A NUMERICAL STUDY FOR THE ASSESSMENT OF POLLUTANT DISPERSION FROM KOSTOLAC B POWER PLANT TO VIMINACIUM FOR DIFFERENT ATMOSPHERIC CONDITIONS

by

Mirko S. KOZIĆ [a], ***Slavica S. RISTIĆ*** [b*],
Srdja M. ŠTETIĆ KOZIĆ [c], **and *Suzana R. POLIĆ*** [d]

[a] Military Technical Institute, Belgrade, Serbia
[b] Institute Goša, Belgrade, Serbia
[c] Faculty of Electrical Engineering, University of Belgrade, Belgrade, Serbia
[d] Central Institute for Conservation, Belgrade, Serbia

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The level of pollution concentration to the archeological site Viminacium caused by the stack of Kostolac B power plant is analysed using CFD software. The wind is directed from the stack toward Viminacium-Archeological Site, Therma and Viminacium-Museum. Three different meteorological conditions resulting in fanning, fumigating, and looping plume are modelled. The temperature gradient as the most important factor defining the conditions of the atmosphere is included through the appropriate boundary conditions. It is shown that concentrations of the pollutants on the objects of Viminacium are very low. It can be attributed to the stack height and high temperature of the smoke at its exit. It also indicates that other sources of pollution such as open ash dumps and acid rain should be checked.

Key words: *numerical simulation, CFD, power plant, pollution, Viminacium*

Introduction

The main sources of air pollution in the region of Kostolac in Serbia are thermal power plants Kostolac A and Kostolac B, erosion from mining zones and open storage yards of fuel, fly ache, and slag, dust scattering during coal unloading and spontaneous combustion of outdoor coal storage yard. Combustion of a coal in the power plants produces large quantities of different residues, which are very harmful to the environment. The emissions include sulphur oxides, nitrogen oxides, carbon monoxide, carbon dioxide, hydrocarbons, mercury, arsenic, lead, cadmium, and other heavy metals. It is known that, among the global environmental problems, global warming effect and acid rain are associated most with the air pollution problems of thermal power plants. Company PD TE-KO Kostolac has set the international standard ISO 14000, but beside that, there is some environmental influence caused by its activities.

Protection of the thermal power plant environment is an important environmental problem worldwide. Atmospheric pollutant spread, coming from stack and from coal and ash storage yards needs to be determined in such zones. It can be done by field measurements and/or

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* Corresponding author; e-mail: s1avce@yahoo.com

using some of dispersion models. The field measurements cannot always be made or give limited quantity of data, and dispersion models are the only available tool for obtaining the complete insight in the environment pollution. This problem has been examined in many independent studies. There are a lot of literature concerning on it. Authors in ref. [1] examined the NO_x and SO_2 emission factors for Serbian lignite Kolubara and announced that the next research will be focused on determination of NO_x and SO_2 emission factors for second Serbian lignite Kostolac. Analysis of the processes that take place in the atmosphere with the emissions of SO_2, NO_2 and particles from thermal power plant and formation of secondary pollutants in the Stara Zagora region and in Šalek valley, Slovenia (Šoštanj thermal power plant), are presented in [2, 3]. In paper [4] authors intended to present possibilities of implementation of advanced control concepts, in selected thermal power plants, in order to increase plant efficiency and to lower pollutants emissions.

There are different methods of experimental, numerical and theoretical researches of the air pollution and protection of the thermal power plant environment. Numerical simulation of the flow is the most economical, fastest, and very reliable method for this purpose. Computer fluid dynamics (CFD) numerically simulate various phenomena in fluid mechanics and regardless of their potential to model the wind [5] and the flow of pollutants for large-scale environmental applications, these have not been yet established as a routine technique [6]. The applications of CFD for pollution dispersion have shown their capabilities during last decade. Comparisons of the CFD results with wind tunnel ones and field measurements, in general, support such approach [7].

The influence of pollution emitted from the stack of Kostolac B power plant to the archaeological site Viminacium, that is less than 2 km far away, is analysed with different methods. In the environment of thermal power plants, there is a risk for the degradation of heritage object material, due to emission of harmful gases and strong sources of dust and ashes [8].

Spreading of harmful substances produced by combustion of a coal in the power plants were analysed [9, 10]. Simulations of the dispersion from a waste incinerator, in different meteorological scenarios, are presented in [11].

