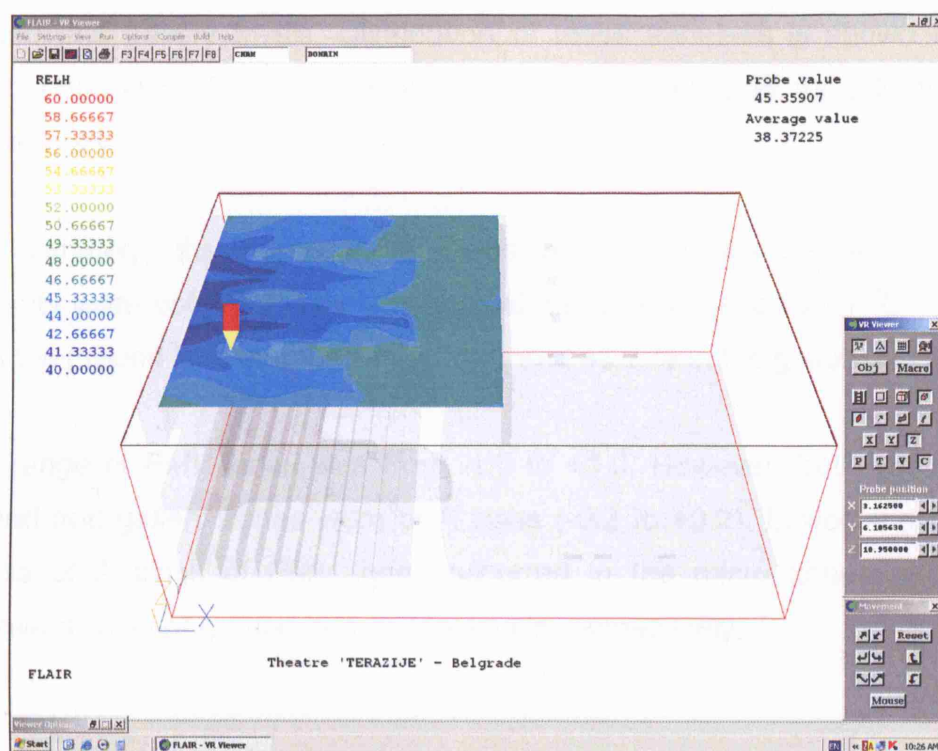
Fig.52. -Relative humidity distribution in horizontal cross-section at the theatre ceiling

Based on relative errors, it can be concluded that the air temperature and volume fraction of carbon dioxide were at the acceptable predicted level. However the predicted level of relative humidity was too high. This was expected since the partial pressure of water vapor, saturation pressure as well as mass fraction of water vapor is very sensitive to air pressure and density. Since the mixture of air, water vapor and carbon dioxide was assumed to be an ideal gas according to the air ideal gas law, it is reasonable to conclude that this was the main reason of high level of under-predicted relative humidity. Nevertheless, it can be observed that the model verification was at acceptable level.

6.2.3 Thermal Comfort Indices

Based on *PMV/PPD* thermal comfort model, the variables of air temperature and *PMV* were presented at the two horizontal planes, located at the ground and gallery levels. Both planes were located at vertical level of 1.2 m above both the ground and gallery floors of the lowest seats row (the highest rows). It is approximately the breathing level of highest person position, both at the

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ground and gallery levels. Distribution of these variables is shown in the Fig.53 and Fig.55, for ground level and in Fig.54 and Fig.56, for gallery level, respectively.

Approximately, the homogenous fields of air temperature and relative humidity were obtained. The average values were between 24.7 $^\circ$C and 47 % in the ground level and between 25 $^\circ$C and 46.7 % in the gallery level.

