DNIPRO NATIONAL UNIVERSITY OF RAILWAY TRANSPORT
NAMED AFTER ACADEMICAIAN V. LAZARYAN
MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

DNIPRO NATIONAL UNIVERSITY OF RAILWAY TRANSPORT
NAMED AFTER ACADEMICAIAN V. LAZARYAN
MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

Qualifying scientific work
on the rights of the manuscript

Oladipo Mutiu Olatoye

UDC 502.3: [504.6: 622.33]

DISSERTATION

MINIMIZATION OF ENVIRONMENT POLLUTION FROM COAL TRAINS

101 – Ecology
10 – Natural sciences

Dissertation for Ph.D. degree

The dissertation contains the results of own research. The use of ideas, results and texts of other authors have references to the relevant source

____________ Oladipo Mutiu Olatoye

Supervisor: **Biliaiev Mykola Mykolaiovych,** D.Sc., professor

Dnipro – 2020

АНОТАЦІЯ

Оладіпо Мутіу Олатойє. Мінімізація рівня забруднення навколишнього середовища при перевезенні вугілля в напіввагонах. – Кваліфікаційна наукова праця на правах рукопису.

Дисертація на здобуття наукового ступеня доктора філософії за спеціальністю 101 – екологія. – Дніпровський національний університет залізничного транспорту імені академіка В. Лазаряна. – Дніпровський національний університет залізничного транспорту імені академіка В. Лазаряна, Дніпро, 2020.

Дисертаційна робота присвячена розробці методів мінімізації рівня забруднення навколишнього середовища від пилового забруднення при перевезенні вугілля залізничним транспортом.

Транспортування вугілля від місць його видобутку здійснюється в напіввагонах. При цьому відбувається інтенсивний винос вугільного пилу з напіввагонів, що супроводжується забрудненням навколишнього природного середовища. Актуальність теми підтверджена тим, що аналіз сучасних методів мінімізації забруднення навколишнього середовища вугільним пилом показав, що вони потребують досить високих витрат, застосування додаткового обладнання на станціях навантаження (розвантаження) вугілля, витрат часу на імплементацію. Аналіз наукових публікацій показав необхідність створення ефективних і економічних методів захисту навколишнього середовища від забруднення при перевезенні вугілля залізничним транспортом. Установлено, що дослідження на базі лабораторних та польових експериментів процесів забруднення навколишнього природного середовища вугільним пилом вимагають значних матеріальних витрат, складного обладнання та великої кількості часу на проведення експерименту. Це створює значні труднощі при виконанні комплексних наукових досліджень з вивчення забруднення навколишнього

середовища при перевезенні вугілля. Для теоретичної оцінки рівня забруднення навколишнього середовища при перевезенні вугілля найбільш широко використовується спрощена модель – модель Гаусса, у якій вагон з вантажем моделюється «точкою». Ця модель не бере до уваги форму вагона, не дозволяє врахувати залежність пиловиділення з поверхні вантажу від локальної швидкості повітряного потоку, що не дозволяє застосовувати таку модель для оцінки ефективності використання різних засобів захисту довкілля при перевезенні вугілля. Тому важливим питанням є створення теоретичних методів оцінки ефективності застосування засобів захисту навколишнього середовища від забруднення при перевезенні вугілля.

Як відомо, інтенсивність пилового забруднення навколишнього середовища при перевезенні вугілля залежить від багатьох факторів, найважливішим з яких є швидкість повітряного середовища біля поверхні вантажу (локальна швидкість повітряного потоку). Тому для зменшення інтенсивності виносу вугільного пилу з напіввагона в дисертації обрано засоби, які дозволяють зменшити значення локальної швидкості повітряного потоку біля поверхні вугілля. Для цього запропоновано використовувати спеціальні додаткові борти на вагоні з вугіллям, екрани. У дисертації на основі експериментальних та теоретичних досліджень показано, що застосування додаткових бортів спеціальної форми («вертикальна стінка», «крило», «внутрішнє крило») та екранів зменшує винос вугільного пилу з напіввагона. На основі проведених експериментальних досліджень встановлено закономірності формування зон забруднення підстильної поверхні при виносі вугільного пилу з вагонів без та з додатковими бортами або екранами.

Для визначення ефективності застосування спеціальних бортів, екрану розроблено комплекс чисельних моделей, що дозволяють прогнозувати забруднення атмосферного повітря в разі перевезення вугілля в напіввагонах та при використанні запропонованих засобів захисту. Моделювання пилового забруднення повітря під час транспортування вугілля в напіввагонах здійснюється на базі багатовимірних диференціальних рівнянь масопереносу. Моделювання процесу забруднення на базі цих рівнянь дозволяє отримувати інформацію про формування поля концентрації вугільного пилу в усій досліджуваній області, а не лише в деякій точці навколишнього середовища. Розроблені моделі дають можливість прогнозувати рівень пилового забруднення атмосферного повітря з урахуванням комплексу фізичних факторів, які раніше не враховувалися в ході досліджень, а саме: геометричної форми додаткових бортів, швидкості повітряного потоку біля поверхні вантажу, інтенсивності емісії вугільного пилу, дифузії вугільного пилу, швидкості руху вагона з вугіллям.

В роботі обґрунтовано застосування в напіввагонах повітряної завіси, що дозволяє зменшити пилове забруднення навколишнього середовища при перевезенні вугілля.

Також набула подальшого розвитку математична модель прогнозу рівня забруднення атмосферного повітря при перевезенні вугілля, що дозволяє, на відміну від існуючих моделей, враховувати при прогнозі швидкість руху потяга з вугіллям і оцінювати рівень забруднення атмосферного повітря після проходження потягу з вугіллям. На основі проведених експериментальних досліджень та обробки даних експерименту отримана емпірична модель оцінки маси вугільного пилу, що виноситься повітряним потоком від поверхні вантажу.

Практична цінність роботи полягає в тому, що запропоновані методи захисту від пилового забруднення навколишнього природного середовища при перевезенні вугілля потребують невеликих економічних витрат на імплементацію. Виготовлення додаткових бортів та екранів може бути виконано із застосуванням типового промислового обладнання. Для імплементації запропонованих методів захисту не потрібно встановлювати спеціальне обладнання на навантажувальних станціях (місцях розвантаження вантажу), а також не потрібна спеціальна перепідготовка кадрів для їх обслуговування. Ефективність застосування запропонованих методів захисту від пилового забруднення навколишнього природного середовища не залежить від кліматичних умов. Розроблені чисельні моделі дозволяють оперативно прогнозувати концентрацію вугільного пилу в атмосферному повітрі з урахуванням основних фізичних факторів, що впливають на процес пилового забруднення. Ці моделі дають можливість зменшити частку фізичного експерименту під час проведення досліджень у рамках розглянутого наукового напрямку. В роботі експериментальні результати порівнювалися з теоретичними, що були отриманими на базі побудованих чисельних моделей. Також була здійснена верифікація розроблених чисельних моделей.

Розроблені чисельні моделі та методи захисту довкілля використовуються в ТОВ «Енергосервіс-КР» для розробки технології захисту атмосферного повітря від забруднення при транспортуванні залізної руди та вугілля, а також у навчальному процесі Дніпровського національного університету залізничного транспорту імені академіка В. Лазаряна.

Ключові слова: забруднення довкілля, вугільний пил, моделювання забруднення, захист навколишнього середовища

ABSTRACT

Oladipo Mutiu Olatoye. Minimization of environment pollution from coal trains. – Qualifying scientific work on the rights of manuscript.

Dissertation for Ph.D. degree in specialty 101 "Ecology". – Dnipro National University of Railway Transport named after Academician V. Lazaryan, Dnipro National University Railway Transport named after Academician V. Lazaryan, Dnipro, 2020.

The dissertation is devoted to the development of methods for minimizing the level of environmental pollution from dust pollution during coal transportation by rail.

The transportation of coal from its production sites is carried out in coal wagons. In this case intensive environment pollution takes place.

The analysis of modern methods of minimizing environmental pollution caused by coal dust showed that they require quite high costs, the use of additional equipment at stations of loading (unloading) of coal, much time for implementation. Analysis of scientific publications has shown the need to create effective and low cost methods of environment protection from pollution during the transportation of coal by rail.

It was established that scientific research of environment pollution from coal trains on the basis of laboratory and field experiments requires significant material costs, complex equipment and a large amount of time for the experiment. This creates significant difficulties in carrying out comprehensive research to study environmental pollution during coal transportation. For the theoretical assessment of the level of environmental pollution from coal trains, the most widely used simplified model is the Gaussian model, in which the coal wagon is modeled as a "point". This does not allow the use Gaussian model to assess the effectiveness of different protection methods which are used to minimize environment pollution during coal transportation. Therefore, an important problem is the development of

theoretical methods for assessing the effectiveness of protection methods aimed to minimize environment pollution during coal transportation.

It is known that the intensity of dust pollution during coal transportation depends on many factors, the most important of which is the speed of the air near the surface of the cargo (local air flow speed). Therefore, to reduce the intensity of coal dust emission from the wagon, in this dissertation, some tools were selected that reduce the value of the local air flow speed near the surface of the coal. For this purpose it is offered to use special additional boards on the coal wagon and screens. In this dissertation on the basis of experimental and theoretical researches it is shown that application of additional boards of the special form ("vertical wall", "wing", "internal wing") and screens reduces coal dust release from a wagon. On the basis of the performed experiments the regularities of dust zones formation on the underlying surface, both for coal wagon without and with additional boards or screens, were established.

To determine the effectiveness of special boards, the screen application on the coal wagon a set of numerical models was developed. The models allow to predict air pollution in the case of coal transportation in wagons and when effectiveness of proposed means of environment protection. Modeling of dust air pollution during coal transportation in wagon is carried out on the basis of multidimensional differential mass transfer equations. Modeling of pollution process on the basis of these equations allows to obtain information about the formation of the coal dust concentration field in the whole study area, and not only at some point in the environment. The developed models allow to predict the level of atmosphere dust pollution taking with account of physical factors which were not previously taken into account in research works in this field, namely: geometric shape of additional boards, air flow speed near the cargo surface, coal dust emission rate, coal dust diffusion, wagon speed.

It was shown that use of air curtain at the coal wagon allows to reduce dust pollution of environment during coal transportation.

Also, the mathematical model for forecasting the level of air pollution during coal transportation in wagons has been developed, which allows, unlike existing models, to take into account the speed of coal train and estimate the level of air pollution after passing of the train. On the basis of the performed experiments and processing of obtained experimental data the empirical model to estimate the coal dust rate from a cargo surface was obtained.

The practical value of the work is that the proposed methods of environment protection during the coal transportation require low economic costs for implementation. The manufacture of additional boards and screens can be performed using standard industrial equipment. The implementation of the proposed methods of protection does not require the installation of special equipment at loading stations (places of unloading), and does not require special retraining of workers. The effectiveness of the proposed methods of protection against environment dust pollution does not depend on climatic conditions. The developed numerical models allow to predict quickly the concentration of coal dust in the air, taking into account the main physical factors influencing the process of dust pollution. These models make it possible to reduce the share of physical experiment during research study in this scientific field. The experimental results obtained were compared with the theoretical ones obtained on the basis of the developed numerical models. The developed numerical models were also verified.

Developed numerical models and methods of environmental protection are used in firm "Energoservice-KR" to develop technology to protect air from pollution during transportation of iron ore and coal, as well as in the educational process of the Dnipro National University of Railway Transport named after Academician V. Lazaryan.

Keywords: environmental pollution, coal dust, pollution modeling, environmental protection.

PUBLICATIONS OF THE AUTHOR

Publications in Ukrainian Journals

Статті в наукових фахових виданнях України

1. Беляев Н. Н., Оладипо Мутиу Олатойе. Минимизация интенсивности выноса пыли из полувагона при транспортировке угля. *Електромагнітна сумісність та безпека на залізничному транспорті* : Науковий журн. 2016. № 11. С. 93–100. *(Видання включено до міжнародної наукометричної бази Index Copernicus).*

2. Беляев Н. Н., Оладипо М. О. Модели оценки уровня загрязнения атмосферы при транспортировке сыпучих грузов. *Наука та прогрес транспорту. Вісн. Дніпропетр. нац. ун-ту залізн. трансп. ім. акад. В. Лазаряна.* 2016. Вип. 5 (65). С. 22–29. *(Видання включено до міжнародної наукометричної бази Index Copernicus).*

3. Беляев Н. Н., Оладипо М. О. Проблема уноса угольной пыли. *Наука та прогрес транспорту. Вісн. Дніпропетр. нац. ун-ту залізн. трансп. ім. акад. В. Лазаряна.* 2016. Вип. 6 (66). С. 17–24. *(Видання включено до міжнародної наукометричної бази Index Copernicus).*

4. Беляев Н. Н., Оладипо М. О. Расчет динамики загрязнения примагистральной территории при перевозке угля. *Наука та прогрес транспорту. Вісн. Дніпропетр. нац. ун-ту залізн. трансп. ім. акад. В. Лазаряна.* 2016. Вип. 1 (67). С. 18–26. *(Видання включено до міжнародної наукометричної бази Index Copernicus).*

5. Biliaiev M. M., Kozachyna V. A., Oladipo M. O. Reducing of environmental pollution during coal transportation. *Collection of Research Papers of National Mining University.* 2017. № 52. P. 325 –329.