Preventive care, research, and restoration of the cultural heritage objects require multidisciplinary approach and involvement of different profiles experts, using high technology equipment. Non-destructive methods and methods of numerical simulations dominate in the diagnosis and protection of cultural heritage objects.

Thermal plant Kostolac B and archeological site Viminacium

Kostolac B power plant has a generating power of 300 MWh. It has one stack 250 m tall and burns sub bituminous coal with an average ash content of 22.2 wt.%. Modern thermal power plants are complex systems where multiphase flow of re-circulation gases, coal powder, sand and other materials directly influences ventilation efficiency of the mill and emission of pollution [12-14]. The pulverization of coal into fine particles is made in ventilation mills (coal pulveriser) to increase the specific surface area and to optimize the rate of heat and mass transfer between the coal particles and surroundings hot gas [15]. An efficient and stable combustion of pulverized coal particles depends upon the physical and chemical properties of coal, the diameter of coal particles and other operating conditions like temperature, pressure and parameters of fluid-dynamic state of the gas mixture [1]. In today's world, increasingly attention to the efficiency of thermal power plants is paid because of economical and environment protection. The papers [12-14] gives the results of the multiphase flow simulation inside the ventilation mill in

Kostolac B power plant in Serbia, using CFD software package ANSYS FLUENT, made to increase the efficiency of thermal plants.

Thermal power plant Kostolac B is equipped with cold side Electro Static Precipitators (ESP) [15, 16]. Stack-emitted particles consist of organic fragments, coal minerals, combustion by-products of coal minerals, and contaminants. Environmental protection measures are taken to reduce pollution from the power plant. In order to check the level of pollution in the surrounding of the thermal power plant and archeological site Viminacium [17], some samples, were taken. SEM and EDX analyses showed that the surfaces of the samples are covered by particles, which may come from plant stack or from open fuel and ache yards [11]. For these reasons, numerical simulations are very important in the study of air pollution area determination under different conditions.

Viminacium was the most important city in the Roman Moesia Superior province [17]. This Roman city was the capital of the province, the administrative, military, commercial, and industrial centre, the city with full autonomy. Viminacium is located in area of about 450 ha. It had been created in the first century, disappeared in the seventh century when Slavs arrived. Since 2002, parallel archeological and multi-disciplinary researches have been systematically carried out in the area of Roman city, Roman legion archeological camp and necropolises.

Numerical model

Three-dimensional numerical simulations have been employed to simulate the wind flow structure over a real coal burned plant site configuration. Dispersion models serve in prediction of pollutant concentrations due to plume spreading by solving a set of equations. These models must involve variables that mostly influence plume dispersion, *i. e.* temperature gradient and wind speed, along with stability and relief map. There are four generic types of dispersion models: Gaussian, statistical, numerical, and experimental. The Gaussian models use the Gaussian distribution equation where the plume spread is given by the root mean square plume widths in the crosswind and vertical directions [18].

In more recent models of this type such as US EPA's AERMOD (AERMOD, American Meteorological Society and US Environmental Protection Agency, EPA) and UK's ADMS 3 (DMS 3, Cambridge Environmental Research Consultants, UK Meteorological Office, National Power, University of Surrey), developments in the field of turbulent motions in unstable conditions, are included. Statistical models are based upon established relationships and usually used in simple urban air pollution modelling when there is no precise data about physical and chemical processes of a source and either Gaussian or numerical models are not expected to be accurate enough. Numerical models are based on fundamental physics, deal with detailed 3-D geometry and local environment conditions, avoiding most limitations of the Gaussian and statistical models [5, 7]. They are especially well suited for sources with reactive pollutants in urban locations but require detailed information about source, pollutants, geometry and meteorological conditions. Experimental models require production of complex and expensive scaled model, wind tunnel tests and visualization of the flow around the model. Experimental models must be used when achieving accurate insight of pollution dispersion is very important but results obtained from the others are not reliable enough. Selection of the model to be used is primarily dependent on the complexity of the landscape and source of pollution, type of pollutants being emitted and meteorological conditions [7].