The range of *PMV* index was from -1.0 to +1.0. However, both occupants ground and gallery zones were of A class (-0.2 to +0.2). Lower and higher values of A class of *PMV* index occurred in the micro zones near the backward walls of ground and gallery levels, respectively.
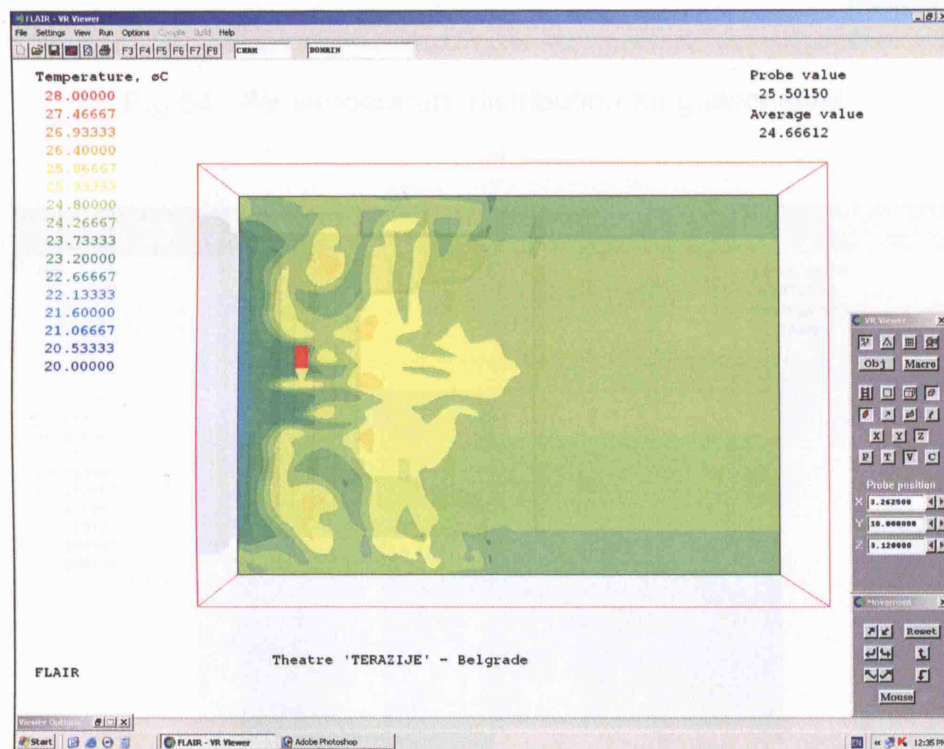
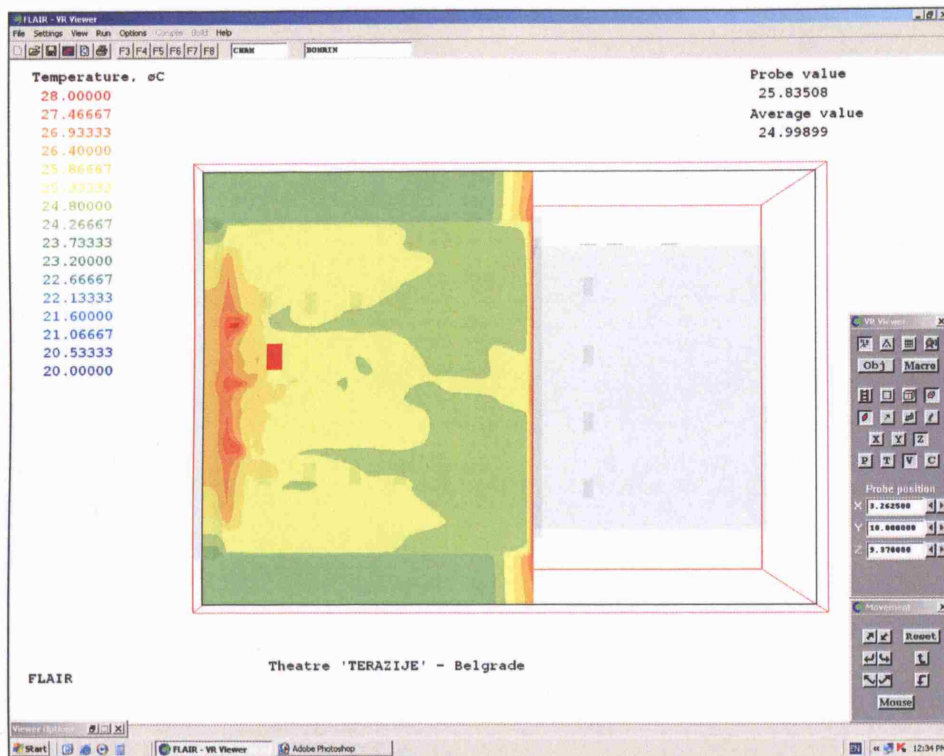**Fig.53.** -Air temperature distribution for ground level