6. Biliaiev M. M., Kozachyna V. A., Oladipo M. O. Dust from coal trains: reducing of environmental pollution in work places near railway. *Науковий вісн. будівництва.* 2017. № 2 (88). С. 268–271.

7. Беляев Н. Н., Оладипо Мутиу Олатойе, Гыркало А. В. Прогнозирование уровня загрязнения рабочих зон возле железнодорожной магистрали. *Строительство. Материаловедение. Машиностроение. Сер.: Энергетика, экология, компьютерные технологии в строительстве.* 2017 . Вып. 98. С. 61–67.

- *Scientific Book*:

8. Беляев Н. Н., Оладипо М. О., Кириченко П. С. Защита окружающей среды при транспортировке угля. Кривой Рог : Изд.: Р. А. Козлов, 2018. 92 с.

Foreign publications

Статті у закордонних наукових періодичних виданнях

9. Biliaiev M. M., Kozachyna V. A., Oladipo M. O. Numerical analysis of atmosphere pollution from coal train. *East European Scientific Journal*. 2019. Vol 3(43). P. 10–15.

10. Modeling of the atmosphere pollution from coal trains / Mykola Biliaiev, Vitalii Kozachyna, Viktoroлaiia Biliaieva, Mutiu Olatoye Oladipo and Kateryna Chernyatyeva. *MATEC Web of Conf. EOT-2019*. Lviv, 2019. Vol. 294. 6 p. https://doi.org/10.1051/matecconf/201929402007

Abstracts of Conferences

Публікації у виданнях, які засвідчують апробацію матеріалів дисертації

11. Беляев Н. Н., Оладипо Мутиу Олатойе. Математическое моделирование уноса угольной пыли. *Інформатика, управління та штучний інтелект. Матеріали третьої міжнарод. науково-техн. конф. студентів, магістрів та аспірантів.* Харків : НТУ «ХПІ», 2016. С. 6.

12. Беляев Н. Н., Оладипо Мутиу Олатойе. Экологические проблемы транспортировки сыпучих грузов железнодорожным транспортом. *Диференціальні рівняння та проблеми аерогідромеханіки й тепломасо-*

переносу : тези доп. Всеукр. наук. конф. (28-30 вересня 2016 р., Дніпро). Дніпро : Дніпропетр. нац. ун-т, 2016. С. 62.

13. Беляев Н. Н., Оладипо Мутиу Олатойе. Теоретическое и экспериментальное исследование уноса угольной пыли. *Теоретичні та практичні аспекти розвитку науки (частина II) : матеріали II Міжнародної науково-практ. конф.* (м. Київ, 29-30 листопада 2016 року). Київ : МЦНД, 2016. С. 15–16.

14. Беляев Н. Н., Оладипо Мутиу Олатойе. Компьютерно-информационная система анализа уноса угольной пыли. *Современные информационные и коммуникационные технологии на транспорте, в промышленности и образовании : тезисы X Международной научно-практ. конф.* (Днепр, 14-15 декабря 2016 г.). Днепр : ДИИТ, 2016. С. 90–91.

15. Беляев Н. Н., Оладипо Мутиу Олатойе. Моделирование загрязнения окружающей среды при транспортировке сыпучих грузов железнодорожным транспортом. *Комп'ютерне моделювання та оптимізація складних систем (КМОСС-2016) : матеріали II Всеукр. науково-техн. конф. з міжнародною участю* (м. Дніпро, 1-3 листопада 2016 р.). Дніпро : ДВНЗ УДХТУ, 2016. С. 26–27.

16. Оладипо М. О. Оценка уровня загрязнения воздушной среды возле железнодорожных магистралей с помощью информационной системы анализа уноса угольной пыли из вагонов. *Международный научный симпозиум «Неделя эколога – 2017»* (ДДТУ, Каменское, 10-13.04.2017). Каменское, 2017. С.35.

17. Беляев Н. Н., Якубовская З. Н., Козачина В. А., Оладипо Мутиу Олатойе. *Математическое моделирование загрязнения транспортного коридора при перевозке угля. Комп'ютерне моделювання та оптимізація складних систем (КМОСС-2018) : матеріали IV Міжнародної науково-техн. конф.* (м. Дніпро, 1-2 листопада 2018 р.). Дніпро : ДВНЗ УДХТУ, 2018. С. 38.

18. Беляев Н. Н., Козачина В. А., Оладипо М. О. Защита атмосферного воздуха от загрязнения при перевозке угля: эксперимент, математическое

моделирование. *79-та Міжнародна науково-практ. конф. «Проблеми та перспективи розвитку залізничного транспорту»*, 16-17.05.2019, Дніпро. Дніпро : ДНУЗТ, 2019. С. 293–294.

19. Оладипо М. О. Экспертная оценка загрязнения рабочих зон при перевозке угля. *77-ма Міжнародна науково-практ. конф. «Проблеми та перспективи розвитку залізничного транспорту»*, 11-12.05.2017, Дніпро. Дніпро: ДНУЗТ, 2017. С. 252.

20. Оладипо М. О. Анализ загрязнения атмосферного воздуха при перевозке угля в полувагонах. Результаты лабораторных исследований и математического моделирования. *Науковий симпозіум «Тиждень еколога – 2019»* (ДДТУ, Кам’янське, 07-10.10.2019). Кам’янське, 2019. С. 17.

CONTENT

INTRODUCTION

Actuality of theme. Nigeria, Ukraine and many other countries have intensive coal mining. It is mined in mines and quarries, which are located at a considerable distance from consumers (industrial facilities, ports, heating plants). Coal is transported in gondola cars, which is accompanied by intensive removal of coal dust from them and, as a consequence, pollution of both atmospheric air and the underlying surface near the railway line. In this regard, the urgent task is to develop methods that aim to reduce the level of environmental pollution during the transportation of coal, while being quite effective and practical implementation of which does not require large economic costs. Another important task is to create calculation methods that will quickly assess the effectiveness of such protection methods at the design stage, as the use of physical modeling to justify the effectiveness of various protection measures requires a lot of time and resources.

Therefore, the solution of the scientific and applied problem of reducing the level of environmental pollution during the transportation of coal by rail by using additional elements on the cars, which reduce the removal of coal dust from them is relevant.

Connection of work with scientific programs, plans, themes. The chosen direction of research is connected with the plan of scientific works of the Dnieper National University of Railway Transport named after academician V. Lazaryan (DNUZT): "Modeling of environmental pollution processes in emergencies and organized emissions of pollutants" (№ DR 0115U 007226).

The purpose and objectives of the study. The purpose of the dissertation is to reduce the level of environmental pollution during the transportation of coal by rail.

To achieve this goal it was necessary to solve the following tasks:

• perform an analysis of factors influencing the removal of coal dust from gondola cars;

• analyze modern methods of protecting the environment from pollution during the transportation of coal in gondola cars;

• analyze modern models and methods used to assess the level of environmental pollution during coal transportation;

• to conduct experiments to confirm the reduction of the level of dust pollution of the environment due to the installation in gondola cars of additional boards of a special shape, screen and air curtain;

• develop and verify numerical models to study the process of environmental pollution during coal transportation and to assess the effectiveness of the proposed methods of protection (additional boards, screen);

• to improve the method of determining the level of air pollution during coal transportation, taking into account the trajectory of the train;

• to obtain the dependence on the determination of the intensity of coal dust emission from the surface of the cargo.

The object of study - the process of scattering of coal dust in the air during the transportation of coal in gondola cars.

The subject of research - methods of minimizing the level of environmental pollution during the transportation of coal by rail.

Research methods. Physical modeling of mass transfer processes of coal dust from gondola cars was performed in laboratory conditions. Mathematical modeling of the process of formation of zones of dust pollution of atmospheric air during coal transportation is carried out on the basis of fundamental equations of mechanics of a continuous environment. Implicit difference splitting schemes were used to numerically integrate the modeling equations, on the basis of which computer programs were created to perform computational experiments. Scientific novelty of the obtained results. The dissertation solves an important scientific and applied problem: minimization of the level of dust pollution of atmospheric air during transportation of coal in gondola cars. The scientific novelty of the results obtained by solving this problem is as follows.

For the first time:

- the use of additional boards of special shape in gondola cars, which allow to reduce dust pollution of the environment during coal transportation, is experimentally and theoretically substantiated;

- experimentally and theoretically substantiated use in screen gondola cars, which allows to reduce dust pollution of the environment during coal transportation;

- the use of an air curtain in gondola cars is experimentally substantiated, which allows to reduce dust pollution of the environment during coal transportation;

- numerical models have been developed that, in contrast to existing models, predict atmospheric air dust during coal transportation in gondola cars, taking into account the shape of additional sides, screens, train speed, weather conditions, and coal dust emission intensity.

Further developed:

- mathematical model for forecasting the level of air pollution during coal transportation, which, unlike existing models, allows to take into account the speed of the train with coal, the trajectory of the train, weather conditions and assess the level of air pollution after its passage;

- an empirical model for estimating the mass of coal dust carried from the surface of the cargo, which allows you to calculate the intensity of dust emissions at different local air velocities.

The practical significance of the obtained results. The practical value of the results is as follows:

1. The proposed methods of protection against dust pollution during coal transportation require low economic costs for implementation. Additional boards and screen can be made using standard industrial equipment.

2. The introduction of the proposed methods of protection does not require the installation of special equipment at loading stations (places of unloading) and special training for their maintenance.

3. The effectiveness of the proposed methods of protection against dust pollution does not depend on climatic conditions.

4. Developed numerical models allow you to quickly predict the concentration of coal dust in the air, taking into account the main physical factors influencing the process of dust pollution. These models allow to reduce the share of physical experiment in research within the considered scientific direction.

The developed models are used in the educational process of the Dnieper National University of Railway Transport named after academician V. Lazaryan to teach the disciplines "Environmental protection from pollution by industrial enterprises", "Environmental safety". Developed methods to reduce air pollution during transportation of coal in gondola cars, developed computer programs for forecasting environmental pollution used in LLC "Energoservice-KR" to develop technology to protect air from pollution during transportation of iron ore and coal.

Personal contribution of the applicant. The author's personal contribution to the works published in co-authorship is as follows: a systematic analysis of modern methods of protection against environmental pollution during coal transportation was performed [8]; developed a numerical model for estimating the level of environmental pollution during coal transportation [4, 9, 20]; a set of physical experiments on the analysis of the formation of pollution zones during the removal of coal dust from the cars, processing, analysis of research results [4 - 8, 12, 15 18]; a physical experiment was performed and an empirical dependence was obtained on the assessment of the intensity of coal dust removal from the cargo area [9, 17]; developed numerical models for predicting the level of environmental pollution during the removal of coal dust from cars with additional sides, injection system, screen, carried out their software implementation, computational experiments, processing and analysis of research results [1 -3, 7, 8, 10 - 14, 16 - 18].

Approbation of dissertation results. The materials of the dissertation were reported and discussed: at the Third International Scientific and Technical Conference of Students, Masters and Postgraduates "Informatics, Management and

Artificial Intelligence" (Kharkov, 2016); All-Ukrainian scientific conference "Differential equations and problems of aerohydromechanics and heat and mass transfer" (Dnipro, 2016); II International scientific-practical conference "Theoretical and practical aspects of science development" (Kyiv, 2016); X International scientific-practical conference "Modern information and communication technologies in transport, industry and education" (Dnipro, 2016); II All-Ukrainian scientific and technical conference with international participation "Computer modeling and optimization of complex systems (CMOSS-2016)" (Dnipro, 2016); 77th International Scientific and Practical Conference "Problems and Prospects of Railway Transport Development", (Dnipro, 2017); International Scientific Symposium "Ecologist's Week - 2017" (Kamyanske, 2017); IV International Scientific and Technical Conference "Computer Modeling and Optimization of Complex Systems" (Dnipro, 2018); Scientific Symposium "Ecologist's Week - 2019" (Kamyanske, 2019); 79th International Scientific and Practical Conference "Problems and Prospects of Railway Transport Development" (Dnipro, 2019).

The full dissertation was reported at the meeting of the Department of "Hydraulics and Water Supply" DNUZT named after Academician V. Lazaryan 02.09.2019, Minutes № 1.

Publications. On the topic of the dissertation published 20 scientific papers, of which: 9 - scientific articles (2 - in periodicals of other countries; 7 - in professional publications of the List approved by the Certification Commission of the Ministry of Education and Science of Ukraine); 1 - scientific monograph; 10 - abstracts of reports.

The structure and scope of the dissertation (text in English). The dissertation consists of an annotation, introduction, four sections, conclusions, references and appendices. The total volume of the work is 132 pages, of which the main text is placed on 92 pages; contains 72 figures, 8 tables. References include 108 literature sources.

