Journal of Chemical Technology and Metallurgy, 58, 3, 2023, 522-528

SIMULATION OF POLLUTANTS DISPERSION BY A STACK: A CASE STUDY

Fatemeh Bahadori

Faculty of Chemical Engineering
Urmia University of Technology, Urmia, Iran
E-mail: F.Bahadori@che.uut.ac.ir

Received 16 May 2022
Accepted 03 September 2022

ABSTRACT

The rapid growth of urbanization and industrialization cause the world face with the most important environmental issues of air pollution in many cities and industrial zones. In the present research, air pollution due to the emission of pollutants air quality is studied. Emission and dispersion of NOx from a stack located in an industrial zone are simulated based on the meteorological data. The geometry of the stack and surrounding area are selected from a power plant data. The analysis is individually performed for four seasons using the wind field and direction. It is shown that wind direction significantly affects the pollutants circulation zone. The pollutants inversion are unpreventable occurred in winter because of the mixing area is not well altitudinal extended.

Keyword: air pollution, NOx emission, stack, the wind, CFD.

INTRODUCTION

Air pollution is an undesirable mixture of solid particles and gasses in the air. Pollutant emission in industrial area and stacks disperse to urban zones and increases dangerous disease associated with the air quality along with environmental crisis of temperature arising due to greenhouse emission. The World Health Organization (WHO) estimates that 500 000 people die an early death each year due to exposure to concentrations of suspended materials in the air [1]. The main part of air pollutants produces during the combustion and chemical reactions [2]. The produced gasses leave the stack, mix with air and disperse in the environment [3]. Pollutant dispersion in the environment is influenced by several parameters such as velocity, temperature, and pollutant concentration of exhaust gasses, air temperature, wind speed and direction, stack construction, meteorology, and topography data [4]. Also, other parameters including type, height, and location of source term and its surrounding region affect the pollutant emission in the environment.

The pollutant can directly affect the world by warming the environment due to greenhouse gasses emission including CO_2, H_2O, and unburned hydrocarbons or toxic gasses that are hazardous materials for human and animals' health. Another challenge of pollutant emission is related to a combination of exhaust gasses with water or oxygen in the presence of sun light that leads to the environment face with acid rain and toxic emissions [3, 5].

Pollutant dispersion studies are mainly involved including wind tunnel testing, field measurement, and Computational Fluid Dynamics (CFD) [6, 7]. The simulation and modeling of dispersion include three parameters: emission values, meteorology of the domain, and pollutant gasses transport [8]. Three different models are used for investigating the pollutants emission [9]:

- Dispersion model forecast the pollutant value at ground level around of constant source.
- The photochemical model estimates the pollutant concentration in a large region with multi-source system.
- Receptor-oriented models employ reception to measure and evaluate the emission of pollutants.

Main dispersion models include Gaussian plume models [1], particle tracking models [2], and puff models [4, 6, 9]. Gaussian models consider a standard Gaussian probability distribution for predicting the pollutant dispersion. Gaussian models for predicting the air pollution behavior emitted form non-continuous source are known as puff models. Particle tracking models are based on the pollutant dispersion and concentration in specified points [10 - 12].

In the last years, pollutant dispersion in urban areas is strongly studied by employing several schemes. Since each part of the plume has a different effect on the environment, concentration tracing regarding wind field is investigated [13 - 15]. In this paper, the wind field impact on nitrogen oxides dispersion is investigated. The convection-diffusion transport is employed to evaluate the components transportation by a single stack located in an industrial zone.

Air pollution modelling

In this paper, the convection-diffusion model is employed for predicting the pollutant emission produced by a single source located in the industrial zone in the north of the city and near to drying Salt Lake of Urmia. This research was carried out numerically by solving the equation of continuity, Navier-Stocks, heat and mass transfer using Fluent 6.3.26. Governing equations for predicting the pollutants dispersion are considered as following:

The continuity equation:

$$\nabla . v = 0 \quad (1)$$

Two-dimensional Navier-Stocks equation:

$$v\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+v_x\frac{\partial v}{\partial x}+v_y\frac{\partial v}{\partial y}=0 \quad (2)$$

Heat transfer equation:

$$\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+v_x\frac{\partial T}{\partial x}+v_y\frac{\partial T}{\partial y}=0 \quad (3)$$

And mass transfer equation:

$$D\left(\frac{\partial^2 c_\alpha}{\partial x^2}+\frac{\partial^2 c_\alpha}{\partial y^2}\right)+v_x\frac{\partial c_\alpha}{\partial x}+v_y\frac{\partial c_\alpha}{\partial y}=0 \quad (4)$$

where α represents a component of exhausts gasses from the stack.