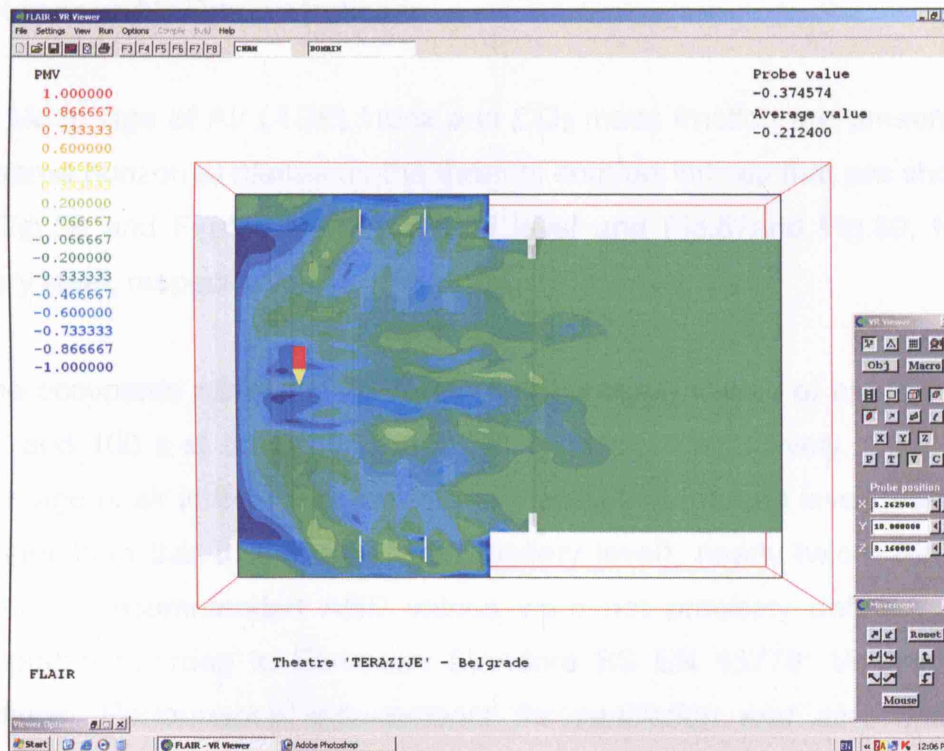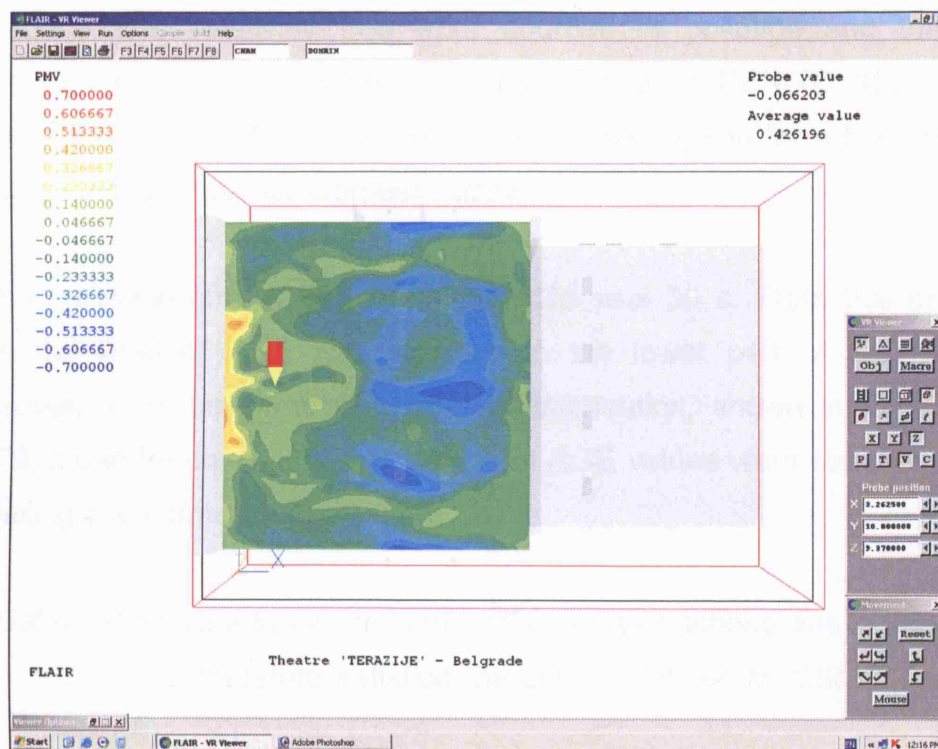**Fig.54.** -Air temperature distribution for gallery level

Fig.55. -*PMV* distribution for ground level

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Fig.56. *-PMV* distribution for gallery level

## 6.2.4 Indoor Air Quality Indices

The Mean Age of Air (*AGE*) index and CO_2 mass fraction are presented at the same horizontal planes as the thermal comfort indices that are shown in the Fig.56 and Fig.58, for the ground level and Fig.57and Fig.59, for the gallery level, respectively.

