ASSESSMENT OF ATMOSPHERIC DISPERSION STABILITY BASED ON THE ATMOSPHERIC BOUNDARY LAYER MONITORING AT THE BELORUSSIAN NUCLEAR POWER PLANT SITE

by

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Due to the fact that the potential threat to the health to the public living near nuclear power plants is largely determined by the level of air pollution by radionuclides, identification of the dispersion conditions of pollutants in the atmospheric boundary layer is of great importance in the development of engineering protection means for nuclear facilities. In turn, the engineering protection of nuclear power plants provides for the development of automated radiation monitoring systems and their main components, *i. e.* atmospheric boundary layer status monitoring systems. When analyzing and predicting the radiation situation in the vicinity of nuclear power plants, the determination of atmospheric dispersion variability parameters over time is essential. This research is aimed at assessing interannual and intra-annual variability of atmospheric dispersion parameters in the Belorussian nuclear power plant siting region based on the atmospheric boundary layer monitoring data. This study has revealed the relative interannual stability of the main average annual atmospheric dispersion characteristics throughout the observation period in 2015-2019. At the same time, the average seasonal values of the atmospheric boundary layer dispersion parameters are characterized by significant fluctuations thereof over the annual course. The feasibility of such monitoring for other potentially hazardous industrial facilities, such as thermal power plants and chemical plants, is also noted.

Key words: air pollution, atmospheric dispersion, radiation safety, nuclear power plant, atmospheric boundary layer

INTRODUCTION

Due to the general upward trend in the environmental safety level of hazardous industries, including nuclear power plants (NPP), the development of environmental monitoring is noted [1]. It is known that NPP are characterized by potential release of radionuclides into the atmosphere, as well as their migration in various landscape components [2]. Radionuclide dispersion mainly occurs in the atmospheric boundary layer (ABL), which extends from the ground surface to the heights of about 1 km. At that, the ABL is the key medium through which radionuclides ingress into other media. The level of atmospheric pollution significantly affects human health [3] and depends on the conditions of atmospheric dispersion, which is a combination of the pollutants transport by directed air-flow (wind) and turbulent diffusion [4].

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Therefore, at various stages of the NPP life cycle (construction, operation, and decommissioning) a detailed study of the ABL atmospheric dispersion conditions is carried out at the NPP sites. In particular, it is envisaged to develop automated radiation monitoring systems and their main components – ABL parameters measuring systems [5]. According to [5, 6], the key tasks of such monitoring are:

- to determine the ABL dispersion characteristics that are required for calculations of the potential radiation impact on plant personnel, the public and the environment in case of violations in normal NPP operation, including accidents,
- to predict and timely detect the trends in fluctuations of the ABL dispersion characteristics over time, and
- to develop recommendations aimed at mitigating the adverse impact of NPP on the environment.

The ABL monitoring provides for implementation of continuous observation of the ABL status, and first of all, the wind speed and direction, as well as the air temperature, which determine the mode of atmospheric dispersion. In addition, the monitoring system ensures archiving observational data and calculating the design dispersion characteristics of ABL.

Currently, in various countries of the world, the ABL status monitoring is usually carried out by means of acoustic and radio-acoustic sensing of the atmosphere with the help of sodars and RASS systems [7-9]. Combined measurement systems consisting of sodars and RASS allow remote recording of vertical profiles of the wind vector and air temperature in the lower atmospheric layer extending to the heights of 600-1000 m [10-12].

This research is aimed at assessing interannual and intra-annual variability of the ABL dispersion parameters in the Belorussian NPP siting region based on the monitoring data of remote sensing of the atmosphere. This article contains the data observed over the last five full years (from 2015 to 2019) and obtained by specialists from the Scientific & Industrial Association Gidrotekhproekt and the Moscow State University of Civil Engineering. The climatic regime of atmospheric dispersion in this area was studied earlier in the framework of engineering surveys using radiosonde observations [13].

METHODOLOGY

The SODAR/RASS-based monitoring system provides for real-time measurement of the following ABL parameters:
– air temperature,
– wind speed and direction, and
– air turbulence.

The SODAR is used for remote measurement of the turbulence structure and wind vector at various heights within the ABL. To detect atmospheric inhomogeneities caused by atmospheric turbulence, sodars emit acoustic waves. The reflected acoustic signal is processed by the built-in software and the resulting values of the intensity and frequency shift are used to determine the wind speed and direction, as well as the turbulence properties [9, 12].