The stack location and boundary condition of the simulated area are illustrated in Fig. 1. It can be seen that one of three inlets is considered for pollutant source of the stack. The other inlets are considered for air entrance. The left-hand wall is velocity inlet for fresh air. However, the top boundary depends on the wind direction. If the wind direction is lower than 180, it is the pressure outlet, while for wind direction is more than 180, it is considered velocity inlet according to velocity components. The right-hand side boundary is considered the pressure outlet.

The numerical analysis is performed using 152481 triangular grids. The exhaust gas properties are selected for a stack in a gas power plant for combustion of natural gas as Table 1.

During the combustion of natural gas, various contaminants are produced. The most significant pollutants in the combustion of natural gas are NOx which strongly depends on fuel composition, flame temperature, and volume of air. In this section, the distribution of nitrogen dioxides, NOx, emitted from a stack located in a gas power plant is investigated

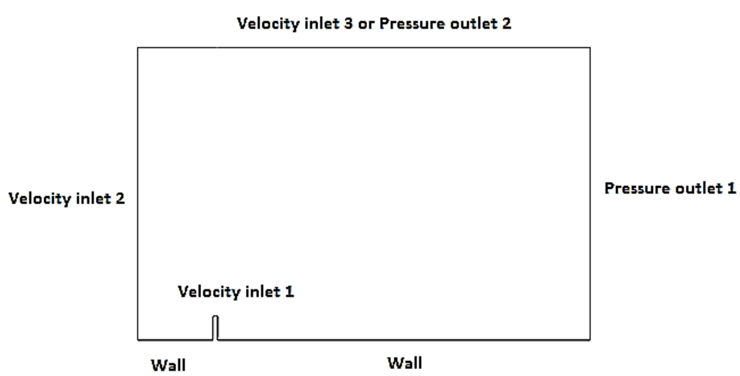


Fig 1. Geometry and boundary condition of stack and its surrounding area.

according to meteorology data of the mentioned area.

For this purpose, wind field of Urmia in the four seasons is used to estimate the pollutant dispersion. Table 2 presents the wind properties for the mentioned area based on meteorology data.

The anemometer usually measures the wind speed in the height of 10 m. Apparently, the pollutants disperse at the higher altitudes; the higher rates are calculated for dispersion prediction. Wind speed at higher elevations is obtained as following empirical relationship (Cooper, 2002):

$$\frac{V}{V_r} = \left(\frac{H}{H_r}\right)^{0.2} \qquad (5)$$

where V represents the wind velocity at height H, and V_r is the wind speed at height H_r (base).

RESULTS AND DISCUSSION

In this section, the pollution distribution in the studied range is investigated. The results are evaluated in four seasons, spring, summer, fall and winter.

Table 1. Specification flue gases composition [16].

Parameter	Value
NOx (ppm)	19.78
SOx (ppm)	0
Gas outlet velocity (m s^{-1})	24
Outlet gas temperature (K)	835
Stack height (m)	25
Stack diameter (m)	6.4

Flow patterns around the stack

To determine the pollution level around the stack, it is necessary to predict the plume dispersion. The simulation results of the stack plume flow in surrounding environment by considering the wind field, ground and atmosphere temperature in four seasons are illustrated in Figs. 2(a), 2(b), 2(c) and 2(d). The results demonstrate that the plume movement strongly depends on the wind speed and direction. In the spring and summer, wind direction disperses the plume in high altitudes of the stack, whereas, in fall and winter downward wind movement cause to plume disperses near the ground. It is shown that the pollutant concentration near ground increases at fall and winter, therefore, air quality for human and environment decreases.