In the occupants zones the *AGE* had the averaged values of approximately 50 s and 100 s at the ground and gallery levels, respectively. Clearly, the mean age of air in the lower part of the theatre hall (ground level) was much younger than that in the upper part (gallery level), nearly twice. Since the criteria of recommended AGE values were not precisely defined; it was acceptable referring to European Standard BS EN 13779: *Ventilation for buildings. Performance requirements for ventilation and air-conditioning systems,* which provides the basic definitions of air quality standards in occupied spaces and relates these to fresh air ventilation rates required for each occupant (in terms of L/s per person). It is important to note that these definitions relate to comfort air quality and do not necessarily reflect the purity of air with respect to health related contaminants. It was assumed that

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the space was relatively free from sources of pollution and that the ventilation air itself was pure. European Standard CEN/TC 156 (2005) requires a minimum ventilation rate of 10 L/s per person for a high level of expectations for most non-domestic applications.

Based on these criteria, the averaged *AGE* was 30 s. From this point of view, the level of *AGE* was satisfied in the lower part of the theatre. Moreover, from the point of *AGE* local distribution, shown in Fig.68 and Fig.70, it can be concluded that criteria of AGE values were satisfied in the prevailing occupants zones.

Ventilation effectiveness Ev, defined by CO_2 mass fractions was in the range of 0.9 to 1.0 and therefore satisfied the criteria defined by CIBSE Guide A (paragraph 1.8).
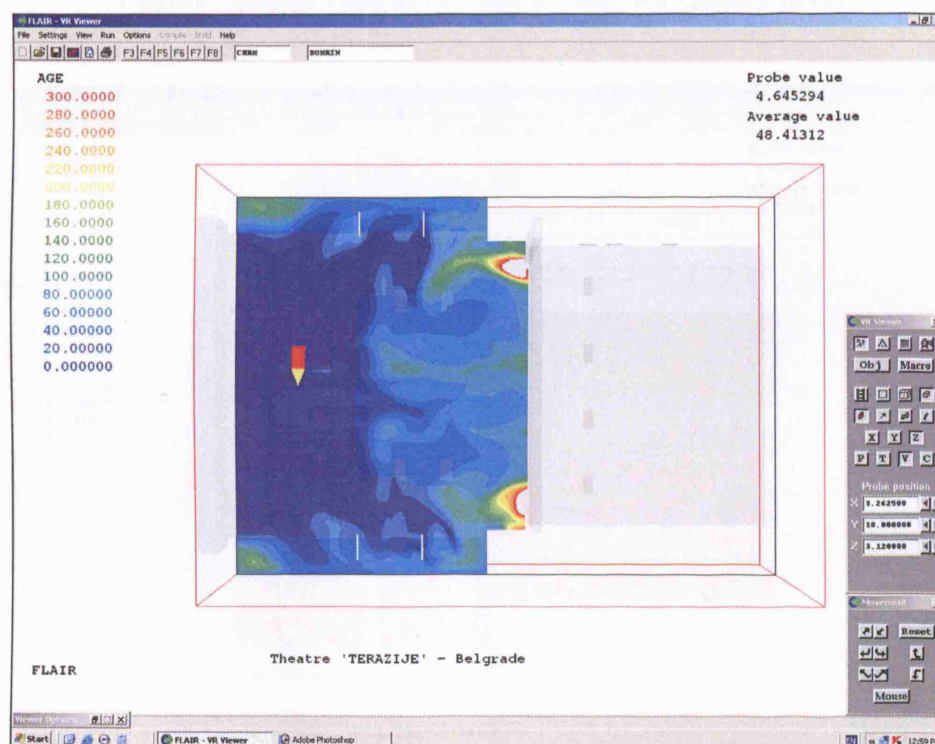
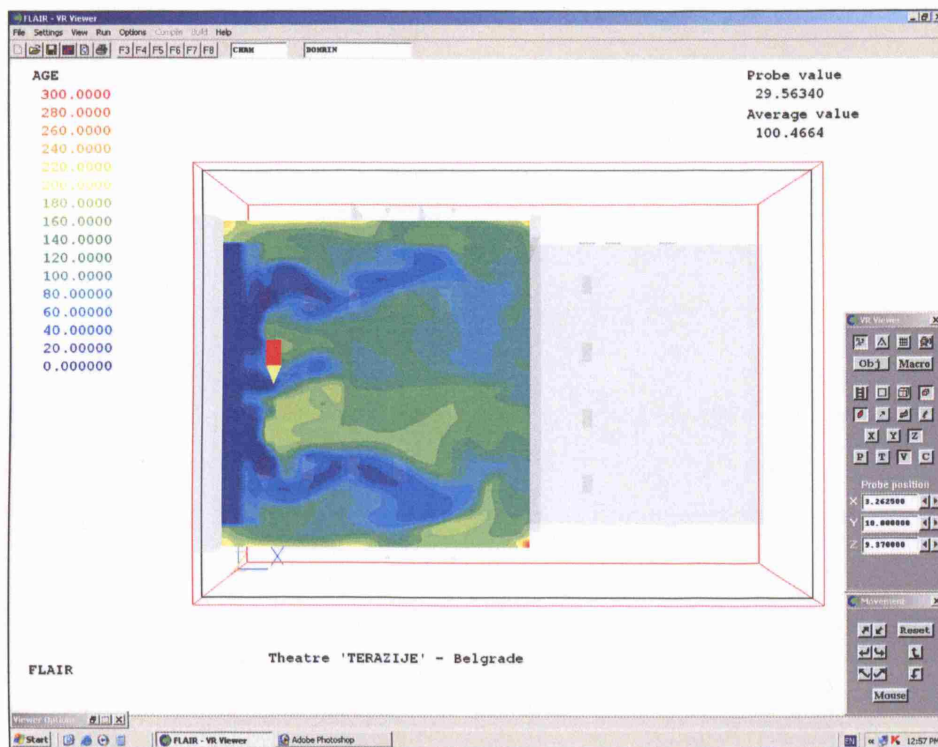**Fig.56.** -Mean Age of Air distribution for ground level