The radio-acoustic method of sensing the atmosphere is based on the fact that RASS systems emit electromagnetic waves that are reflected from atmospheric inhomogeneities created by acoustic waves during the operation of sodars. Electromagnetic radiation passing through the air causes periodic changes in the dielectric constant of air, which scatter electromagnetic waves with a coherent addition of scattered energy [12]. Electromagnetic radiation reflected from the periodic structure of inhomogeneities is received by the RASS antenna. Using the parameters of the received signal, it is possible to determine the speed of sound at various heights of the ABL, and consequently, the air temperature. Initial processing of received signals and temperature calculations are performed by the software built into the RASS system. [12].

The observation monitoring system, which includes the SODAR/RASS measuring complex and a data processing subsystem, carries out automatic recording and accumulation of the measurement data. This subsystem provides for maintaining a database and calculating a set of the ABL dispersion characteristics by means of the specially developed software [5].

A SODAR/RASS measuring complex developed by the METEK GmbH (Germany) was installed at a weather station in the village of Markuny located 4.5 km east-northeast of the Belorussian NPP site (see fig. 1). The area adjacent to the Belorussian NPP is slightly hilly: elevation difference varies from 10 m to 20 m per 1 km. Upon completion of the equipment adjustment and commissioning, continuous sensing of the atmosphere was launched in August 2014 and it is going on to date. The ABL parameters are automatically measured and recorded every 10 minutes. A photo image of the measuring complex is presented in fig. 2.

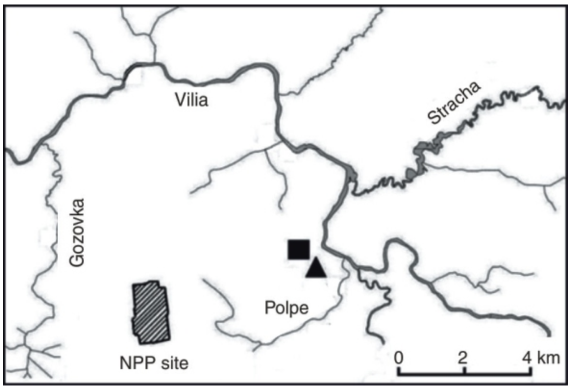

Figure 1. Location of the ewather station ▲ and the observation monitoring point ■ in relation to the NPP site

Figure 2. Measuring and monitoring SODAR/RASS system

The operation of the SODAR/RASS complex at the Belarusian NPP site has demonstrated that in some cases there are significant errors in measuring the air temperature. Earlier, such errors with a systematic component were identified in [14]. Along with this, measurements of wind speed and direction provide quite reliable results. So, according to [15], the error in the wind speed measuring does not exceed 1 m/s, while the error in measuring the wind direction is several degrees. Moreover, the components of the wind vector do not have systematic errors. To eliminate erroneous air temperature values at the stage of statistical data processing, the temperature data is controlled based on the climatic norms for standard heights in different months of the year and corresponding standard deviations.

Taking into account the wide distribution of SODAR/RASS complexes at the sites of various NPP and the positive experience of their operation, such complexes can be considered optimal for ABL monitoring. The economic benefits of SODAR/RASS complexes versus the conventional methods for ABL studies, such as radio sensing systems and meteorological masts, should also be noted. Besides, a significant altitude limit of measurements (up to 500-900 m) provides additional advantages of SODAR/RASS over meteorological masts, usually having a small height (up to 150 m). However, it should be emphasized that the ABL characteristics are measured more or less reliably up to the heights of 500-600 m.

In the course of monitoring, the database is being maintained and updated. Data arrays are formed for the current months. The data processing programs developed by the author include data control, their interpolation to heights, as well as calculation of the following characteristics:

- average air temperatures at altitudes of 0, 100, 300, 600 m,
- repeatability of atmospheric stability classes,
- average values of the vertical temperature gradient in layers 0-300 m and 0-600 m,
- repeatability and average values of thickness and intensity of surface inversions in layers 0-300 m and 300-600 m,
- repeatability and average values of the thickness and intensity of elevated inversions in the 0-600 m layer according to the gradations of heights of the lower inversions: 0-300 m and 300-600 m,
- average wind speeds at heights of 0, 100, 300, 600 m,
- speeds and directions of the average resulting wind vector at heights of 0, 100, 300, 600 m,
- standard deviations of the components of the wind vector at heights of 0, 100, 300, 600 m,
- repeatability of wind directions in 16 points of the compass and calm at heights of 0, 100, 200 m,
- average wind speeds at 16 points of the compass and calm at heights of 0, 100, 200 m, and
- an array of joint repeatability of atmospheric stability classes, wind speeds and directions at 16 points of the compass at heights of 0, 100, 200 m.