As it is shown in Fig. 2(a) and 2(b), wind direction is approximately parallel to the ground surface, whereas, the effluent plume from stack rises vertically by its buoyancy force. In the absence of wind, the plume leaves the stack vertically. However, the inertial force of wind blowing changes the direction of plume rising between vertical and longitudinal directions and push it near the ground. Since temperature and density of air and plume are different, the surrounding air entrains into the plume and produces a mixing zone for the plume. For spring, ground temperature is 5°C, and wind speed is 12.63 m s^{-1} at a height of 10 m; thus, the produced mixing zone in spring has lower height rather those in summer with ground temperature of 14.4°C and wind speed of 8.86 m s^{-1}. The produced mixing loop in fall and winter has a lower height and longer length according to downward wind direction along with the low temperature of air and ground. In this seasons, downward wind against vertical buoyancy force prevents the plume rises vertically; therefore, in cold seasons, the smoke inverses proximity of ground where decreases the quality of air for staffs of the industrial zone.

Table 2. Meteorology data for wind field [17].

Season	Wind speed (m s^{-1})	Air temperature (°C)	Humidity (gr m^{-3})	Ground temperature (°C)	Wind direction
Spring	12.63	16.27	56.67	5.03	184.00
Summer	8.86	23.90	50.67	14.40	181.00
Fall	7.54	7.33	66.33	-3.03	210.00
Winter	9.19	2.10	66.67	-7.63	204.67