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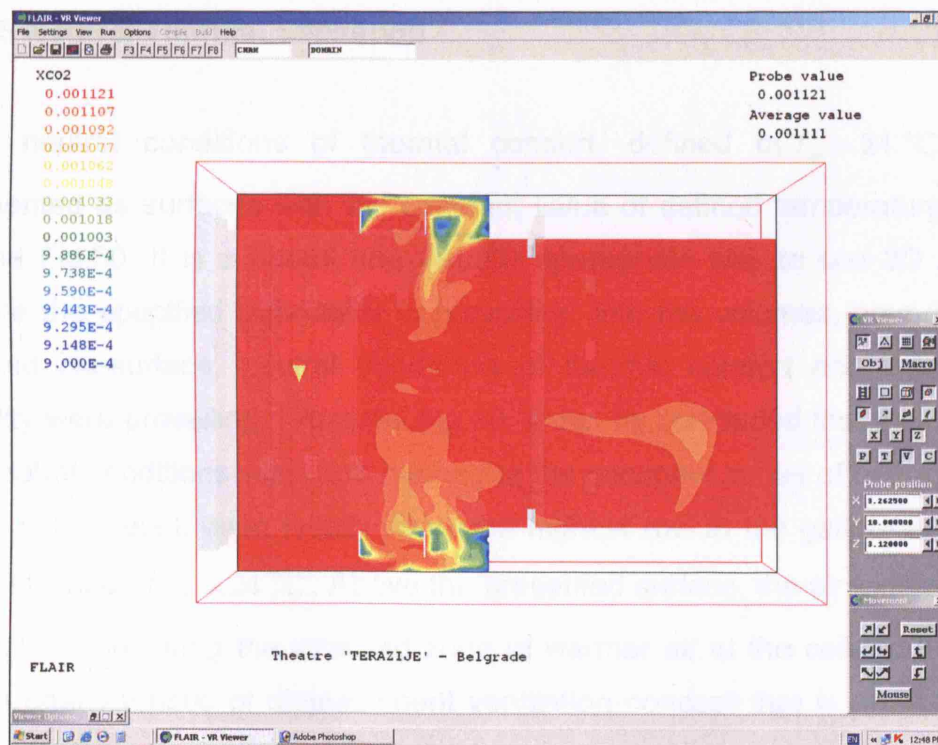
Fig.57. -Mean Age of Air distribution for gallery level