The previously listed parameters above allow the subsequent calculation of the concentration fields of polluting agents in the ABL. The results of calculating ABL parameters over the past five full years make it possible to identify the main features of interannual and intra-annual changes in the dispersion characteristics of the ABL.

RESULTS AND DISCUSSION

The following main characteristics of the ABL are discussed: vertical gradient of air temperature, atmospheric stability classes, modulus, and direction of the horizontal wind vector. The interannual changes in these characteristics averaged over current years are presented in tab. 1 and 2.

Table 1. Interannual changes of the average annual temperature gradient and atmospheric stability classes

Years	Temperature gradient (°C per 100 m)	Repeatability of atmospheric stability classes [%]					
		A	B	C	D	E	F
2015	1.29	8.5	21.2	23.8	39.4	4.4	2.7
2016	1.30	7.4	21.2	21.9	41.4	5.1	3.0
2017	1.63	10.7	23.6	22.8	37.0	3.6	2.4
2018	1.49	11.1	24.2	20.7	35.5	5.0	3.6
2019	1.66	9.6	23.6	24.0	35.4	4.2	3.3

Table 2. Interannual changes of the average annual values of the wind vector

Years	Modulus of the wind vector [ms^{-1}]				Direction of the wind vector (degree)			
	0 m	100 m	200 m	300 m	0 m	100 m	200 m	300 m
2015	1.3	1.6	1.8	2.4	234	240	242	243
2016	1.0	1.2	1.6	2.7	231	236	237	238
2017	1.7	2.0	2.8	3.9	230	234	237	238
2018	0.9	1.1	1.7	2.7	224	224	226	230
2019	1.3	1.6	2.2	3.1	217	220	224	229

According to tab. 1, the vertical temperature gradient throughout the entire study period 2015-2019 is positive and varies between 1.29 and 1.29-1.63 ºC per 100 m. Such pattern of temperature changes with height characterizes a high degree of ABL turbulence that is favorable for the intense dispersion of radionuclides. Table 1 shows the atmospheric stability classes as per Pasquill-Vogt: A – extremely unstable, B – moderately unstable, C – weakly unstable, D – neutral, E – weakly stable, and F – stable [16, 17]. As follows from this table, classes B, C, and D characteristic of favorable radionuclide dispersion conditions were prevailing throughout the entire observation period. Adverse stability classes (E and F) are observed quite rarely, and their total repeatability does not exceed 12 %.

The Pasquill-Vogt atmospheric stability class system used [16, 17] has a significant advantage over other systems, for example, the Pasquill atmospheric stability classes and their modifications, are widely applied in the ABL state studies in the vicinity of nuclear facilities and thermal power plants [16-19]. Stability classes make it possible to determine the dependence of the parameters of vertical and horizontal dispersion of contaminants in the ABL, under different weather conditions, used in mathematical models for calculating the concentration fields of contaminants. The advantage of the Pasquill-Vogt stability class system over the Pasquill stability classes is that there is no need to use additional data from meteorological stations to determine the atmospheric stability classes and they can be determined based on the data from the SODAR/RASS measuring complex, based on the wind speed at a height of 10 m and the vertical gradient of the air temperature in the lower 120-meter of the ABL [5].

Individual classes in both aforementioned systems have the same qualitative matter and are characterized by some quantitative differences in the parameters of vertical and horizontal dispersion. At the same time, the experience indicates that the calculated concentrations of contaminants in the ABL, at medium and long distances from the source (approximately 0.5-10 km), for the Gaussian model of atmospheric dispersion [16] and its modifications, do not have significant differences when using both mentioned atmospheric stability class systems. It should be noted that the greatest hazard to the population is represented by such weather conditions, which are characterized by E and F classes, which account for the long-distance transport of contaminants. However, a favorable circumstance is that such conditions occur quite rarely (see tab. 1).

The results presented in tab. 2 demonstrate that the wind sharply increases with height, and the characteristic values of its speed vary within 1-4 ms^{-1}. In the long term, interannual variations in wind speed are insignificant and commensurate with the measurement accuracy. Table 2 shows that west-southwest winds prevail during the entire period of monitoring observations.

Thus, the relative stability of the main average annual characteristics of atmospheric dispersion is noted throughout the entire observation period, 2015-2019.