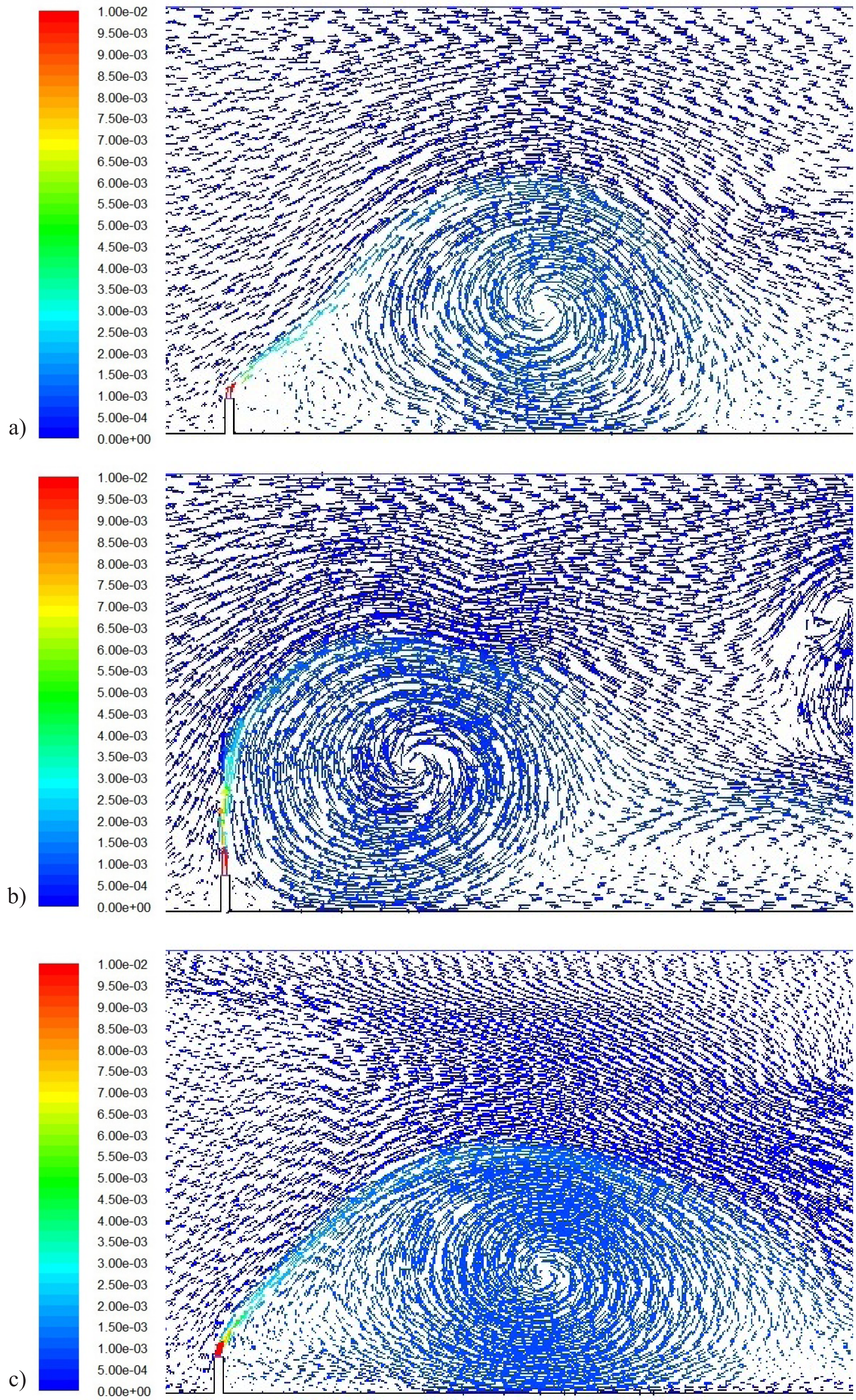


Fig. 2. The velocity vectors highlighted by NOx concentration of stack in (a) spring, (b) summer, (c) fall and (d) winter.

d)

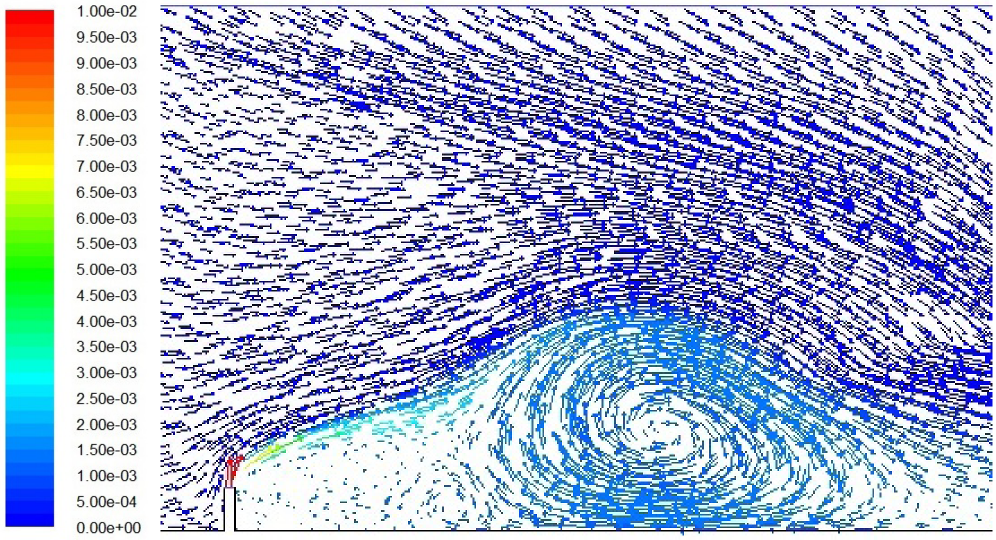


Fig. 2. The velocity vectors highlighted by NOx concentration of stack in (a) spring, (b) summer, (c) fall and (d) winter - *continued*.

It is clear that the plume dispersion is affected by wind speed and direction, ground temperature and buoyancy force related to the temperature difference between plume and air temperature [18, 19]. The presence of mountains and other equipment in the industrial zone create more than a circulation area and complicate the emission of pollutants. In the case of this research, industrial zone is located at a champaign in the north of the city whereby wind blowing, the pollutants are propelled to the city.

Figs. 3(a), 3(b), 3(c) and 3(d) illustrate NOx concentration distribution in heights of 50 m, 100 m, 150 m and 200 m of the ground surface. It is shown that wind direction significantly affects the pollutants dispersion. In an altitude of 50 m, the concentration of NOx is 7×10^{-7} ppm, 5×10^{-7} ppm, 5.86×10^{-7} ppm and 1.47×10^{-6} ppm for spring, summer, fall, and winter, respectively. It is seen that although the wind speed in the winter is more than summer, the concentration of NOx in altitude of 50 m at the winter is approximately three times of those in the summer; however, by increasing the altitude from ground surface in the winter, the NOx concentration reaches near zero. In fact, in the winter, pollutants accumulate near the ground and decrease the quality of air, while in the summer; pollutants vertically rise and leave the ground surface. It is mentioned that pollutants dispersion pattern also depends on other conditions such as ground and air temperature. Fig. 3