Fig.58. -CO$_2$ mass fraction distribution for ground level
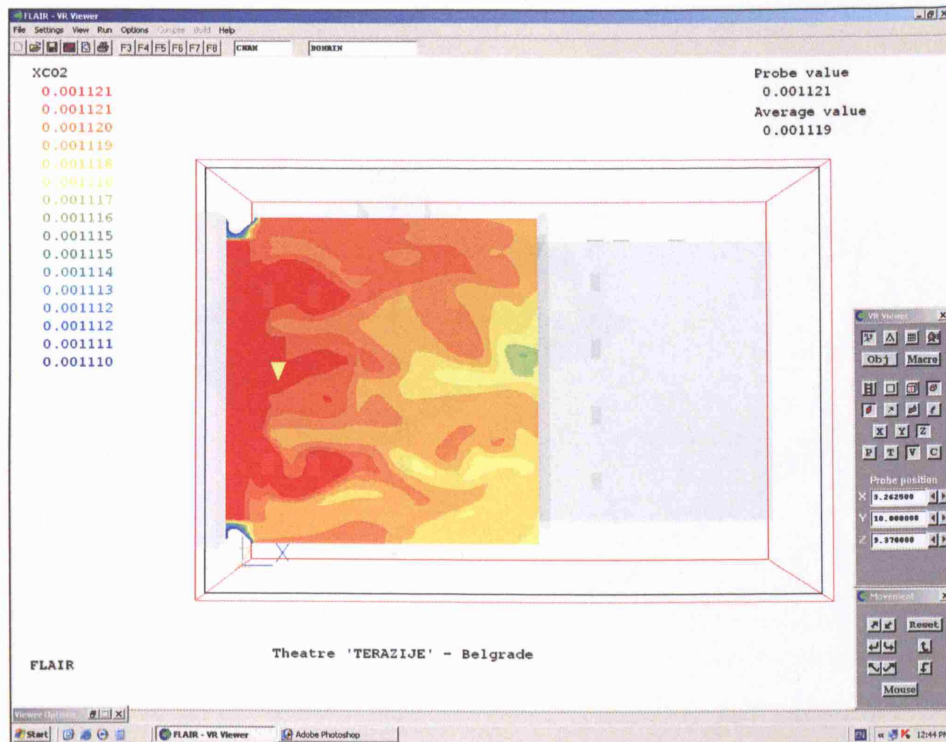
Fig.59. -CO$_2$ mass fraction distribution for gallery level

6.2.5 Neutral Thermal Sensation

The neutral conditions of thermal comfort, defined by $T_{ai} = 24\ ^\circ C$, are presented as surfaces with the constant value of defined temperature level in the Fig.60. It is a useful and visually appropriate way to see 3D zones where the specified parameter is prevailing. Into the volumes, bounded by related iso-surface, neutral conditions of thermal comfort and indoor air quality were prevailing. From the Fig.60, it can be concluded that the criteria of neutral conditions were approached to the occupant zones of both ground and gallery level, even locally. Only the highest row at the gallery exceeds critical value of $T_{ai} = 24\ ^\circ C$. Above the presented surface, the air temperature is higher, indicating the stratified zone of warmer air at the ceiling. It is the main characteristic of displacement ventilation concept that is proved both numerically and experimentally.

Fig.60. -Iso-surface of neutral air temperature

CHAPTER 7: Discussion and Conclusions

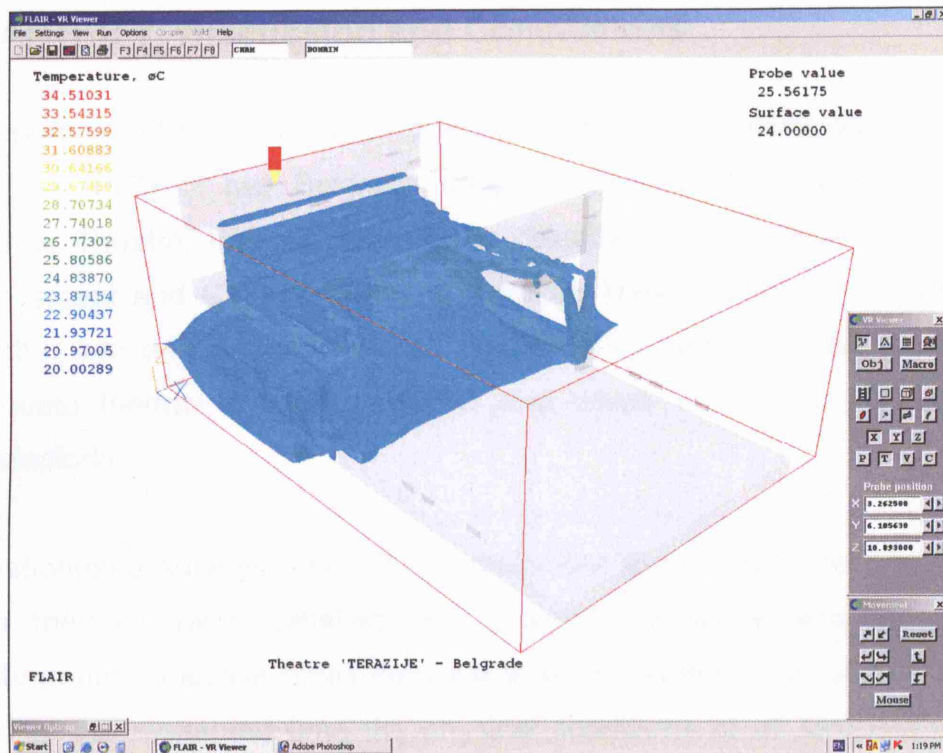The purpose of this study was to compare thermal comforts and indoor air qualities (IAQ) of two Belgrade theatres, Belgrade Drama Theatre and Terazije Theatre. Results obtained by objective measurements, subjective assessment and CFD modeling of Terazije Theatre enabled investigation whether two different mechanical ventilation systems are able to provide adequate thermal comfort and IAQ and which of them performs more satisfactorily.