CHAPTER 1
ANALYSIS OF THE STATE OF THE PROBLEM UNDER STUDY

This section analyzes the factors that lead to the removal of coal dust from the cars, and methods to reduce dust pollution during the transportation of coal. Theoretical and experimental methods for solving problems of this class are also considered.

1.1 Negative impact of coal dust on the environment

Pollution of the air, the underlying surface by dust is an extremely dangerous phenomenon in the field of ecology [25, 27, 28, 35, 36, 38, 50, 54, 59, 66, 67]. Within the framework of this problem it is possible to allocate pollution of the natural environment by dust at coal transportation [4, 69, 74, 75, 77-83, 89]. Coal dust removed from gondola cars (Fig. 1.1) has a significant negative impact on the environment.

Figure 1.1 - Removal of dust from gondola cars during coal transportation (https://images.app.goo.gl/fPdPY1FJt3Gushxm7)

This dust gets on vegetation, soil, but due to the movement of air flows, as well as the movement of trains in the transport corridor, dust from vegetation, soil rises again into the atmosphere and creates a new cloud near the transport corridor. This cloud then spreads in the air and leads to pollution of other areas adjacent to the transport corridor (secondary pollution of the environment). A cloud of fine coal dust can remain in the surface layer of the atmosphere for a very long time. Therefore, a person who is near the transport corridor falls under its influence.

Human inhalation of fine coal dust can lead to a number of diseases (eg, bronchitis, etc.). Coal dust enters the deep respiratory tract. In addition, it can penetrate the pores of some glands and cause them to become blocked. As a result, there may be an inflammatory process in the body.

It should be emphasized that coal dust has a very negative impact on the properties of soil and plants: reduced fertility and concentration of humic substances in the soil, there is a negative transformation of metabolism in plants. As a result, there is suppression of phytocenoses, reduction of biological diversity. In addition, coal dust falling on plants reduces the absorption of solar energy, which is very necessary for plants. Also, getting on the ground, it is one of the causes of soil erosion.

1.2 The problem of environmental pollution during the transportation of coal by rail

Today, Nigeria is intensively mining coal (Fig. 1.2). Its transportation from the place of extraction to industrial centers and ports is carried out in this country by rail. This is due to two reasons:

1. Nigeria has a well-developed railway network that connects coal-producing areas with industrial regions and ports (Fig. 1.3).

2. Transportation of coal by rail provides a low cost of delivery of goods in industrial volumes.

(https://panafricanvisions.com/2020/05/a-shift-from-coal-mining-is-urgently-needed-to-protect-the-lives-of-rural-communities-in-nigeria/)

Figure 1.2 - Coal mining in Nigeria

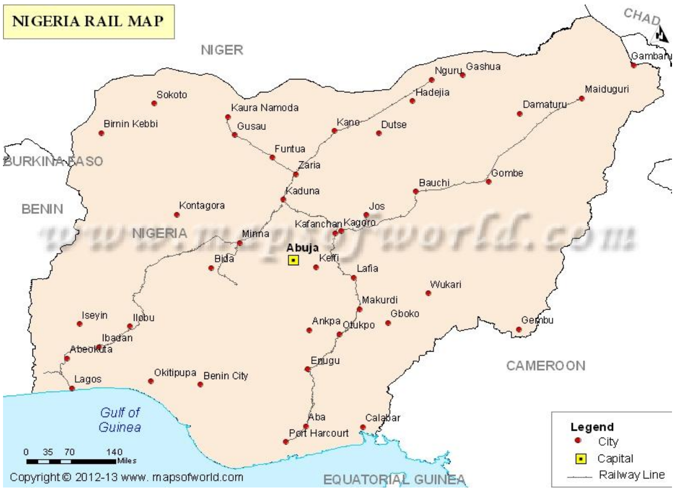


Figure 1.3 - Nigeria railway network

(https://www.mapsofworld.com/nigeria/rail-map.html)

However, it is known that the transportation of coal in gondola cars leads to a big problem, namely: the removal of coal dust from gondola cars, the formation of a concentration field of dust over the cargo, in the transport corridor and in the area adjacent to the highway. Such removal of fine fractions of coal dust from gondola cars in the foreign literature is called "fugitive dust emission" [90, 95, 96, 100, 102]. As noted in the scientific papers devoted to this study [74, 87, 89, 92, 101], we still have a shortage of knowledge about the process of scattering coal dust in the air of transport corridors. In addition, the main priority of research in this area remains the development of a strategy to minimize environmental pollution during coal transportation.

During the transportation of coal in hot climates (Nigeria) there is a rapid loss of moisture in the cargo transported in the gondola, the adhesion forces between the coal particles are reduced. Therefore, during such transportation, conditions quickly arise for intensive removal of coal dust from gondola cars.

During transportation in gondola cars there are losses of cargo (so, according to [25], loss of cargo on one car can make approximately 0,5 t in case of transportation of coal on distance less than 500 km and almost 1 ton in case of transportation of coal on distance more than 500 km). In addition, the properties of the cargo and its appearance deteriorate.

It should be noted that the purpose of research in foreign scientific publications devoted to the study of the problem of removal of coal dust from gondola cars, is to determine the mass of dust removed without decomposing it into fractions.

In addition to the problem of environmental pollution (Fig. 1.4), the removal of coal dust from gondola cars poses a threat to the health of people near the transport corridor. Dust can also get not only into the residential area (Fig. 1.5), but also inside locomotives, cars of other trains moving along the transport corridor.

Figure 1.4 - Railway workers in a polluted transport corridor (https://media.gettyimages.com/photos/two-railway-workers-picture-id458131533?s=170667a)

Figure 1.5 - Pollution of the residential area during the transportation of coal (https://energynews.us/2013/02/20/midwest/research-finds-additional-harm-from-coal-dust-exposure/)

In addition, during the passage of a freight train with coal at railway stations there is coal dust on the technical structures of the railway (stations, control rooms, warehouses, etc.), ie there is air pollution where employees of the station, dispatchers, station attendants, assemblers trains, signalmen, etc.).

1.3 Reasons for removal of dust from wagons during coal transportation

The analysis of literature data showed that the problem of coal dust removal during coal transportation is very relevant today [25, 74, 78, 80-81, 88, 103, 106-107]. In these works, a comprehensive analysis and generalization of the results of the study of coal dust removal processes during coal transportation was performed. Sources of emissions can be dust emissions from hatches, emissions from the surface of the cargo and so on. According to the results of the study of scientific publications [80-82, 87-89], the most powerful source of dust is the removal of dust from the surface of the cargo in the car. It occurs under the influence of a number of factors. Systematic analysis of literature sources has identified the following factors:

1) type of coal;

2) moisture content of the cargo;

3) the size of coal particles;

4) the size of the open part of the car;

5) the shape of the "cap" of the cargo and its dimensions;

6) position and vibration of the car in the train;

7) train speed;

8) wind speed, its direction;

9) precipitation that falls on the cargo during its transportation;

10) the presence or absence of special means of extinguishing dust;

11) local air flow rate near the surface of the cargo.

It should be emphasized that the most important parameter that affects the intensity of coal dust emissions from the gondola is the air flow rate near the cargo surface, ie the local flow rate. Figure 1.6 shows a diagram of the separation of coal particles from the surface of the cargo: at low local air velocity, the movement of particles on the surface of the cargo (creep) or near its surface (saltation). But when the local velocity of the air flow exceeds the limit value (the so-called threshold velocity), there is a separation of particles from the surface of the cargo (suspension) and their drift with the air flow.

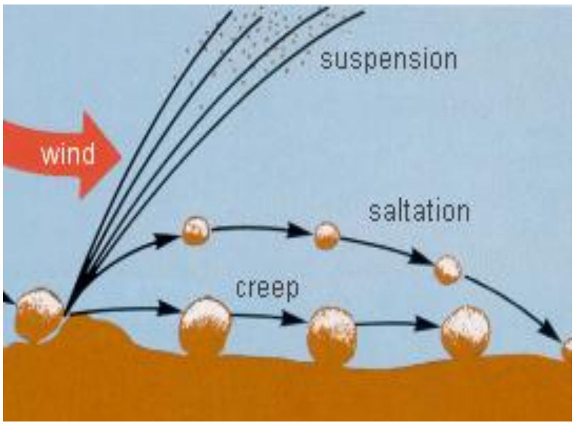


Figure 1.6 - Scheme of separation of coal particles from the surface of the cargo (https://courses.lumenlearning.com/suny-geophysical/chapter/transport-of-particles-by-wind/)

This information is very important, because it outlines a way to solve the problem of reducing the intensity of coal dust emissions from the gondola, namely: if you reduce the local air flow rate - will reduce the intensity of separation of dust particles and their drift into the air. The reduction of the local speed can be achieved due to the aerodynamic effect on the flow in the gondola. This approach was used in this work.

It should be noted that the complexity of scientific research of problems of this class is due to the fact that this parameter depends on the speed of the train, wind speed and its direction, which are constantly changing in the process of train movement. In many cases, the speed of the air flow induced by the movement of the train consists of the wind speed, which creates the worst aerodynamic conditions for dust from the surface of the load. It is almost impossible to do research in the course of a full-scale experiment, when the train is moving in the conditions of difficult terrain, makes turns, braking, etc.

There are additional factors that affect the intensity of dust during coal transportation, namely:

1) the number of locomotives in the train (in the US, for example, can be used up to 6 locomotives);

2) type of locomotive and its technical condition;

3) technical condition of cars;

4) acceleration during train movement;

5) the direction of the oncoming train;

6) terrain.

Thus, the processes of dust release during coal transportation and environmental pollution in transport corridors are multifactorial, which makes it extremely difficult to conduct physical experiments and create a universal model for their prediction. The study of dust pollution in transport corridors remains an urgent research problem.

1.4 Methods of environmental protection from pollution near transport corridors

Various methods are used to minimize the process of environmental pollution during coal transportation. Based on the known literature data [80-81, 89], the analysis of these methods was performed, their advantages and disadvantages were highlighted. The results of this analysis are given below. In a number of cases, the analytical evaluation of some methods also indicates their effectiveness on a scale adopted in Australia: High, Medium, Low.

A review of scientific papers on the problem of removal of coal dust from gondola cars, showed that the following methods are used to solve it:

1. **Sealing cracks in the car.** For this purpose film materials, pastes, special mastics are used.

Advantages: this method prevents the load from spilling through the cracks in the gondola cars and thus reduces the entry of dust into the environment during transportation. The cost of materials is relatively low, and transport companies can afford it without compromising their budget.

Disadvantages: this method does not allow to reduce dust from the surface of the cargo in the gondola. The presence of special materials, points for sealing cracks, periodic inspection of cars and sealing cracks, if there is a destruction of the film material, etc. is required. Personnel are needed to inspect and process a large number of cars.

2. **Sealing of cargo in a gondola car** (fig. 1.7). Advantages: according to the literature allows to reduce dust emissions by increasing the forces of adhesion between dust particles.

Disadvantages: requires the presence of special points with equipment (rollers, vibrators) to perform leveling (and compaction) of the cargo surface, and specially trained personnel. The operation of vibrators leads to a dynamic impact on the connection of cars, which accelerates their destruction. The time for preparation of cargo before its sending increases.

Figure 1.7 - The use of a special roller for leveling and compacting the surface of the load (http://p-zpo.ru/images/stories/flexicontent/item_34_field_16/l_urus2.jpg)

3. Limiting the height of the cargo cap in the gondola. To reduce the intensity of removal of coal dust from the gondola, it is recommended to form a "cap" of the load no more than 750 mm above the sides (Fig. 1.8, 1.9). Advantages: this approach allows to reduce the area of the blown surface and, consequently, to reduce the amount of dust emissions.

Figure 1.8 - Limit on the height of the "cap" of the cargo ("cap" of the cargo slightly exceeds the height of the board) (https://bl.thgim.com/migration_catalog/article18178902.ece/alternates/WIDE_615/BL22_P2_WAGON)

Figure 1.9 - Limit on the height of the "cap" of the cargo ("cap" of the cargo exceeds the height of the sides, but within the recommendations) (https://image.shutterstock.com/image-photo/freight-train-wagons-full-coal-260nw-347157941.jpg)

Disadvantages: with increasing train speed and wind speed, dust from the surface of the cargo will increase and the efficiency of the method decreases.

4. Installation of deflectors in gondola cars. On the end sides of the car can be installed deflectors such as "hungry board" (Fig. 1.10) and inclined plates (Fig. 1.11). These elements affect the aerodynamics of the air flow near the upper part of the gondola, as a result of which there is a change in the intensity of dust emissions during coal transportation. From a quantitative point of view, the effectiveness of such deflectors is not specified in the literature.

1 - deflector "hungry board" (Australia)

Figure 1.10 - The use of deflectors in the gondola (http://medicalrepublic.com.au/wp-content/uploads/2019/07/Screen-Shot-2019-07-17-at-11.00.18-am-680x334.png)

Figure 1.11 - Application of inclined plates in a gondola car (Australia) (http://2.bp.blogspot.com/-POZRFm5aJIw/UhqpOaA6xQI/AAAAAAAAF-Y/IzQk_UNRN6Q/s1600/_3-Fish+Wagon+(Large).jpg)

Disadvantages: it is necessary to modernize the design of the car directly at the factory, material costs.