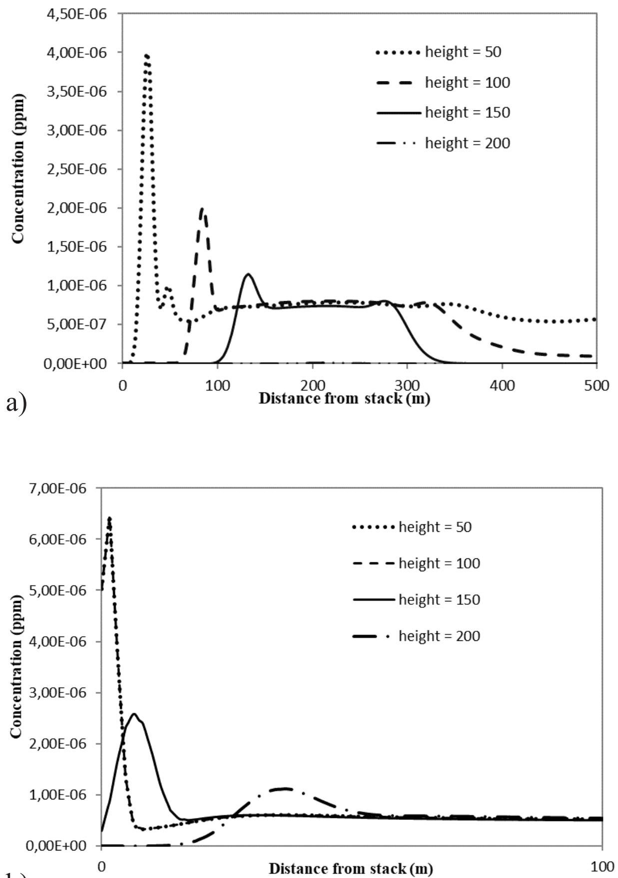
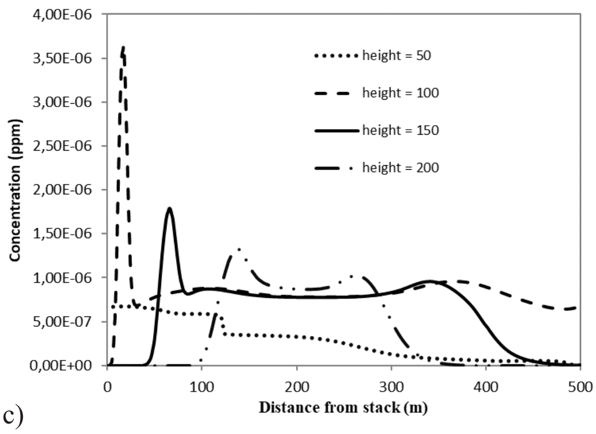
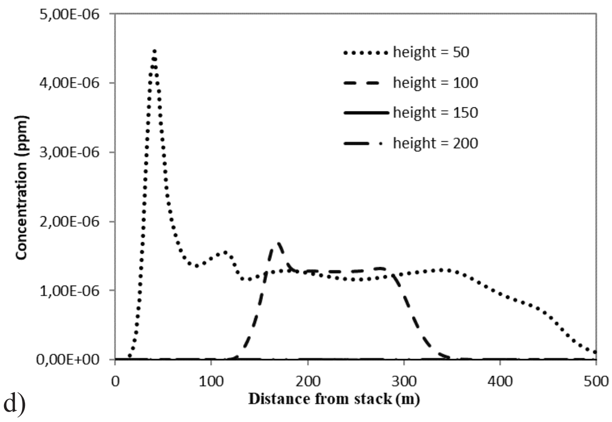


Fig. 3. NOx concentrations as a function of the distance from the stack in different heights in (a) spring, (b) summer, (c) fall and (d) winter.



c)



d)

Fig. 3. NOx concentrations as a function of the distance from the stack in different heights in (a) spring, (b) summer, (c) fall and (d) winter - *continued*.

shows the NOx concentration decreases by increasing the distance from ground surface in consequence of surrounding air penetration to the vortex and dilution of pollutants.