Questionnaire surveys have shown that more than 50% of respondents in both theatres were satisfied with internal conditions and air quality. Furthermore, objective measurements in both theatres have shown that for most of the measured time the physical conditions of air temperature, air velocity, relative humidity, and CO_2 concentration were within the limits set by the ISO Standard 7730. Yet, air temperatures in both theatres on a number of occasions reached the extreme values. Moreover, in Belgrade Drama Theatre the maximum CO_2 concentration of 1156 ppm during the occupancy was above the recommended limit of 1000 ppm. This could have been caused by a much higher average air ventilation rate of 14.9 l/s in Terazije Theatre, while the average air ventilation rate in Belgrade Drama Theatre was 9.5 l/s. Therefore, it can be concluded that displacement ventilation system designed in Terazije Theatre performs slightly better than the mixing ventilation system designed in Belgrade Theatre.

From the facility manager of Belgrade Drama Theatre it was found out that during the performances the mechanical ventilation system works in the lower regime because of the noise it makes. However, in these conditions the system was unable to cope with the peak occupancy level. Therefore, the advice for the project company which carried out the work would be either to use the sound-attenuating background ventilators, or a better inner insulation of the supply ducts, since their enlargement was not possible due to the existing auditorium form. However, inner isolation of supply ducts is expensive and very difficult to maintain.

Moreover, it has been discovered that the most frequent problem Terazije Theatre public faces is the unpleasant draught from the supplying grilles located beneath the seats which causes discomfort of cold feet. Therefore, the advice to the project company would be either enlargement of the supply ducts and inlet grilles, which would decrease the inlet velocity of the air or relocation of the inlet grilles to a sufficient distance from the occupants. Furthermore, the supply air temperature should not be lower than 18 °C for sedentary occupancy.

Displacement ventilation installed in Terazije Theatre has many advantages over the traditional mixed flow ventilation strategy applied in Belgrade Drama Theatre for the following reasons: this system is considered to provide 'less polluted' air within the occupied zone and is 100% fresh air based; it is also thought to be energy efficient in that both fan power and cooling requirements are reduced. Only the occupied zone is conditioned, not the entire space and the potential for 'free cooling' is maximised as supply air temperatures are usually 19-20 °C; displacement ventilation can be employed for many applications and building types. However, in displacement ventilation, air movement above the occupied zone is often mixed and it is when this mixed region extends down into the occupied zone that the air quality becomes similar to that in a mixed flow system. Furthermore, displacement strategies have some restrictions such as: adequate floor to ceiling heights are required, a minimum floor to ceiling height of 2.7 m is recommended; there is limited cooling capacity unless it is combined with active cooling systems such as chilled beams; appropriate diffusers must be selected. Moreover, there are conditions under which mixing ventilation is more effective than displacement strategies, such as: where the supply air is warmer than the room air (except under particular circumstances where cold downdraughts exists over the supply position); where contaminants are cold and/or more dense than the surrounding air; where surface temperatures of heat sources are low; where ceiling heights are low; where disturbance to room airflows is unusually strong. In addition, the advantages of mixing ventilation are: mixing systems allow for recirculation, although the mixing within the space must be uniform; the system performance is not dependent upon room height or room layout; air

can enter the space either via the floor or via the ceiling. Furthermore, ceiling-based supply system applied in Belgrade Drama Theatre allows greater flexibility of furniture layout and also allows heat to be more efficiently extracted from light fittings (CIBSE Guide B).