5. Watering the surface of the cargo. This method is relatively easy to implement. Water supply is almost 2 l/m^2. The increase in the moisture content of the cargo leads to an increase in the adhesion forces between the coal particles.

The efficiency of this method is the level of "Medium" ("medium") in the case of transportation of goods within 2 hours and the level of "Low" ("low") in the case of transportation for more than two hours [89]. *Advantages* - the cost of this approach is less than the use of special solutions provided for the cargo.

Disadvantages: necessary pumps, distributors for water supply, control and measuring equipment, as well as vessels with water supply. For example, in Nigeria, this method cannot be used because there is a significant shortage of water in the country, and due to the high ambient temperature almost all year round (there will be rapid evaporation of water from the surface of the cargo and the efficiency of the method will decrease sharply).

6. Coating the cargo with special solutions. This method of reducing the removal of coal dust from the gondola is used in some countries. The supply of the solution to the surface of the coal leads to an increase in the adhesion forces between the particles. The consumption of the solution on the surface of the cargo is determined experimentally and depends on a number of factors, in particular on the properties of a solution, ambient temperature and so on.

Advantages: waste from various industries is often used to make solutions, ie this approach can be partially considered as waste disposal.

The effectiveness of this method is the level of "Medium / High" ("medium / high") [89].

Disadvantages: necessary centers (so-called "veneering stations") for the preparation of a sufficient amount of solution, containers for its storage, equipment for feeding solutions to the surface of the cargo, as well as sensors and monitors to control the quality of cargo handling and devices to protect the environment from pollution during solution supply. The solutions used must create films that have sufficient adhesion, strength and damping ability to withstand dynamic loads. In the case of, for example, vibration of the car, the temperature difference may be the destruction of the protective film. In some cases, the price of a special solution can be quite high.

7. Covering the cargo with tarpaulin (Fig. 1.12). *Advantages*: an effective way to reduce dust removal during cargo transportation, as its containerization is ensured.

Figure 1.12 - Covering the cargo with tarpaulin (https://5.imimg.com/data5/QY/CC/PO/IOS-22159606/product-jpeg-500x500.png)

Disadvantages: a large enough amount of tarpaulin or similar material is required to cover the cargo in the cars. The time to prepare the goods for shipment increases. It takes time for the procedure of opening the cargo before unloading the cars. During operation, the coating material may be destroyed. It is possible to demolish the tarpaulin during transportation.

8. Profiling the shape of the "cap" of the cargo in the gondola. Recommendations for profiling the shape of the cargo in the gondola (Fig. 1.13) were developed by BNSF Railway Company (Australia) and UNION PACIFIC (USA). There is no access to the results of the research on the basis of which the recommendations were obtained. It is known that the purpose of profiling is to avoid the presence of "sharp" corners in the form of a "cap" of the load (Fig. 1.14).

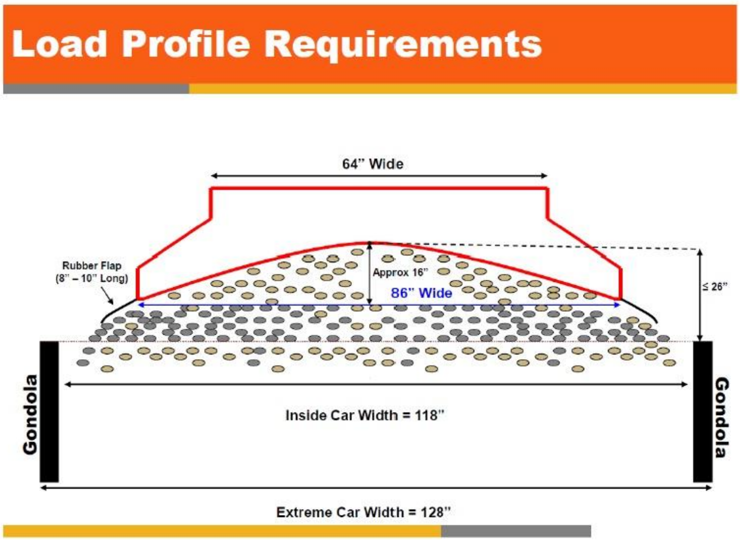


Figure 1.13 - BNSF Railway Company recommendations for cargo surface profiling [89]

Figure 1.14 - Cargo surface profiling, garden bed surface (Australia) [89]

Advantages: it is believed that by giving a special shape to the "cap" of the cargo, the size of this "cap", the presence of gaps between the cargo and the walls of the car can reduce dust from the surface of the cargo. Also, the load can be distributed in the gondola in the form of a set of "bunches". There is no data in the literature to estimate this distribution from a quantitative point of view.

The effectiveness of this method is the level of "Low / Medium" ("medium / low") [89].

Figure 1.15 - Coal loading point (Australia) [89]

Disadvantages: the need for special equipment (Fig. 1.15), increases the time to send the cargo by giving the desired shape of the "cap" of the cargo.

9. Containerization of cargo. *Advantages:* an effective means of protecting the environment from pollution, as there is a "sealing" of the cargo.

Disadvantages: requires the presence of specially made cars. High material costs.

10. Use of special, additional covers which are established on the car. An additional cover is installed in the gondola car, which can completely (Fig. 1.16) or partially (Fig. 1.17) cover the load.

Figure 1.16 - Modernized coal gondola on which the lid is installed, Australia (for comparison, see Figure 1.11) [89]

Advantages: an effective means of protecting the environment from pollution, because there is a reduction in the surface area of dust (partially or completely).

The effectiveness of this method has a level of "High" ("high") [89].

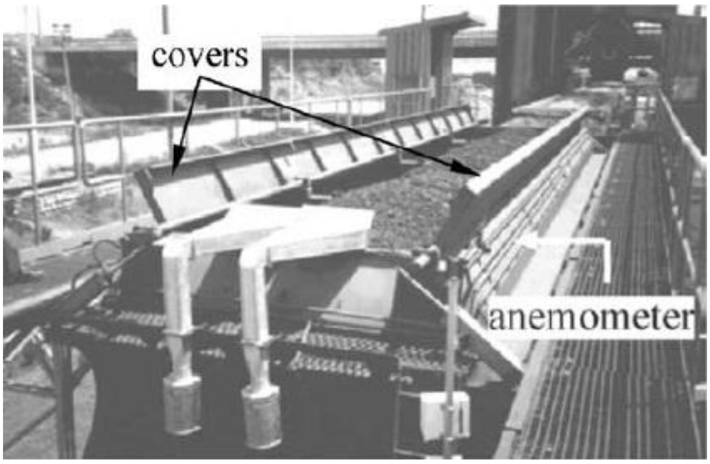


Figure 1.17 - Use of sash-type lids in gondola cars [80] (lids raised and inoperative), Portugal

Disadvantages: to install the cover requires modernization of the gondola at the factory.

High material costs - the cost of one cover in Australia is almost 10 thousand dollars. During transportation of cargo, the cover may fall out of the car, which will create an emergency situation in the transport corridor.

11. The use of special tunnels, inside which trolleys with coal move. Advantages: complete isolation of the environment from coal dust, a very effective way to protect work areas near the highway [77].

Disadvantages: it is necessary to create special tunnels and cars, which requires large funds. This method can be used when transporting small volumes of cargo. Air pollution inside the tunnel is not excluded.

Based on the analysis of methods of environmental protection from pollution during the transportation of coal, the following conclusions can be drawn:

1. Existing methods of protection can be divided into two main groups: physico-chemical (wetting the cargo with water, solutions) and mechanical (complete containerization of cargo, the use of lids, sealing cracks, etc.).

2. The scientific literature provides extremely limited information on the quantitative assessment of the effectiveness of each specific method of protection.

3. The data presented in the publications are practically not systematized.

An analytical review of scientific research on environmental pollution during coal transportation shows that today the development and justification of methods aimed at minimizing dust pollution continue to be an extremely important issue [80 - 82].

It should be emphasized that Nigeria does not use the above methods of protection when transporting coal by rail, which leads to intense dust pollution in transport corridors and residential areas.

1.5 Analysis of methods for studying the process of scattering of coal dust in the air

Analysis of the literature devoted to the studied problem showed that two approaches are used to study the process of air pollution during coal transportation:

1. Method of physical modeling (laboratory and field research).

2. Method of mathematical modeling.

The method of laboratory modeling (small-scale study) is based on studies performed in a wind tunnel (Fig. 1.18) or on specially made experimental stands.

a

б

Figure 1.18 - Models of wagons before tests in the wind tunnel (Portugal, University of Coimbra) [81]: a - model of gondola; b - tandem of gondola models

During laboratory experiments, both the model of a car or a tandem of cars and the "part" of the cargo that is exposed to air flow are considered. The formulation and conduct of laboratory tests are usually limited to the consideration of only individual issues within the research problem, rather than a comprehensive formulation and analysis of all those problems that arise in the problem of dust generation and dust scattering in the air. This is due to the multifactorial nature of the dust process, the high time spent on laboratory tests and the inability to often match the similarity criteria for the model and nature, in particular, the Reynolds number.

The use of modern laboratory equipment, wind tunnels is associated with high material costs. Therefore, research in this area is supported by grants from the largest energy companies or carriers.

It should be noted that when studying the processes of aerodynamics near the coal car is also used the method of visualization of the flow (visualization test), which is to attach thin strips to the object and photograph them during the movement of air flow. This method is cheaper than using special equipment.

It is very important to point out that due to the multifactorial nature of the studied process, researchers who first considered the problem of coal dust removal in kind [80], moved to research on models in the laboratory [81], which made it possible to systematize the obtained results.

Carrying out a full-scale study (full-scale study) within the research problem is an extremely difficult task. This is due to many factors, namely:

1) large dimensions of coal dust emission sources (wagon complex);

2) the complexity of measuring the concentration of dust simultaneously at different points of the transport corridor;

3) the complexity of the analysis of measurement results (dust from the car can not only be released during the movement of the train, but also come to them from neighboring cars);

4) cumulative effect - the value of the concentration of dust in the air is affected by both the emission of each car in the train, and the rise of dust into the air from the ground due to the movement of the train.

5) the need to install on cars, in the working areas of expensive measuring equipment, sensors, monitors and research in the process of train movement;

6) a variety of real situations for coal transportation (cars with different degrees of wear, different modes of transportation, different accelerations, the degree of turbulence of the atmosphere, changes in humidity during transportation, etc.) - all this greatly complicates the analysis and systematization of research data;

7) fluctuations of meteorological conditions, the presence of "external" pollutants (unregulated parameters) during the field experiment and the impact of such fluctuations on these studies;

8) the need to perform measurements for a long time (experiments can last several weeks);

9) large time spent on processing, "filtering" the results of field experiments in order to analyze and systematize them.

Due to the listed reasons and uncertainties that exist in the scientific literature, the data on the intensity of coal dust emission and its removal from gondola cars are very different. The presence of these reasons, which arise during the field experiment, is an incentive to develop mathematical models in order to quickly obtain the necessary data and reduce the cost and time to obtain them.

Carrying out a full-scale experiment always requires a lot of time. For example, in [80] the results of a field experiment to determine the air flow rate near gondola cars with coal and the amount of coal dust that was carried out from the gondola cars during transportation are presented (Fig. 1.19). This experiment was conducted for 16 days, the route of coal transportation was almost 350 km. The full-scale experiment was sponsored by one of Spain's largest energy companies, Tejo Energia.

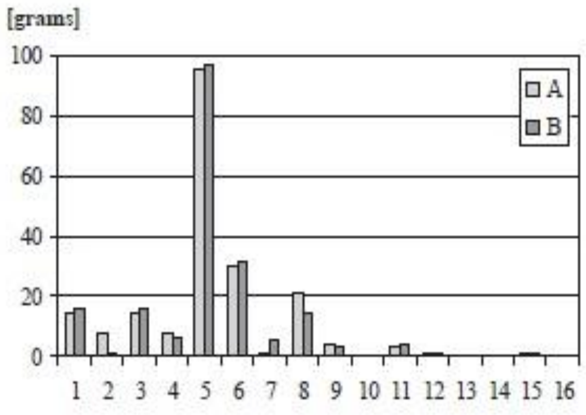


Figure 1.19 - The amount of coal dust removed from the gondola (the results of the field experiment [80])

It should be noted that due to the complexity of the field experiment, the significant cost of time to conduct it, it can be argued that this method can not be a "daily" tool in research. Therefore, the development of theoretical research methods - more economical, operational and universal - becomes especially important.

It should also be noted that in the developed countries of the world along the transport corridors are installed specialized equipment for assessing the concentration of coal dust. Such measurements are performed as part of the monitoring of the state of the environment and are associated with the need for constant monitoring of this state to inform the population and minimize social tensions in residential areas adjacent to the railway.