The influence of pollution emitted from the stack of Kostolac B power plant to the archeological site Viminacium is analysed using CFD commercial software ANSYS FLUENT. The wind direction is from the stack toward Viminacium-archeological site and Viminacium-

-museum, while its speed is defined according to wind rose [19]. Three different atmospheric conditions chosen to generate fanning, fumigating, and looping plume are analysed. The temperature gradient as the most important factor defining the conditions of the atmosphere is included through the appropriate boundary conditions on the inlet, upper and lateral sides of the numerical domain. The Pasquill stability classes [20] are used in categorizing atmospheric turbulence. The level of pollution on the objects of Viminacium should show the real impact of the pollutants from the stack and indicate the possible influence of other sources.

This paper presents the results of 3-D numerical simulations of pollution spread on the archeological site Viminacium, to highlight the influence of the atmospheric condition..

Pollutants transport equations

The transport and mixing of chemical species are modelled in ANSYS FLUENT [21]. The model includes convection, diffusion, and reaction sources for species. The local mass fraction for *i*-th species is calculated from general conservation equation given as:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla(\rho \vec{\upsilon} Y_i) = -\nabla \vec{\mathrm{J}}_i + R_i S_i \tag{1}$$

where Y_i is the local mass fraction, $\vec{\mathrm{J}}_i$ – the diffusion flux for *i*-th species, R_i – the net rate of production of species *i* by chemical reaction, S_i – the rate of creation by addition from the dispersed phase, ρ – the density, and v – the velocity.

In the energy equation for multicomponent mixture the transport of enthalpy h_i due to species diffusion should be taken into account for its significant influence on the enthalpy field. There was no need to write the complete energy equation, but only the term (2) that represents energy transfer due to species diffusion.

This term is given as:

$$\nabla \sum_i h_i \vec{\mathrm{J}}_i \tag{2}$$

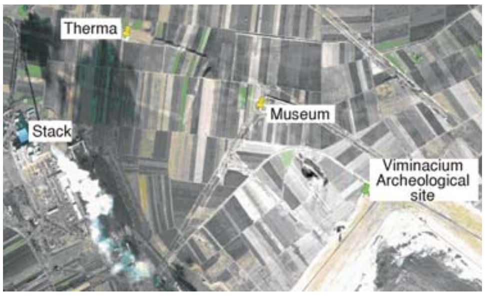

Figure 1. Map of the terrain around Kostolac B power plant, view from above of power plant stack and three objects of Viminacium

Numerical modelling

The computational domain is 6000 m long, 5000 m wide and 1000 m high. Digitalized data with nodes every 25 m in both directions are used to describe the terrain [22]. The stack height is 250 m, with diameter of 9.8 m at the exit. The model also includes simplified buildings of Viminacium-Archeological site, Viminacium-Museum and Viminacium-Therma (fig. 1).

An unstructured volume mesh of 2,983,911 tetrahedral cells is generated. The volume mesh is shown in fig. 2(a), while surface mesh on the ground and lower part of the stack can be seen in fig. 2(b).

Steady solution is obtained solving the Reynolds averaged Navier-Stokes equations. The standard *k*-*ε* turbulence model is employed. Buoyancy is included in the calculation. Dispersion of the pollutants from the stack and plume shape is mostly influenced by the wind velocity, vertical gradient of temperature and turbulence at the inlet (inlet is a part (surface) of the numerical domain where fluid enters the domain, and where boundary conditions must be specified). In order to model different states of the atmosphere properly, appropriate temperature profiles are defined on the lateral sides of the numerical domain. The SLIP WALL was set and temperature profile was defined by User Defined Function (UDF). For upper boundary of the domain SLIP WALL was also used with constant temperature compatible with one on the lateral sides. The flow field is initialized with the same temperature profiles.

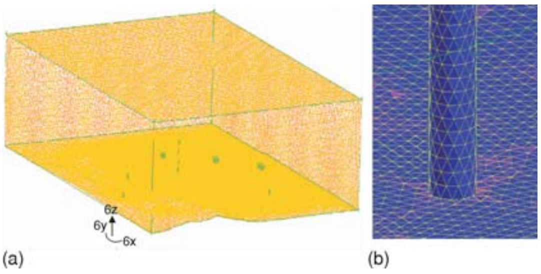

Figure 2. Volume mesh in the whole domain (a); surface mesh on the ground and lower part of the Smoke stack (b) *(for color image see journal web-site)*