For Terazije Theatre CFD tools were used to simulate IAQ and the indoor comfort parameters such as temperature, airflow rate and relative humidity. Corroboration between results from the objective measurements and predicted values was conducted. It can be concluded that the air temperature and volume fraction of carbon dioxide were at the acceptable predicted level.

Furthermore, approximately the homogenous fields of air temperature and relative humidity were obtained. The average values were between 24.7 $^{\circ}C$ and 47 % in the ground level and between 25 $^{\circ}C$ and 46.7 % in the gallery level. However the predicted level of relative humidity was too high. This was expected s ince t he mixture o f air, w ater vapor a nd c arbon d ioxide was assumed to be an ideal gas according to the air ideal gas law. Therefore, this was the main reason of high level of under-predicted relative humidity. Nevertheless, it can be observed that the model verification was at acceptable level. The range of PMV index was from -1.0 to +1.0. However, both occupants ground and gallery zones were of A class (-0.2 to +0.2). In the same zones, PPD and DR indices were below 15%. Lower and higher values of A class of PMV index occurred in the micro zones near the backward walls of ground and gallery levels, respectively. At the same micro zones, PPD a nd DR indices h ad greater v alues than 15%, but did not exceed 25%. Moreover, in the occupants zones the mean age of air (AGE) had the averaged values of approximately 50 s and 100 s at the ground and gallery levels, respectively. Clearly, the mean age of air in the lower part of the theatre hall (ground level) was much younger than that in the upper part (gallery level). Since, the criteria of recommended AGE values were not precisely defined; it was acceptable referring to European Standard BS EN 13779: V entilation f or b uildings. V entilation e ffectiveness E v, w as in t he range of 0.9 to 1.0 and therefore satisfied the criteria defined by the (CIBSE Guide A).

The auditoriums' forms significantly influenced the choice of the mechanical ventilation strategies, especially in Belgrade Drama Theatre where old supplying and extracting ducts were preserved. Therefore, the applied mixing ventilation strategy with ceiling-based supply system was the only possible solution.

On the other hand, in Terazije Theatre a completely new system was designed. However, the auditorium form also conditioned the applied strategy for the following reasons: in the gallery level only displacement ventilation was possible due to the low ceiling height; in the ground level mixing ventilation was possible. However, because of high ceiling height air inlet velocities would be higher, which could cause discomfort to the occupants. On the other hand, applying the wider supplying ducts was not possible because of the limited space. The enlargement of the designed supplying ducts and inlet grilles, beneath the seats, was also restricted due to the limited space.

To summaries, considering the budget that was available to the construction company as well as the original state of the two theatres, it can be argued that the systems installed during the restoration were the best solution possible. The analysis performed in this dissertation reaches the conclusion that these systems meet the needs of the theatres and adequately fit in the construction of the building.

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Appendix A:

A sample of the questionnaire survey

1. Gender:

   Male   ☐   Female   ☐

2. Do you often experience following symptoms:

   Dry eyes   ☐   Dry or irritated throat   ☐

   Watering eyes   ☐   Headaches   ☐

   Block or stuffy nose   ☐

   Chest tightness and breathing   ☐

   Runny nose   ☐

3. Have you ever had asthmatic problems?   ☐

4. Have you ever suffered from sinusitis?   ☐

5. Are you currently a smoker?   ☐

6. Do you wear contact lens?   ☐

7. How would you describe your typical level of thermal comfort in this auditorium?

   Comfortable   ☐

   Slightly   ☐

   Uncomfortable   ☐

   Very uncomfortable   ☐

8. How would you describe the indoor conditions in this auditorium?

   Temperature:

   Cold   ☐   O.K.   ☐   Warm   ☐

   Humidity:

   Dry   ☐   O.K.   ☐   Humid   ☐

   Air movement:

   Still   ☐   O.K.   ☐   Draughty   ☐

Air quality:

Fresh   ☐   O.K.   ☐   Stuffy   ☐

Loudness of the mechanical ventilation system:

Quiet   ☐   Tolerable   ☐   Loud   ☐

Overall impression:

Satisfactory   ☐   O.K.   ☐   Unsatisfactory   ☐

9. How would you describe the cleanliness of this auditorium?
   Satisfactory   ☐   Unsatisfactory   ☐

10. Do you detect any odour in this auditorium?
    Yes   ☐   No   ☐

(If yes, please indicate against the relevant sources)

Cigarettes   ☐

Food   ☐

Others   ☐