It is known that the problem of pollution of transport corridors with coal dust from the standpoint of mathematical modeling belongs to the problems of mass transfer of conservative heavy impurities in the atmosphere. It is known that to solve problems related to the scattering of dust or other pollutants, you can use balance, analytical, numerical models and CFD models [1, 2, 5-7, 21-22, 26, 29, 32, 33-34, 42, 45, 51-52, 56, 61, 62, 66, 76, 85-86, 93-94, 97-98, 104, 108]. However, in practice, two main approaches are used to calculate air pollution in the case of open-air coal dust emissions. The first is the use of specialized codes such as AERMOD, CALPUFF, Cal3QHCR, which implement different versions of the

Gaussian model [5, 22, 29, 62]. This approach is widely used by one of the most reputable organizations in the world that deals with this problem - EPA (Environmental Protection Agency, USA). Based on this code, the level of pollution of transport corridors in the United States, Australia and India is forecast. That is, to assess the level of air pollution in transport corridors, an analytical model is used, supplemented by certain empirical parameters. The Gaussian model allows you to quickly obtain forecast data, but at the same time has significant shortcomings. For example, it does not take into account the shape of the car, does not allow to take into account the dependence of dust from the surface of the cargo on the local velocity of air flow. The main disadvantage of the Gaussian model is that it takes the car as a "point". Therefore, this model cannot be used to conduct research to assess the impact of the shape of the car, the shape of the cargo, additional boards, and so on.

The second approach is a method of CFD research based on the equations of aerodynamics. The Navier-Stokes equation is most often used to solve aerodynamic problems, including the determination of the velocity field. Abroad, this approach is used much less frequently than the Gaussian model. As a rule, commercial software packages, such as "ANSYS" (Fig. 1.20), are used during CFD research [66]. To do this, highly qualified specialists who have a license to work with commercial code are involved. The computer time for solving one variant of the problem in the case of using the Navier – Stokes equations can be from 3 days and more.

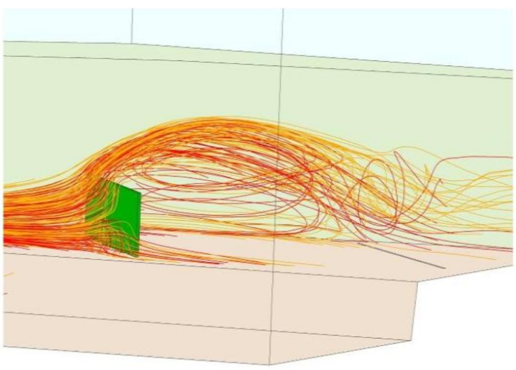


Figure 1.20 - The trajectories of impurity particles near the barrier. Calculation based on the commercial code "ANSYS" [66]

The analysis of literature data allowed us to highlight one very important fact: when studying the process of removal of coal dust from cars using CFD modeling, the process of scattering coal dust into the environment is not modeled, ie authors who use CFD modeling do not solve the mass transfer equation saw. This method is used only to estimate the local velocity field near the gondola with coal and the value of the speed is concluded as to whether the coal dust will be intensively carried out of the gondola [82]. Therefore, based on this approach [82], it is not possible to predict the concentration of dust in the air near the highway and thus quantify the effectiveness of various methods of protecting the environment from dust pollution. This is due to the fact that for the theoretical solution of such a multifactor problem it is very difficult to build a working mathematical model of mass transfer.

It should be emphasized that the use of known CFD models that implement numerical integration of the Navier-Stokes equations, together with one or another model of turbulence requires the use of powerful computers. It should be noted that the use of licensed commercial packages that implement CFD models is a very expensive approach.

Mathematical modeling as an independent research method is an important tool for substantiation of engineering methods of environmental protection from coal dust pollution, as it allows to quickly study the process taking into account the most important factors and does not require such large funds compared to physical experiment.

The analysis of literature sources on the researched problem showed that in Ukraine and Nigeria mathematical models for estimation of level of atmospheric air pollution during coal transportation are not developed and there are practically no laboratory or field researches devoted to this problem.

1.6. Substantiation of the chosen scientific direction

The analysis of literature sources on the research problem allowed to establish the following:

1. Transportation of coal in gondola cars leads to intense dust pollution of the environment.

2. Nigeria does not use methods to control dust during coal transportation, which is due, in particular, to the relatively high cost of existing methods used, for example, in the United States, Australia, Portugal, and the lack of relevant experience and research.

3. In Nigeria, there are no CFD methods for assessing dust pollution during coal transportation.

4. In Nigeria and Ukraine, there are no theoretical methods for estimating the level of environmental pollution during the transportation of coal in gondola cars.

Thus, the urgent task is to develop effective and cost-effective methods of combating dust pollution during coal transportation and creating mathematical models to assess the level of environmental pollution in the case of using certain methods of protection

Conclusions to Chapter 1

1. The analysis of literature sources showed that the intensity of dust pollution during the transportation of coal depends on many factors, the most important of which is the speed of the air near the surface of the cargo.

2. Analysis of modern methods of minimizing environmental pollution by coal dust revealed that the existing methods of protection require quite high costs, the use of additional equipment at the stations of loading (unloading) of coal, the time spent on the implementation of these methods.

3. Based on the study of literature data revealed the need to create effective and cost-effective methods of environmental protection from pollution during the transportation of coal by rail.

4. The analysis of methods of research of process of environmental pollution at coal transportation has shown that laboratory and full-scale researches demand considerable material expenses for statement of experiment, the difficult

equipment and big expenses of time for its carrying out. This creates significant difficulties in conducting comprehensive research to study environmental pollution during coal transportation.

5. It was found that for the theoretical assessment of the level of environmental pollution in the transportation of coal, the most widely used simplified model - the Gaussian model, in which the freight car is modeled "point". This does not allow to use this model to assess the effectiveness of the developed protection measures in the transportation of coal. 6. There are no effective mathematical models to assess the level of environmental pollution and the effectiveness of various methods of its protection in the transportation of coal.

CHAPTER 2
THEORETICAL BASIS FOR MODELING THE PROCESS OF ATMOSPHERE POLLUTION BY COAL DUST NEAR RAILWAY

In this chapter, the mathematical models, that are the basis for prediction of the atmosphere pollution level during coal transportation in wagons (gondola cars), are considered. Also, these models allow to calculate effectiveness of the proposed methods of nature environment protection from pollution [8-14].

Well known, that nowadays models development for theoretical investigation of the environmental pollution is carried out in account with process scale, that is modelled (for example, «Canopy», «Urban» etc.). Further, model development to study atmosphere pollution with scales «Microscale» and «Local» is considered. «Microscale» is used to predict atmosphere pollution level directly near wagon with coal, and «Local» is used to predict atmosphere pollution level in the area, adjacent to the railway road.

2.1 Features of the studied process

Simulation of coal dust dispersion during coal transportation is often considered in relation to a specific transport corridor. Let’s consider the transportation of coal near the station of Enugu (Fig. 2.1) – one of the largest railway stations in Nigeria, through which the transportation of minerals extracted in the country is carried out. The city of Enugu is called the city of miners.

Figure 2.1 – Railway station of Enugu, Nigeria (Google image)

Various wagons (gondola cars) are used to transport coal in Nigeria (Fig. 2.2), often with payloads of 60 tons. At the same time, there are no ways to minimize dust emission, as result, there is no protection from air pollution near railway.

Figure 2.2 – Wagon for coal transportation (https://www.progressiverailroading.com/railproducts/graphics/CACO-JOAM-HIGH16.jpg)

It should also be noted, that the transportation of coal in Nigeria often takes place when gondola car is loaded «with a cap», ie when part of the cargo exceeds the level of the sides of the wagon (in foreign literature, the term "poorly loaded wagon" is used for this type of loading). With such loading, the dust dispersion zone is actively affected by wind flow and, as a result, there are an intensive coal dust release from the gondola car, air pollution and the underlying surface pollution near the railway line.

To minimize the level of such pollution, in this work two methods of engineering protection (aerodynamic protection) are proposed to use:

1. Installation of additional boards with special shape on the gondola car.

2. Installation of aerodynamic protection (the screen) on the gondola car.

Two main features of the studied process, which greatly complicate the process of theoretical study, are distinguished:

1. A complex geometric region where the emission and transfer of coal dust occurs, which does not allow the use of analytical models of impurity dispersion to assess the level of environmental pollution.

2. Dependence of the intensity of dust emission from the gondola car on the value of the local air flow velocity near the surface of the cargo.

The mathematical models, proposed in this chapter, and their numerical analogues given in the third section allow to take into account the specified features.

2.2 Models to assess the atmosphere pollution level during coal dust transportation

The process of coal dust release from the gondola car and its dispersion in the air is multifactorial. For a theoretical study of this process, the following factors are considered:

1. The geometric shape of the gondola car.

2. Local air flow rate and its change near the gondola car.

3. Turbulent diffusion.

4. The shape of the "cap" of the cargo in the gondola car.

5. Presence on the gondola car of additional boards of the difficult form or screens.

6. Speed of the gondola car.

7. The dependence of the intensity of coal dust emission on the local velocity near the dust surface.

To model coal dust dispersion from the gondola car, taking into account listed factors, the equations of mass transfer are used in the following form [22, 40, 42, 63]:

$$\frac{\partial C}{\partial t}+\frac{\partial uC}{\partial x}+\frac{\partial vC}{\partial y}+\frac{\partial (w-w_S)C}{\partial z}+\sigma C=$$
$$=\frac{\partial}{\partial x}\left(\mu_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_y\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu_z\frac{\partial C}{\partial z}\right)+\sum Q_i(t)\,\delta(x-x_i(t))\,\delta(y-y_i(t))\,\delta(z-z_i), \tag{2.1}$$

where C is concentration of coal dust in the air; u,v,w are components of the air velocity vector; w_S is velocity of coal dust gravity sedimentation; μ_x,μ_y,μ_z are atmosphere turbulent diffusion coefficients; $Q_i(t)$ *is* coal dust emission intensity; t is time; $\delta(x-x(t)_i)\delta(y-y(t)_i)\delta(z-z_i)$ is Dirac delta-function; x_i,y_i,z_i are Cartesian coordinates of coal dust emission point source location on the cargo surface.

During the simulation of the process of atmosphere pollution, the surface of dust emission in the gondola car is replaced by a set of point sources of emission specified by the Dirac delta function.

Thus, to estimate the level of air pollution near the railway, it is necessary to solve equation (2.1) according to the relevant initial data.

To take into account meteorological factors that affect the coal dust dispersion, the following dependences are used [21, 22]:

$$u=u_1\left(\frac{z}{z_1}\right)^p,\ \mu_z=k_1\left(\frac{z}{z_1}\right)^m, \tag{2.2}$$

where u_1 is air flow velocity on the level z_1 (usually, it’s taken equal 10 м); p=0,16; k_1=0,2; $m\approx1$.

The first dependence from (2.2) determines the longitudinal component of wind speed change with height, and the second – the value of the vertical coefficient of atmospheric turbulent diffusion, which changes with height (the degree of the atmospheric stability). The values of the other diffusion coefficients are determined by the following formulas [21, 22]:

$$\mu_y=\mu_x,\ \mu_y=k_0u, \tag{2.3}$$

where k_0=0,1.

To determine the value of coal dust gravity sedimentation rate, the results of experimental studies or calculating on the basis of known dependencies can be used.

To obtain an unambiguous solution of the boundary value problem, it is necessary to specify the boundary and initial conditions for equation (2.1). These are the following conditions [42, 63]:

1. Where the air flows into the calculation region, it's realized the boundary condition of the form [42, 63]:

$$C\big|_{inlet} = \tilde{N}_{entrance}\,, \qquad (2.4)$$

where $\tilde{N}_{entrance}$ is set value of coal dust concentration; during the computational experiment it is assumed that $\tilde{N}_{entrance} = 0$.

2. Where the air flows out of the calculation region, it's realized the boundary condition of the form [42, 63]:

$$\frac{\partial C}{\partial n} = 0\,, \qquad (2.5)$$

where *n* is unit vector of the external normal to the output boundary of the flow. As is known, such a boundary condition at the initial boundary has a certain physical meaning – neglect of diffusion at the boundary of the computational domain. Note that at this boundary there is a transfer of dust due to convection.

3. On the upper and lower planes of the calculation area, the boundary condition is written as [42, 63]:

$$\frac{\partial C}{\partial n} = 0\,,$$

where *n* is unit vector of the external normal to the surface. In the numerical model, fictitious cells are used to implement this boundary condition.

4. The initial condition for the studied process of air pollution is written as follows:

$C = 0$ in the calculation area at $t = 0$. (2.6)

Note that the peculiarity of the equation (2.1) application to the problems studied in this paper is that this equation, in the opposite to the classical version, takes into account the motion of the emission source (train) by specifying its time-dependent coordinates.

Equation (2.1) in this paper will be applied in two cases:

1) for 3D CFD modeling of the process of air pollution in the case of emission of coal dust from the gondola car;

2) for 3D modeling of air pollution at the station during the movement of the train with coal.