The inlet wind profile is represented by a simple power low given as:

$$\frac{u}{u_{\mathrm{ref}}} = \left(\frac{z}{z_{\mathrm{ref}}} \right)^{p} \tag{3}$$

where u_{ref} is the wind speed at the reference height z_{ref} while power law index p is a function of the roughness length and stability of the atmosphere [23, 24]. The velocity profile can be shown along any chosen line in the domain, *i. e.* the wind profile in the domain will be changed due to the influence of the ground and solid walls of the stack and archaeological objects. The exit of the domain is modelled as an outflow. Standard no-slip condition is applied along with constant temperature and zero normal flux of all species on the ground. Velocity and temperature of the smoke gas at the exit are 19.1 m/s and 443 K, respectively. The mass fractions of pollutants defined at the exit of the stack are:

$$Y_{\mathrm{SO_2}} = 3.199 \cdot 10^{-3}, \quad Y_{\mathrm{NO}_x} = 2.798 \cdot 10^{-4}, \quad Y_{\mathrm{CO}} = 2.062 \cdot 10^{-5}, \quad Y_{\mathrm{CO_2}} = 0.154 \tag{4}$$

Results and discussions

Numerical simulations are performed for wind blowing in the direction from the stack toward archeological site and Viminacium-museum. Three different conditions of the atmosphere are modelled resulting in different plume shape and level of pollution at buildings of Viminacium.

The first condition is related to moderately stable atmosphere that occurs during clear nights, slight wind between 2 and 3 m/s and inversion, giving fanning plume. This condition refers to Pasquill stability class F [21]. In the calculation wind speed at height of 10 m and temperature of the terrain are 2.9 m/s and 288 K, respectively. According to relation between Pasquill-Turner stability categories and temperature gradient given in [20-25], its value is set to 1.6 °C/100 m. In fig. 3 side and top view of the plume shape are shown.

Figure 4 shows mass concentration of SO_2 in the vertical plane perpendicular to the wind direction and placed at Viminacium-archeological site. Details of the concentration on the surface of archeological site and museum are given in fig. 5 showing higher values on the former. The highest value of SO_2 concentration is below 1 ppb. It should be mentioned that for all three considered atmospheric conditions, mass concentrations of NO_x and CO compared to SO_2, are one and two order of magnitude lower, respectively.

The second model includes state of the atmosphere at dawn after calm and clear night with slight wind, when night inversion near the ground disappears due to heating. The stable lower layer of the atmosphere is transformed into very unstable with super-adiabatic lapse rate, in time

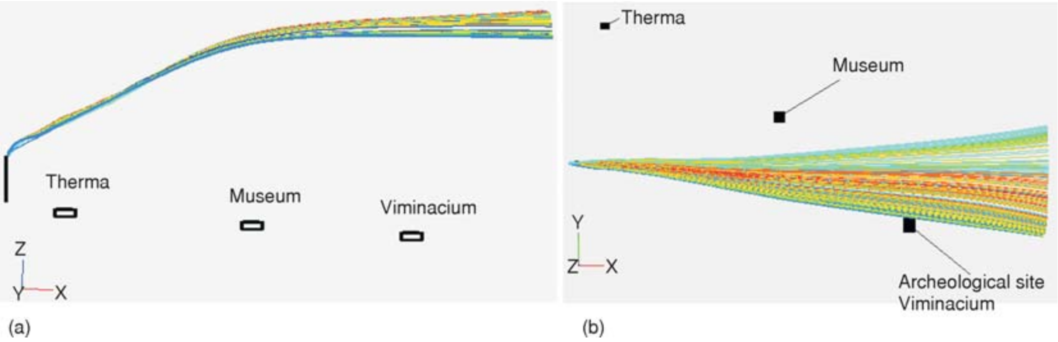

Figure 3. Fanning plume, wind speed 2.9 m/s, terrain temperature 288 K, temperature gradient 1.6 °C/100 m; (a) – side view, (b) – top view *(for color image see journal web-site)*