At the same time, the average seasonal characteristics of atmospheric dispersion demonstrate significant variability in the annual course (see tab. 3). The

Table 3. Intra-annual changes of the atmospheric dispersion parameters

ABL dispersion characteristics	Seasons			
	Winter	Spring	Summer	Autumn
Temperature gradient in the 0-300 m layer (ºC per 100 m)	2.03	1.56	0.90	1.40
Repeatability of stability classes [%]				
A	11.7	9.3	9.7	6.7
B	22.1	25.2	21.6	22.1
C	26.3	23.6	17.9	22.9
D	35.2	34.9	39.1	41.7
E	2.8	4.4	6.4	4.4
F	1.9	2.6	5.3	2.2
Wind vector modulus at ABL heights [ms^{-1}]				
0	1.8	0.8	1.4	1.6
100 m	2.3	0.9	1.7	1.9
200 m	3.0	1.1	2.2	2.7
300 m	3.8	1.8	3.0	3.7
Wind vector direction (degree)				
0	217	242	274	213
100 m	219	250	275	227
200 m	226	248	272	212
300 m	230	235	263	220

air temperature gradient in the 0-300 m layer is positive and reaches its maximum in the winter months and the minimum – in the summer months. The repeatability of adverse atmospheric stability classes (E and F) increases from winter to summer from 4.7 to 11.7 %. In spring and autumn months it is about 7 %. In all seasons, the wind speed significantly rises with height, while its direction remains relatively stable. In the annual course, the wind speed weakens from the winter months to the spring and summer ones, but its direction is characterized by relative stability.

The experience gained in the ABL monitoring with the use of SODAR/RASS system at the Belorussian NPP site has shown that it is an effective means of obtaining initial data for assessing the current and time-averaged characteristics of radionuclide dispersion in the atmosphere. Similar studies of the ABL status have prospects for assessing dispersion conditions of the pollutants released into the atmosphere by thermal power plants and chemical enterprises.

CONCLUSION

Based on the ABL remote sensing data of the atmosphere at the Belorussian NPP site, the interannual and intra-annual variability of the main ABL dispersion parameters was assessed. It was established that the ABL state is characterized by a high degree of the ABL turbulence that is favorable for dispersion of the polluting agents. At the same time, the repeatability of adverse atmospheric stability classes is insignificant and does not exceed 12 %. It is demonstrated that the main average annual characteristics of atmospheric dispersion (such as vertical gradient of temperature, atmospheric stability classes, wind speed and direction) are characterized by interannual stability throughout the 2015-2019 observation period. Along with this, the average seasonal values of these dispersion parameters are characterized by significant changes over the annual course. It is noted that the ABL monitoring is also promising for assessing dispersion conditions of the pollutants released into the atmosphere by thermal power plants [19] and chemical enterprises [20].

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ПРОЦЕНА СТАБИЛНОСТИ АТМОСФЕРСКЕ ДИСПЕРЗИЈЕ НА ОСНОВУ МОНИТОРИНГА АТМОСФЕРСКОГ ГРАНИЧНОГ СЛОЈА У ОКОЛИНИ БЕЛОРУСКЕ НУКЛЕАРНЕ ЕЛЕКТРАНЕ

Због чињенице да је потенцијална претња здрављу становништву које живи у близини нуклеарних електрана у великој мери одређена нивоом загађености ваздуха радионуклидима, идентификација услова дисперзије загађивача у атмосферском пограничном слоју је од великог значаја за развој средстава инжењерске заштите нуклеарних постројења. За узврат, инжењерска заштита нуклеарних електрана омогућава развој аутоматизованих систрема за праћење зрачења и њихових главних компоненти, то јест, система за праћење стања атмосферског граничног слоја. Када се анализира и предвиђа стање радијације у близини нуклеарних електрана, важно је одредити параметре промењљивости атмосферске дисперзије током времена. Ово истраживање има за циљ да процени сезонску и вишегодишњу промењљивост параметара атмосферске дисперзије у региону белоруске нуклеарне електране на основу података праћења атмосферског граничног слоја. Ова студија открила је релативну стабилност током година главних просечних годишњих карактеристика атмосферске дисперзије у посматраном периоду 2015-2019. Истовремено, просечне сезонске вредности параметара дисперзије граничног слоја атмосфере карактеришу значајну флуктуације током годишњег курса. Уочава се примењљивост таквог надзора за остале потенцијално опасне индустријске објекте, попут термоелектрана и хемијских постројења.

Кључне речи: загађење ваздуха, атмосферска дисперзија, радијациона сигурност, нуклеарна електрана, атмосферски гранични слој