Also, it will be used two-dimensional analogue (profile problem) of (2.1) to study the processes of contamination of working areas near the railway when emitting coal dust from a gondola car with additional boards of complex shape or air curtain. The two-dimensional analogue has the following form [42, 63]:

$$\frac{\partial C}{\partial t}+\frac{\partial uC}{\partial x}+\frac{\partial vC}{\partial y}+\sigma C=div\left(\mu gradC\right)+\sum_{i=1}^{N}Q_i\left(t\right)\,\delta\left(x-x(t)_i\right)\,\delta\left(y-y(t)_i\right)\,, \qquad (2.7)$$

where C is the average value of coal dust concentration; u, v are is the average values of air flow velocity components near gondola car; $\mu=\left(\mu_x,\mu_y\right)$ are atmosphere turbulent diffusion coefficients; Q_i is coal dust emission value from point source; t is time; x_i, y_i are coordinates of coal dust emission point source location in the gondola car; $\delta(x-x(t)_i),\delta(y-y(t)_i)$ – Dirac delta function.

In the case of practical application of equation (2.6) for the calculation of meteorological parameters, the following formulas will be used [21, 22]:

$$u=u_1\left(\frac{y}{y_1}\right)^p,\mu_y=k_1\left(\frac{y}{y_1}\right)^m,\mu_x=k_0u\,, \qquad (2.8)$$

The boundary conditions for equation (2.7) are written as follows:

1. Where the air flows into the calculation region, the boundary condition of the form (2.4) is realized [42, 63]

2. Where the air flows out of the calculation region, the boundary condition of the form (2.5) is realized.

3. The initial condition for equation (2.7) is written in the form (2.6).

Since this paper consider the transfer of coal dust in a non-uniform air flow, only a numerical solution of the considered differential equations can be obtained.

2.3 Modeling of air flow aerodynamics around gondola car with coal

To assess adequately the level of atmospheric air dust pollution, it is necessary to take into account the local change in the field of air flow velocity near the freight wagon. This airflow velocity field is used to solve equations (2.1) or (2.7). In addition, it is extremely important to know the local velocity field near the cargo surface, because coal dust release from different parts of the cargo surface depends on the value of the local air flow velocity in this place. Therefore, there is an important problem in calculating the velocity field near the freight wagon and near the surface of the cargo.

To solve this problem, the equation for the velocity potential is used [40-41, 63]:

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} = 0, \qquad (2.9)$$

where φ is velocity potential.

It should be noted that equation (2.9) for this problem of calculating air flow around a wagon with a cargo can be solved only numerically.

If the velocity potential field is determined, the components of the air flow velocity vector are calculated by the following formulas [41]:

$$u = \frac{\partial \varphi}{\partial x}, \; v = \frac{\partial \varphi}{\partial y}, \; w = \frac{\partial \varphi}{\partial z}. \qquad (2.10)$$

Consider the formulation of boundary conditions for the equation of aerodynamics (2.9). These are the following conditions [41, 63]:

– on firm borders (walls of the wagon, freight surface, upper and lower borders of calculation region and lateral faces) the condition of non-leakage is written as follows:

$$\frac{\partial P}{\partial n}=0, \tag{2.11}$$

where *n* is unit vector of the external normal to the boundary;

– at the boundary, where air flows out of the calculation area, the Dirichlet boundary condition of the form *P*=const is set;

– at the boundary, where air flows into the calculation area, the Neumann boundary condition is set: $\partial P/\partial n=V$, where *V* is the known air flow velocity;

After determining the velocity potential field and calculating the components of the air flow velocity vector near the gondola car, the second stage of modeling solves the problem of transferring dust contaminants from the gondola car to the working area by solving equation (2.1).

In this paper, also the two-dimensional equation for the velocity potential to model the process of air pollution is used. The modeling equation in this case is the following [41, 63]:

$$\frac{\partial^2 \varphi}{\partial x^2}+\frac{\partial^2 \varphi}{\partial y^2}=0, \tag{2.12}$$

where φ is velocity potential, the Y axis is directed vertically upward.

The components of the air velocity vector are calculated by the dependences [41, 63]:

$$u=\frac{\partial \varphi}{\partial x},\ v=\frac{\partial \varphi}{\partial y}. \tag{2.13}$$

Statement of boundary conditions for this equation is similar to boundary conditions for the three-dimensional equation [41, 63].

2.4 Coal dust release intensity assessment during coal transportation

Estimation of coal dust release intensity from the cargo surface is absolutely important task in predicting the level of air pollution during coal transportation. This is due to the fact that the dust release intensity directly affects the intensity of air pollution. Nowadays, this problem is still far from being solved [80-81].

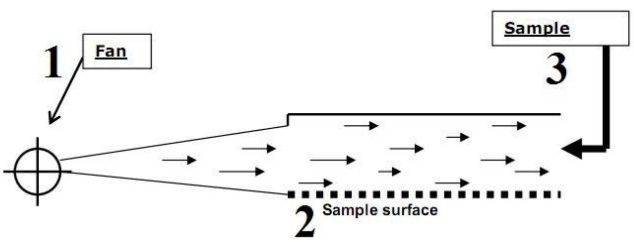
Literature analysis has shown that there are a limited number of scientific publications devoted to this problem. Data on the intensity of dust emissions from the surface of coal, given in the scientific literature, differ significantly.

For example, [50] indicates the intensity of coal dust emission in the amount of Q = 1.0-6.5 mg/(m^2·s) at an air flow rate of almost 3-5 m/s and the order of Q=9 mg/(m^2·s) at an air flow rate of 7-8.5 m/s. On the other hand, in [77] the emission intensity in the amount of Q=0.044-0.44 g/(m^2·s) at an air flow rate of approximately 6-10 m/s is noted. During coal transportation by railway, according to an experimental study [80], its losses are approximately 0.05-1% weight of the cargo, while in [82] it is indicated that such losses can be equal to about 0.5-3% weight of cargo.

It should be noted that the data in the scientific literature on the mass of coal loss during railway transportation also differ significantly in different scientific studies. This is due to the fact that experimental studies are performed for different types of coal, under different experimental conditions. It is certainly, that a particularly difficult problem is theoretical assessment of dust release intensity.

An analysis of the scientific literature on this issue revealed the following:

1. The main method of studying the process of dust release is method of physical modeling – laboratory research or field experiment (for example, Fig. 2.3 shows a diagram of an experimental installation (Netherlands) to study the process of coal dust release from the sample [84]. This installation has fan to produce an air stream onto a prototype of a coal pile and the equipment for collecting dust).



1 – fan; 2 –coal sample to research; 3 – equipment for collecting dust

Figure 2.3 – Scheme of the experimental installation to study coal dust release intensity from coal pile [84]

2. Physical experiments are conducted in different conditions: for different types of coal (often in scientific publications, this information is not detailed); for different transportation conditions (different terrain, uneven train speed, etc.); under different atmospheric conditions (atmospheric humidity, insolation, etc.). For this reason, the value of the intensity of coal dust emissions reported in scientific publications varies greatly.

3. The results of physical experiments are subjected to mathematical processing and on this basis empirical or regressive models are obtained to calculate the intensity of coal dust emission. The scope of such models is limited by the conditions of the experiment.

4. The obtained models take into account a limited number of physical factors that affect the intensity of the dust release process (for example, only the air flow rate or air flow rate + humidity + coal mass, etc.). The choice of these factors is not always clearly justified by the authors of the study.

5. There are no systematized data in the literature, models for estimating the intensity of coal dust emission depending on various factors (local air flow rate, humidity, etc.).

Thus, one of the most «complete» empirical models for calculating the intensity of coal dust emissions from the gondola car is the following dependence [25]:

$$Q = \rho \cdot V_B \cdot S \cdot t \cdot (0{,}10837 \cdot \frac{\rho \cdot V_B^2}{\rho_{ОБ}} + 0{,}1703 \cdot \frac{j_В}{g} - 0{,}3217 \cdot \omega - 0{,}3546) \cdot 10^{-2}, \quad (2.14)$$

where Q is coal losses during transportation; ρ is air density; V_B is air velocity near streamlined surface (local velocity); S is a surface area from which coal is emitted; t is duration of coal release; $\rho_{ОБ}$ is volumetric mass of cargo; d is average coal particles diameter; j_B is acceleration of wagon vertical oscillations; g is acceleration of gravity; ω is air humidity.

It should be noted, that there are other empirical models for solving this problem. Unfortunately, it is not possible here to present foreign models for estimating the intensity of coal dust emission due to the prohibition of the authors of these works to reproduce materials from their publications.

Analysis of the models used to estimate the intensity of coal dust emissions allows to draw the following conclusions:

1. Models take into account a limited number of physical factors that determine the intensity of the dust release process.

2. From the preliminary follows the conclusion, that the results, obtained on the basis of the application of different models for estimating the intensity of dust release, may not coincide with each other.

3. The discrepancy between the calculated data, obtained using different models, will also be due to the fact that different models are obtained under different experimental conditions.

4. There is no universal model for estimating the intensity of dust release.

Therefore, estimating the intensity of dust release remains an important scientific problem.

Conclusions to Chapter 2

1. To estimate the level of air pollution during the coal transportation in gondola cars, it is proposed to use a multidimensional differential equation of mass transfer, which is a fundamental equation of the mechanics of a continuous medium.

2. The calculation of atmosphere pollution by coal dust on the basis of the proposed equation of mass transfer allows to obtain information about the formation of the field of coal dust concentration in the whole study area, and not only at some point in the environment.

3. The application of the airflow aerodynamics model allows to determine the flow velocity field near the coal wagon. This makes it possible to adequately predict the level of dust pollution of atmospheric air by taking into account dependence the intensity of emissions from the local velocity value and geometric shape of the wagon.

4. The use of multidimensional mass transfer equation together with the equation of aerodynamics allows for the first time to predict the level of dust pollution taking into account a set of basic physical factors influencing the level of air pollution during coal transportation, namely: air flow rate near the cargo surface, coal dust emission intensity, the speed of coal wagon.

5. The implementation of the models proposed in the chapter can be performed on the basis of standard information: train speed, wind velocity, emission parameters, gondola car shape, cargo shape in the gondola car.

CHAPTER 3
DEVELOPMENT OF NUMERICAL MODELS TO ASSESS ATMOSPHERE POLLUTION LEVEL BY COAL DUST DURING COAL TRANSPORTATION

This section considers the development of numerical models for estimating the level of air pollution during coal transportation [15-20, 47-49, 71-73, 91]. Note that the numerical model is a combination of the following elements: differential equations that simulate the process, difference schemes and code (program).

3.1 Calculation region formation

As mentioned earlier, the study of dust pollution will be performed on a scale:

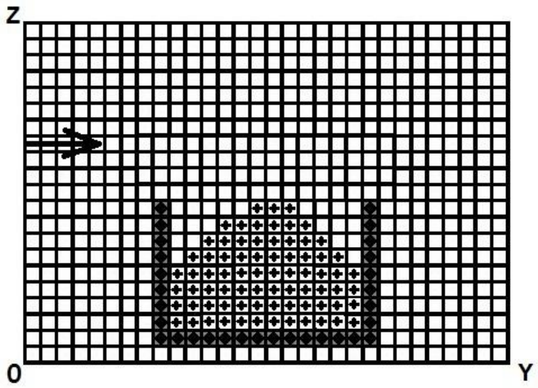
1. «Microscale» (the scale of impurity transfer in the atmosphere at a distance of several meters – near the gondola);

2. «Local» (the scale of impurities transfer in the atmosphere at a distance of almost a few tens of meters – in the case of a train with coal through the residential area).

In the case of using the scale "Microscale" it is required to take into account the geometric shape of the gondola car, which greatly complicates the task of a numerical model development. This is due to the fact, that in this case the calculation area has a very complex geometric shape, different from the canonical, such as rectangular. Inside the calculation area there is a wagon having a certain shape, a cargo that also has a complex geometric shape, in addition, an uneven field of wind velocity near the surface of the cargo is formed.

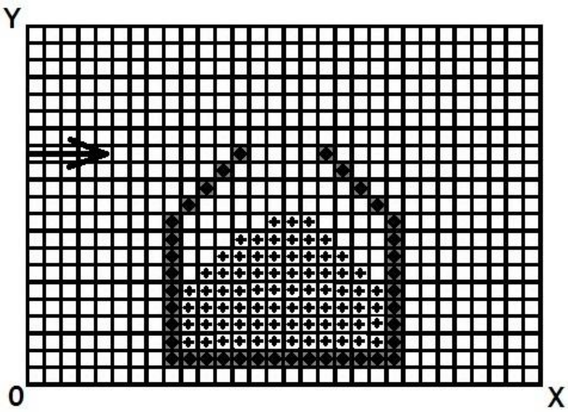
The basis for obtaining information about air pollution intensity as the theoretical solution of the problem is the solution of modeling differential equations, which are considered in the second chapter. This can only be done numerically. In this paper, finite-difference methods to solve modeling equations are used. Their essence is the transition from differential equations to algebraic relations, with which you can find the values of unknown functions (dust concentrations in atmospheric air, the component of the air velocity vector). The set of such relations, which are programmed further, forms a numerical model of the studied process.