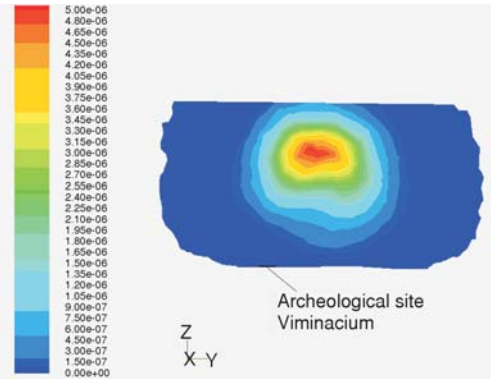

Figure 4. Mass concentration of SO_2 in vertical plane perpendicular to wind direction and passing through archeological site, wind speed 2.9 ms^{-1}, terrain temperature 288 K, temperature gradient 1.6 °C/100 m
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less than one hour. But still there is inversion above the unstable layer resulting in fumigating plume. The calculation is performed with wind speed 2.9 m/s at height of 10 m, terrain temperature 288 K, lapse rate –1.8 °C/100 m and inversion temperature gradient 2 °C/100 m. Three cases are considered with inversion starting at 150, 250, and 350 m. Because the mass concentration of SO_2 on archeological site and museum is largest for inversion starting at 150 m, results are shown only for this case.

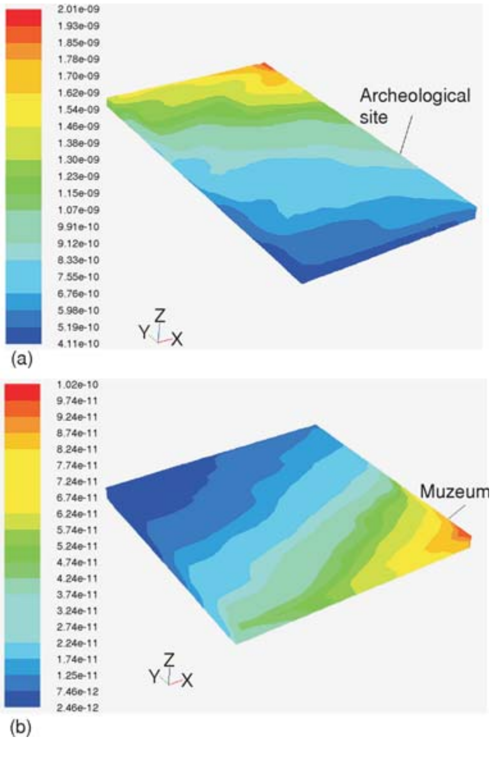

Figure 5. Mass concentration of SO_2 on the surface of archeological site and museum, wind speed 2.9 ms^{-1}, terrain temperature 288 K, temperature gradient 1.6 °C/100 m
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Details of the SO_2 concentration on the archeological site and museum can be seen in fig. 7, showing that highest value is about 10 ppb, *i. e.* one order of magnitude larger than for fanning plume.