CONCLUSIONS

CFD simulations were carried out with the aim of studying the air pollution level dispersed by a stack in an industrial zone. The finite volume method was used to investigate the effects of wind field on the plume dispersion around the stack. It is shown that the wind direction has a significant effect on the plume flow pattern around the stack. The concentration of pollution is investigated in altitude of 50, 100, 150 and 200 meters for the four seasons. As the altitude increases, NOx concentrations in the surrounding area decrease due to dilution by surrounding air; however, the NOx concentration in winter accumulates near the ground surface.

REFERENCES

1. J. Colls, Air Pollution, Second Edition, Spon Press, 2002.
2. M. Ghiyasuddin, Comprehensive public health, Tehran University Publication, Tehran, 1991.
3. N. Nevers, Air pollution control engineering, McGrow-Hill, 2000.
4. B.R. White, W. Stein, Wind-tunnel studies of variable stack heights for a low profile building. Journal of Wind Engineering and Industrial Aerodynamics 36, 1990, 675-687.
5. Y. Ding, H. Feng, B. Zou,Y. Nie, Heterogeneous air pollution controls its correlation to urban heat island: A satellite perspective, Advances in Space Research, 69, 12, 2022, 4252-4262.
6. B. Blocken, T. Stathopoulos, On the use of CFD for modeling air pollutant dispersion around buildings. The 4th Int. Conference on Advances in Wind and Structures (AWAS'08), Jeju, Korea, 2008, 37-55.
7. Y. Zhao, R. Li, L. Feng, Y. Wu, J. Niu, N. Gao, Boundary layer wind tunnel tests of outdoor airflow field around urban buildings: A review of methods and status, Ren. Sust. Energy Reviews, 167, 2022, 112717.
8. K. Wark, F. Warner, T. Davis, Air pollution Its Origin and control, Third Edition, Addision Wesley longman, 1998.
9. A. Oliver, G. Montero, R. Montenegro, E. Rodríguez, J.M. Escobar, A. Pérez-Foguet, Adaptive finite element simulation of stack pollutant emissions over complex terrains, Energy 49, 2013, 4760.
10. D. Cooper, Air Pollution Control: a design approach, 2002.
11. M. Kargar, D. Kahe, Air pollution, Khaniran Publication, Tehran, 2013.
12. N.K. Valuing, The wind: renewable energy policies and air pollution avoided Centre for Energy and Environmental Economics, UC, 2011.
13. L.M. Zwack, C.J. Paciorek, J.D. Spengler, J.I. Levy, Characterizing local traffic contributions to particulate air pollution in street canyons using mobile monitoring techniques, ... 45, 1, 2011, 2507-2514.
14. F. Galatioto, M.C. Bell, Exploring the processes governing road side pollutant concentrations in urban street canyon, Environ. Sci. Pollut. Res., 20,

7, 2013, 4750-4765.
15. Rakowska, K.C. Wong, T. Townsend, K.L. Chan, D. Westerdahl, S. Ng, G. Močnik, L. Drinovec, Z. Ning, Impact of traffic volume and composition on the air quality and pedestrian exposure in urban street canyon, Atmos. Environ., 98, 2014, 260-270.
16. M. Esmaeilzadeh, E. Bazrafshan, M. Nasrabadi, Dispersion Modeling of NOx and SO2 Emissions from Tous Gas Power Plant, J. Health & Environ., 6, 1, 2013, 77-90.
17. F. Bahadori, Sh. Nasiri, Feasibility analysis for installation of wind power plant in Iran: a case study, Int. J. Power Energy Systems, 36, 2015, 1-5.
18. L.H. Hu, R. Huo, D. Yang, Large eddy simulation of fire-induced buoyancy driven plume dispersion in an urban street canyon under perpendicular wind flow, J. Hazard. Mater. 166, 2009, 394-406.
19. J. Pesic, D. N. Zigar, I. Anghel, S. M. Glisovic, Large Eddy Simulation of wind flow impact on fire-induced indoor and outdoor air pollution in an idealized street canyon, J. Wind Eng. Ind. Aerodyn., 155, 2016, 89-99.