The solution of modeling equations is performed using a rectangular difference grid (fig. 3.1, 3.2). To form the outer and inner boundaries of the calculation region, to highlight features within the calculation region the marking method is used, which is sometimes called the method of «porosity technique» [63]. By means of markers the position of the railway wagon, its form, the pile form of bulk (granular) cargo in a gondola car is set (fig. 3.1, 3.2).



● – wagon boundary marker; ✚ – cargo (coal) boundary marker

Figure 3.1 – The principle of marking the calculation region on the difference grid in the 3D numerical model, cross-section x = const



● – wagon boundary marker; ✚ – cargo (coal) boundary marker

Figure 3.2 – The principle of marking the calculation region on the difference grid in the 3D numerical model (setting the wagon shape with a board type «wing»)

The place of coal dust emission from the coal pile in the gondola car is also set using markers. The application of the marking method makes it possible to:

1. Quickly form the shape of a gondola car in a numerical model.

2. Quickly form the shape of the «cap» of the cargo in a numerical model.

3. Quickly form the shape of additional boards (or screen), which are used to reduce the intensity of air pollution.

4. Take into account during the calculation the influence of the geometric shape of the cargo cap on the formation of the local field of air flow velocity, and hence the unevenness of coal dust emissions from different parts of the cargo.

3.2 Numerical solution of coal dust dispersion equation in the atmosphere

Consider the development of a numerical model for calculating the concentration of coal dust in atmospheric air on the basis of three-dimensional equation (2.1). Before the numerical solution of equation (2.1), its splitting at the differential level is made as follows [42, 63]:

$$\begin{gathered}\frac{\partial C}{\partial t}+\frac{\partial uC}{\partial x}+\frac{\partial vC}{\partial y}+\frac{\partial\left(w-w_S\right)C}{\partial z}=0,\\ \frac{\partial C}{\partial t}=\frac{\partial}{\partial x}\left(\mu_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_y\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu_z\frac{\partial C}{\partial z}\right),\\ \frac{\partial C}{\partial t}=\sum Q_i\left(t\right)\delta\left(x-x_i(t)\right)\delta\left(y-y_i(t)\right)\delta\left(z-z_i\right).\end{gathered}\tag{3.1}$$

For convenience in description of the difference scheme development, the designation is made:

$$w\ =w-w_S\,.$$

It should be noted, that from the standpoint of physics, the first equation from system (3.1) describes the transfer of coal dust along trajectories, the second equation describes the transfer due to diffusion, and the third describes the change in dust concentration due to the action of its emission sources. Approximation of the derivatives included in the system (3.1) is performed. It is noteworthy, that the function C is determined in the center of the control volumes (cells), the components of the air velocity vector are defined on the faces of the control volume (these parameters are determined after solving the aerodynamics problem).

Consider the approximation of derivatives in modeling equations. Convective derivatives are written as follows [63]:

$$\frac{\partial uC}{\partial x} = \frac{\partial u^+ C}{\partial x} + \frac{\partial u^- C}{\partial x},$$

$$\frac{\partial vC}{\partial y} = \frac{\partial v^+ C}{\partial y} + \frac{\partial v^- C}{\partial y},$$

$$\frac{\partial wC}{\partial z} = \frac{\partial w^+ C}{\partial z} + \frac{\partial w^- C}{\partial z},$$

where $u^+ = \frac{u+|u|}{2}$; $u^- = \frac{u-|u|}{2}$; $v^+ = \frac{v+|v|}{2}$; $v^- = \frac{v-|v|}{2}$; $w^+ = \frac{w+|w|}{2}$; $w^- = \frac{w-|w|}{2}$.

Конвективні похідні апроксимуємо розділеними різницями проти потоку [63]:

Convective derivatives are approximated by separated differences against the flow [63]:

$$\frac{\partial u^+ C}{\partial x} \approx \frac{u^+_{i+1,j,k} C^{n+1}_{i,j,k} - u^+_{i,j,k} C^{n+1}_{i-1,j,k}}{\Delta x} = L^+_x C^{n+1}$$

$$\frac{\partial u^- C}{\partial x} \approx \frac{u^-_{i+1,j,k} C^{n+1}_{i+1,j,k} - u^-_{i,j,k} C^{n+1}_{i,j,k}}{\Delta x} = L^-_x C^{n+1},$$

$$\frac{\partial v^+ C}{\partial y} \approx \frac{v^+_{i,j+1,k} C_{i,j,k} - v^+_{i,j,k} C_{i,j-1,k}}{\Delta y} = L^+_y C^{n+1},$$

$$\frac{\partial v^- C}{\partial y} \approx \frac{v^-_{i,j+1,k} C_{i,j+1,k} - v^-_{i,j,k} C_{i,j,k}}{\Delta y} = L^-_y C^{n+1},$$

$$\frac{\partial w^+ C}{\partial z} \approx \frac{w^+_{i,j,k+1} C_{i,j,k} - w^+_{i,j,k} C_{i,j,k-1}}{\Delta z} = L^+_z C^{n+1},$$

$$\frac{\partial w^{-}C}{\partial z} \approx \frac{w^{-}_{i,j,k+1}C_{i,j,k+1} - w^{-}_{i,j,k}C_{i,j,k}}{\Delta z} = L_z^{-}C^{n+1},$$

where L_x^{+}, $L_y^{+}, L_y^{-}, L_z^{+}, L_z^{-}$ are designations of difference operators.

To approximate the second derivatives, the following formulas are used [63]:

$$\frac{\partial}{\partial x}\left(\mu_x \frac{\partial C}{\partial x}\right) \approx \mu_x \frac{C^{n+1}_{i+1,j,k} - C^{n+1}_{i,j,k}}{\Delta x^2} - \mu_x \frac{C^{n+1}_{i,j,k} - C^{n+1}_{i-1,j,k}}{\Delta x^2} = M^{-}_{xx}C^{n+1} + M^{+}_{xx}C^{n+1},$$

$$\frac{\partial}{\partial y}\left(\mu_y \frac{\partial C}{\partial y}\right) \approx \mu_y \frac{C^{n+1}_{i,j+1,k} - C^{n+1}_{i,j,k}}{\Delta y^2} - \mu_y \frac{C^{n+1}_{i,j,k} - C^{n+1}_{i,j-1,k}}{\Delta y^2} = M^{-}_{yy}C^{n+1} + M^{+}_{yy}C^{n+1},$$

$$\frac{\partial}{\partial z}\left(\mu_z \frac{\partial C}{\partial z}\right) \approx \mu_z \frac{C^{n+1}_{i,j,k+1} - C^{n+1}_{i,j,k}}{\Delta z^2} - \mu_z \frac{C^{n+1}_{i,j,k} - C^{n+1}_{i,j,k-1}}{\Delta z^2} = M^{-}_{zz}C^{n+1} + M^{+}_{zz}C^{n+1}.$$

The time derivative is written as follows:

$$\frac{\partial C}{\partial t} \approx \frac{C^{n+1}_{i\,j} - C^{n}_{i\,j}}{\Delta t}.$$

Over the time interval *dt* a sequential solution of the equations from the system (3.1) taking into account the considered difference analogues is performed. First, the first equation from the system (3.1) is solved. To do this, the splitting of this equation in difference form is performed as follows [63]:

– *on the first step* $k = n + \frac{1}{4}$ difference equation is written as follows:

$$\frac{C^{k}_{i,j,k} - C^{n}_{i,j,k}}{\Delta t} + \frac{1}{2}\left(L_x^{+}C^{k} + L_y^{+}C^{k} + L_z^{+}C^{k}\right) = 0.$$

Solving this equation with respect to the unknown value of the dust concentration on the upper time layer, the calculation formula is obtained:

$$C^{k}_{i,j,k} = C^{n}_{i,j,k} - \frac{\Delta t}{2}\left(L_x^{+}C^{k} + L_y^{+}C^{k} + L_z^{+}C^{k}\right); \qquad (3.2)$$

– *on the second step* $k = n + \frac{1}{2}$; $c = n + \frac{1}{4}$ difference equation is written as follows:

$$\frac{C^k_{i,j,k}-C^c_{i,j,k}}{\Delta t}+\frac{1}{2}\left(L^-_x C^k+L^-_y C^k+L^-_z C^k\right)=0 .$$

Solving this equation with respect to the unknown value of the dust concentration on the upper time layer, the calculation formula is obtained:

$$\frac{C^k_{i,j,k}-C^c_{i,j,k}}{\Delta t}+\frac{1}{2}\left(L^-_x C^k+L^-_y C^k+L^-_z C^k\right)=0 ; \qquad (3.3)$$

– *on the third step* $k=n+\frac{3}{4}; c=n+\frac{1}{2}$ formula (3.3) is used;

– *on the fourth step* $k=n+1; c=n+\frac{3}{4}$ formula (3.2) is used.

The given difference scheme (formulas (3.2), (3.3)) is called a change-triangular implicit difference scheme of splitting.

Thereafter, the second equation from system (3.1) (the equation of diffusion dust transfer) is solved. To do this, this equation is split into two steps (difference scheme of total approximation) [58]:

– in the first step of splitting, the difference equation has the form:

$$\frac{C^{n+\frac{1}{2}}_{i,j,k}-C^n_{i,j,k}}{\Delta t}=\left[\mu_x\frac{-C^{n+\frac{1}{2}}_{i,j,k}+C^{n+\frac{1}{2}}_{i-1,j,k}}{\Delta x^2}\right]+\left[\mu_y\frac{-C^{n+\frac{1}{2}}_{i,j,k}+C^{n+\frac{1}{2}}_{i,j-1,k}}{\Delta y^2}\right]+\left[\mu_z\frac{-C^{n+\frac{1}{2}}_{i,j,k}+C^{n+\frac{1}{2}}_{i,j,k-1}}{\Delta z^2}\right].$$

Solving it with respect to the value of the concentration on the upper time layer, the calculation formula is obtained:

$$C^{n+\frac{1}{2}}_{i,j,k}=C^n_{i,j,k}+\Delta t\left(\left[\mu_x\frac{-C^{n+\frac{1}{2}}_{i,j,k}+C^{n+\frac{1}{2}}_{i-1,j,k}}{\Delta x^2}\right]+\left[\mu_y\frac{-C^{n+\frac{1}{2}}_{i,j,k}+C^{n+\frac{1}{2}}_{i,j-1,k}}{\Delta y^2}\right]+\left[\mu_z\frac{-C^{n+\frac{1}{2}}_{i,j,k}+C^{n+\frac{1}{2}}_{i,j,k-1}}{\Delta z^2}\right]\right). \qquad (3.4)$$

– in the second step of splitting, the difference equation has the form:

$$\frac{C^{n+1}_{i,j,k}-C^{n+\frac{1}{2}}_{i,j,k}}{\Delta t}=\left[\mu_x\frac{C^{n+1}_{i+1,j,k}-C^{n+1}_{i,j,k}}{\Delta x^2}\right]+\left[\mu_y\frac{C^{n+1}_{i,j+1,k}-C^{n+1}_{i,j,k}}{\Delta y^2}\right]+\left[\mu_z\frac{C^{n+1}_{i,j,k+1}-C^{n+1}_{i,j,k}}{\Delta z^2}\right],$$

Solving it with respect to the value of the concentration on the upper time layer, the calculation formula is obtained:

$$C_{i,j,k}^{n+1} = C_{i,j,k}^{n+\frac{1}{2}} + \Delta t\left(\mu_x\left[\frac{C_{i+1,j,k}^{n+1} - C_{i,j,k}^{n+1}}{\Delta x^2}\right] + \mu_y\left[\frac{C_{i,j+1,k}^{n+1} - C_{i,j,k}^{n+1}}{\Delta y^2}\right] + \left[\mu_z\frac{C_{i,j,k+1}^{n+1} - C_{i,j,k}^{n+1}}{\Delta z^2}\right]\right). \quad (3.5)$$

In the next step, the third equation from the system (3.1) is solved. This equation is approximated as follows:

$$\frac{C_{ijk}^{n+1} - C_{ijk}^{n+A}}{\Delta t} = \sum Q_{ijk}(t)\delta_l(x - x_i(t))\delta_l(y - y_i(t))\delta_l(z - z_i),$$

where C_{ijk}^{n+A} is value of dust concentration on the lower time layer.

Solving this equation with respect to the value of the concentration on the upper time layer, the calculation formula is obtained:

$$C_{ijk}^{n+1} = C_{ijk}^{n+A} + \Delta t\sum Q_{ijk}(t)\delta_l(x - x_i(t))\delta_l(y - y_i(t))\delta_l(z - z_i). \quad (3.6)$$

It should be emphasized, that to solve equation (3.6) the following value of the emission value is used:

$$Q_{ijk} = Q_k / \Delta x / \Delta y / z,$$

where Q_k is known value of dust emission point source from streamlined area.

Thus, the solution of the problem of determining the concentration of coal dust in the air is reduced to the sequential calculation of this concentration by the difference formulas (3.2)-(3.6). These formulas have a simple structure, do not contain complex or tabular functions, and so on.

The initial condition for each difference equation is written as follows:

$$C^1\Big| = C(x, y, t^n), \; C^k\Big| = C^{k-1}\Big|.$$

On solid walls to implement the boundary condition of the form

$$\frac{\partial C}{\partial n} = 0$$

«fictitious» cells are used [18, 63].