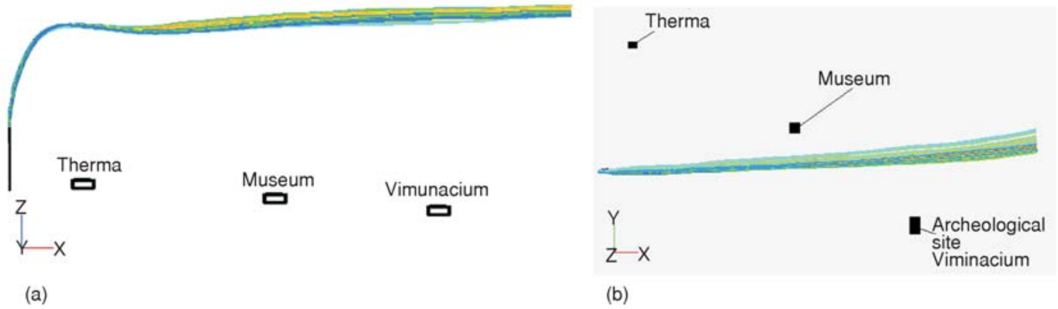

Figure 6. Fumigating plume, wind speed 2.9 m/s, terrain temperature 288 K, lapse rate –1.8 °C/100 m, inversion temperature gradient 2 °C/100 m, inversion starts at 150 m; (a) side view, (b) top view
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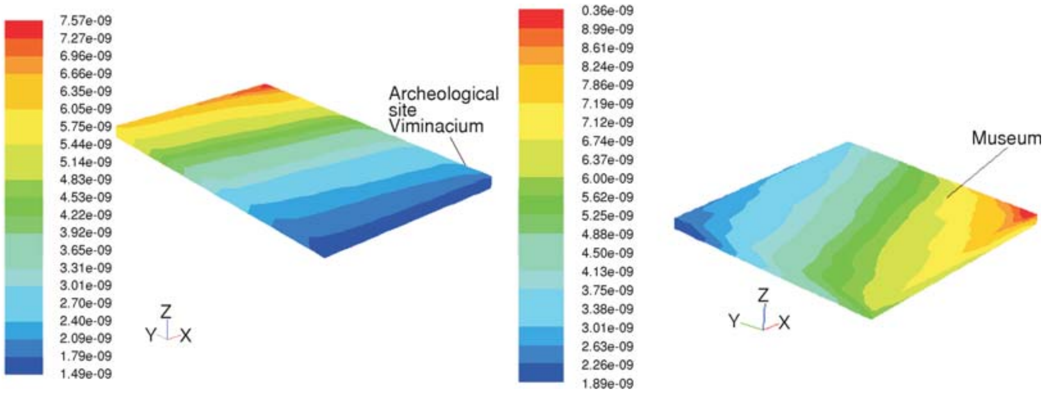

Figure 7. Mass concentration of SO_2 on the surface of archeological site and museum, wind speed 2.9 m/s, terrain temperature 288 K, lapse rate –1.8 °C/100 m, inversion temperature gradient 2 °C/100 m, inversion starts at 150 m *(for color image see journal web site)*

In the third model we set conditions corresponding to Pasquill stability class A-B, between extremely and moderately unstable atmosphere. This condition occurs during sunny days with strong solar radiation warming ground, slight wind between 2 and 3 m/s and super-adiabatic lapse rate in the range from –1.9 to –1.7 °C/100 m, characterized by looping plume. The calculation made with wind speeds 2.9 and 4.9 m/s at height of 10 m, terrain temperature 308 K, and lapse rate –1.8 °C/100 m gave constantly changing shape and position of the plume both in horizontal and vertical plane, fig. 8. High physical instability due to pronounced convection was not able to be resolved by the computation. For that reason we had to increase wind speed until it reached 8 m/s in order to obtain fixed plume shape and position, (fig. 9). This condition correspond no more to stability class A-B, but to slightly unstable atmosphere or Pasquill stability class C.

From fig. 9 it is obvious that plume lost its looping shape due to large wind speed. Now, atmospheric conditions are closer to neutral than to extremely or moderately unstable and mechanical turbulence prevail over thermal convection one [23-25].

Details of the mass concentration of sulphur dioxide on the surfaces of Viminacium buildings are shown. Obtained value of approximately 25 ppb is highest for all three modelled atmospheric conditions.

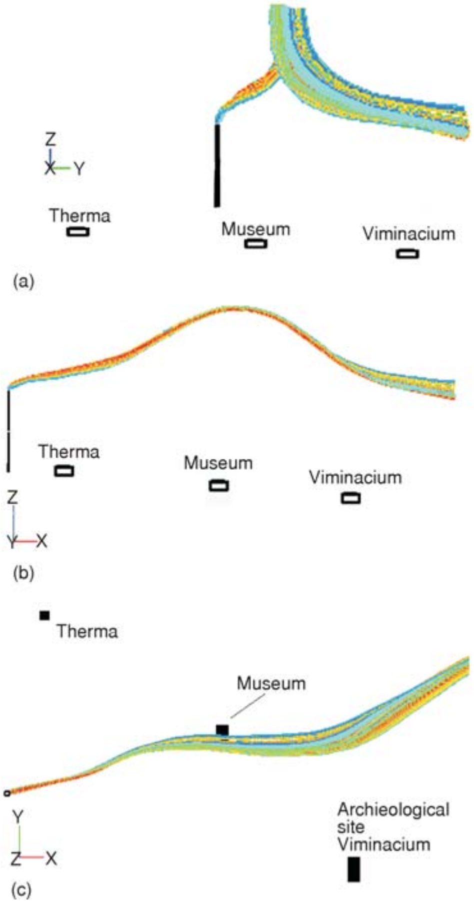

Figure 8. Looping plume at wind speed 4.9 m/s; (a) rear view, (b) side view, (c) top view
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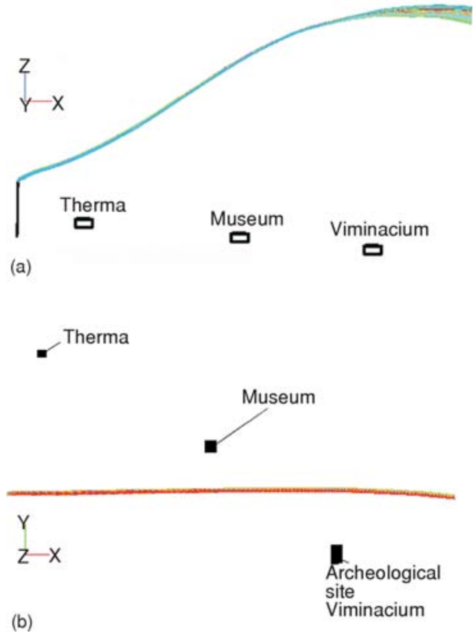

Figure 9. Looping plume at wind speed 8 m/s, terrain temperature 308 K, lapse rate –1.8 °C/100 m; (a) side view, (b) top view
(for color image see journal web site)

The concentration of the pollutants will vary in different atmospheric conditions but limit values are predefined by Law on air protection conducted by the state government with the help of measuring stations [26]. Limit values for SO_2 and NO_x in uninhabited area for different periods of time are given in tab. 1. For popu-

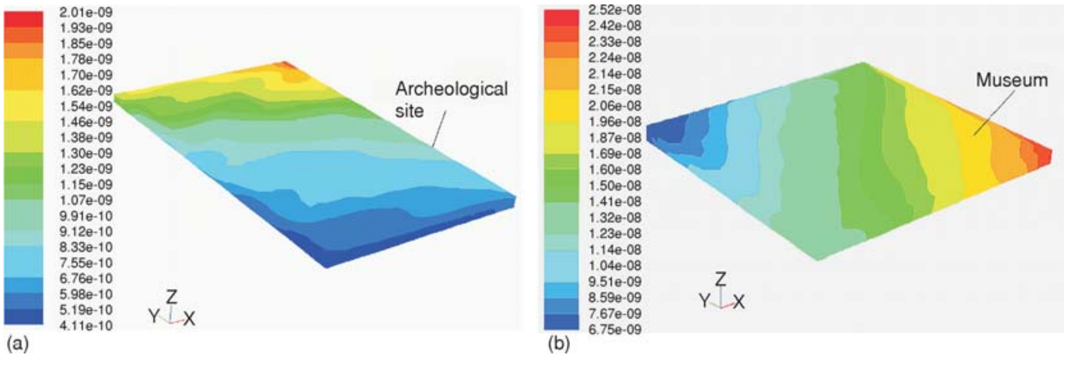

Figure 10. Mass concentration of SO_2 on the surface of archeological site and museum, wind speed 8 m/s, terrain temperature 308 K, lapse rate –1.8 °C/100 m *(for color image see journal web site)*

lated areas limit concentrations are equal only for period of 1 year, otherwise concentrations are larger.

Table 1. Polutant concentration in populated area

Period	Average concentration [mgm^{-3}]		Average concentration (at standard conditions) [ppb]	
	SO_2	NO_x	SO_2	NO_x
24 hour	100	70	35	34
1 hour	150	85	52.4	41.5
1 year	30	50	17.5	29.3

Conclusions

The influence of different atmospheric conditions on pollution dispersion from the stack of Kostolac B power plant is numerically modelled, in order to obtain concentration on the buildings of Viminacium-archaeological site and museum. Three different atmospheric conditions are defined with different temperature gradients and wind speeds. The direction of the wind is from the stack toward Viminacium. Fanning, fumigating and looping plume occur at considered temperature profiles. Commercial software ANSYS FLUENT is used in the numerical modelling and because of importance of the temperature gradient on the pollution dispersion, appropriate boundary conditions must be defined with care. Calculations show that for all considered atmospheric conditions, highest mass concentration of SO_2 on the buildings of Viminacium is about 25 ppb, *i. e.* very low indicating that the influence of an ash dumps and acid rains on Viminacium pollution must be investigated. Also, mass concentrations of NO_x and CO are one and two order of magnitude lower, respectively.

For atmospheric condition between extremely and moderately unstable, where thermal convection turbulence is pronounced, convergent solution wasn't obtained.

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