Turn to the numerical model for calculating the level of air pollution on the basis of the two-dimensional equation of coal dust transfer (2.7). To solve this problem, an implicit change-triangular difference splitting scheme is used [18, 63]. The development of the numerical model is carried out by applying such a procedure.

Convective derivatives are written as follows [18, 63]:

$$\frac{\partial uC}{\partial x}=\frac{\partial u^{+}C}{\partial x}+\frac{\partial u^{-}C}{\partial x},\ \frac{\partial vC}{\partial y}=\frac{\partial v^{+}C}{\partial y}+\frac{\partial v^{-}C}{\partial y},$$

where $u^{+}=\frac{u+|u|}{2}$; $u^{-}=\frac{u-|u|}{2}$; $v^{+}=\frac{v+|v|}{2}$; $v^{-}=\frac{v-|v|}{2}$.

Approximation of these derivatives is carried out according to the formulas [18, 63]:

$$\frac{\partial u^{+}C}{\partial x}\approx\frac{u^{+}_{i+1,j}C^{n+1}_{ij}-u^{+}_{ij}C^{n+1}_{i-1,j}}{\Delta x}=L^{+}_{x}C^{n+1},$$

$$\frac{\partial u^{-}C}{\partial x}\approx\frac{u^{-}_{i+1,j}C^{n+1}_{i+1,j}-u^{-}_{ij}C^{n+1}_{ij}}{\Delta x}=L^{-}_{x}C^{n+1},$$

$$\frac{\partial v^{+}C}{\partial y}\approx\frac{v^{+}_{i,j+1}C^{n+1}_{ij}-v^{+}_{ij}C^{n+1}_{i,j-1}}{\Delta y}=L^{+}_{y}C^{n+1},$$

$$\frac{\partial v^{-}C}{\partial y}\approx\frac{v^{-}_{i,j+1}C^{n+1}_{i,j+1}-v^{-}_{ij}C^{n+1}_{ij}}{\Delta y}=L^{-}_{y}C^{n+1}.$$

The time derivative is approximated as follows:

$$\frac{\partial C}{\partial t}=\frac{C^{n+1}_{ij}-C^{n}_{ij}}{\Delta t}.$$

To approximate the second derivatives, the following formulas are used [18, 63]:

$$\frac{\partial}{\partial x}(\mu_x\frac{\partial C}{\partial x})\approx\tilde{\mu}_x\frac{C^{n+1}_{i+1,j}-C^{n+1}_{ij}}{\Delta x^2}-\tilde{\mu}_x\frac{C^{n+1}_{ij}-C^{n+1}_{i-1,j}}{\Delta x^2}=M^{-}_{xx}C^{n+1}+M^{+}_{xx}C^{n+1},$$

$$\frac{\partial}{\partial y}(\mu_y\frac{\partial C}{\partial y})\approx\tilde{\mu}_y\frac{C^{n+1}_{i,j+1}-C^{n+1}_{ij}}{\Delta y^2}-\tilde{\mu}_y\frac{C^{n+1}_{ij}-C^{n+1}_{i,j-1}}{\Delta x^2}=M^{-}_{yy}C^{n+1}+M^{+}_{yy}C^{n+1}.$$

The two-dimensional equation of dust transfer in differential form is written as follows [18, 63]:

$$\frac{C^{n+1}_{ij}-C^{n}_{ij}}{\Delta t}+L^{+}_{x}C^{n+1}+L^{-}_{x}C^{n+1}+L^{+}_{y}C^{n+1}+L^{-}_{y}C^{n+1}+\sigma C^{n+1}_{ij}=$$
$$=(M^{+}_{xx}C^{n+1}+M^{-}_{xx}C^{n+1}+M^{+}_{yy}C^{n+1}+M^{-}_{yy}C^{n+1})+Q_{ij}\delta_{ij}. \quad (3.7)$$

In this equation, the symbol δ_{ij} denotes the number "1" or "0", depending on whether or not the difference cell «ij» contains the source of dust emission. The value is calculated as follows:

$$Q_{ij} = Q_k / \Delta x / \Delta y \,,$$

where Q_k is the emission intensity of the k-th point source of dust emission, which is located in the difference cell «ij»

The splitting of the difference equation (3.7) is performed as follows [18, 63]:

– in the first step of splitting $k = \frac{1}{4}$ difference equation has the form:

$$\frac{C_{ij}^{n+k} - C_{ij}^{n}}{\Delta t} + \frac{1}{2}(L_x^+ C^k + L_y^+ C^k) + \frac{\sigma}{4} C_{ij}^k = \\ = \frac{1}{4}(M_{xx}^+ C^k + M_{xx}^- C^k + M_{yy}^+ C^n + M_{yy}^- C^n) + \sum_{l=1}^{N} \frac{Q_l}{4} \delta_l \,; \qquad (3.8)$$

– in the second step of splitting $k = n + \frac{1}{2}$; $c = n + \frac{1}{4}$ difference equation has the form:

$$\frac{C_{ij}^{k} - C_{ij}^{c}}{\Delta t} + \frac{1}{2}(L_x^- C^k + L_y^- C^k) + \frac{\sigma}{4} C_{ij}^k = \\ = \frac{1}{4}(M_{xx}^- C^k + M_{xx}^+ C^c + M_{yy}^- C^k + M_{yy}^+ C^c) + \sum_{l=1}^{N} \frac{Q_l}{4} \delta_l \,; \qquad (3.9)$$

– in the third step of splitting $k = n + \frac{3}{4}$; $c = n + \frac{1}{2}$ difference equation has the form:

$$\frac{C_{ij}^{k} - C_{ij}^{c}}{\Delta t} + \frac{1}{2}(L_x^+ C^k + L_y^- C^k) + \frac{\sigma}{4} C_{ij}^k = \\ = \frac{1}{4}(M_{xx}^- C^c + M_{xx}^+ C^k + M_{yy}^- C^k + M_{yy}^+ C^c) + \sum_{l=1}^{N} \frac{Q_l}{4} \delta_l \,; \qquad (3.10)$$

– in the fourth step of splitting $k = n + 1$; $c = n + \frac{3}{4}$ difference equation has the form:

$$\frac{C_{ij}^{k}-C_{ij}^{c}}{\Delta t}+\frac{1}{2}(L_x^{-}C^{k}+L_y^{+}C^{k})+\frac{\sigma}{4}C_{ij}^{k}=$$
$$=\frac{1}{4}(M_{xx}^{-}C^{k}+M_{xx}^{+}C^{c}+M_{yy}^{-}C^{c}+M_{yy}^{+}C^{k})+\sum_{l=1}^{N}\frac{Q}{4}\delta_l\,. \tag{3.11}$$

From equations (3.8) - (3.11) the unknown value of dust concentration on the upper time layer is determined by the explicit formula of the running calculation [42, 58, 63]. The initial condition for these equations is written in the form:

$$C^{1}\Big| = C(x,y,t^{n}),\; C^{k}\Big| = C^{k-1}\Big|.$$

To implement the boundary condition on the solid walls of the form:

$$\frac{\partial C}{\partial n}=0,$$

fictitious cells are used.

На закінчення зауважимо, що застосовані різницеві схеми мають важливу перевагу: розрахунок невідомого значення концентрації пилу в робочій зоні здійснюється за явними формулами, які мають просту програмну реалізацію.

In conclusion, it should be noted, that the difference schemes used have an important advantage: the calculation of the unknown value of the dust concentration in the work area is carried out according to explicit formulas that have a simple software implementation.

3.3 Numerical solution of air flow velocity calculation task

To determine the velocity field in the case of a gondola car with coal, the equation for the velocity potential is used. To numerically integrate this equation, the method of total approximation is used [58]. If a two-dimensional equation for the velocity potential is considered, first it need to be written in evolutionary form [58]:

$$\frac{\partial P}{\partial t}=\frac{\partial^2 P}{\partial x^2}+\frac{\partial^2 P}{\partial y^2}\,, \qquad (3.12)$$

where t is fictitious time.

It is known, that if $t \to \infty$ the solution of this equation will lead to the solution of the Laplace equation for the velocity potential. In the numerical solution of equation (3.12) it is necessary to specify the potential field at t=0.

For example, before the calculation, P=0 can be taken in the entire calculation region for t=0.

Obtaining the solution of equation (3.12) is performed on a rectangular grid, the function P is defined in the center of the difference cells. (3.12) solving is split into two steps. The difference equations at each step are written as follows:

$$\frac{P_{i,j}^{n+\frac{1}{2}}-P_{i,j}^{n}}{\Delta t}=\left[\frac{-P_{i,j}^{n+\frac{1}{2}}+P_{i-1,j}^{n+\frac{1}{2}}}{\Delta x^2}\right]+\left[\frac{-P_{i,j}^{n+\frac{1}{2}}+P_{i,j-1}^{n+\frac{1}{2}}}{\Delta y^2}\right],$$

$$\frac{P_{i,j}^{n+1}-P_{i,j}^{n+\frac{1}{2}}}{\Delta t}=\left[\frac{P_{i+1,j}^{n+1}-P_{i,j}^{n+1}}{\Delta x^2}\right]+\left[\frac{P_{i,j+1}^{n+1}-P_{i,j}^{n+1}}{\Delta y^2}\right].$$

At each splitting step, the unknown value of the velocity potential is determined by the explicit formula of the running calculation. The calculation is terminated if the condition is met:

$$\left|P_{i,j}^{n+1}-P_{i,j}^{n}\right|\le \varepsilon\,, \qquad (3.13)$$

where ε is a small number (for example, ε = 0.001); n is an iteration number.

After determining the velocity potential field, the components of the air velocity vector are calculated according to the dependences:

$$u_{ij}=\frac{P_{i,j}-P_{i-1,j}}{\Delta x},v_{ij}=\frac{P_{i,j}-P_{i,j-1}}{\Delta y}.$$

The components of the air velocity vector are calculated on the faces of the difference cells (control volumes), which allows to construct a conservative difference scheme for the dust transfer equation.

The Richardson method is used to solve the three-dimensional equation for the velocity potential [55]. To do this, the initial equation for the velocity potential is preliminarily reduced to the evolutionary form:

$$\frac{\partial P}{\partial t} = \frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} + \frac{\partial^2 P}{\partial z^2}, \tag{3.14}$$

where t is fictitious time.

Further, the derivatives are approximated and the calculation of the unknown value of the velocity potential in the new iteration is reduced to the calculation by the formula [55]:

$$P_{ijk}^{n+1} = P_{ijk}^{n} + \Delta t \frac{P_{i+1,j,k}^{n} - 2P_{ijk}^{n} + P_{i-1,j,k}^{n}}{\Delta x^2} + \\ + \Delta t \frac{P_{i,j+1,k}^{n} - 2P_{ijk}^{n} + P_{i,j-1,k}^{n}}{\Delta y^2} + \\ + \Delta t \frac{P_{i,j,k+1}^{n} - 2P_{ijk}^{n} + P_{i,j,k-1}^{n}}{\Delta z^2}.$$

Based on this dependence, the value of the velocity potential in the cells corresponding to the air flow region is calculated. The calculation is stopped if the condition is met:

$$\left| P_{i,j,k}^{n+1} - P_{i,j,k}^{n} \right| \le \varepsilon,$$

where ε is a small number (i.e., $\varepsilon = 0.001$); n is an iteration number.

Fictitious difference cells are used to realize the boundary condition of non-leakage. After determining the field of the velocity potential, the components of the velocity vector on the faces of the difference cells is calculated. The following formulas are used for this:

$$u_{i,j,k} = \frac{P_{i,j,k} - P_{i-1,j,k}}{\Delta x}, v_{i,j,k} = \frac{P_{i,j,k} - P_{i,j-1,k}}{\Delta y}, w_{i,j,k} = \frac{P_{i,j,k} - P_{i,j,k-1}}{\Delta z} \tag{3.15}$$

In addition to the considered Richardson method, the Liebman method is also used [55]. Preliminary approximation of derivatives is carried out:

$$\frac{\partial^2 P}{\partial x^2} = \frac{P_{i+1,j,k} - 2P_{i,j,k} + P_{i-1,j,k}}{\Delta x^2}$$

$$\frac{\partial^2 P}{\partial y^2} = \frac{P_{i,j+1,k} - 2P_{i,j,k} + P_{i,j-1,k}}{\Delta y^2}$$

$$\frac{\partial^2 P}{\partial z^2} = \frac{P_{i,j,k+1} - 2P_{i,j,k} + P_{i,j,k-1}}{\Delta z^2}$$

where $\Delta x, \Delta y, \Delta z$ are steps of difference cell in directions OX, OY, OZ respectively.

According to this, the Laplace equation in the differential form can be written as follows:

$$\frac{P_{i+1,j,k} - 2P_{i,j,k} + P_{i-1,j,k}}{\Delta x^2} + \frac{P_{i,j+1,k} - 2P_{i,j,k} + P_{i,j-1,k}}{\Delta y^2} + \\ + \frac{P_{i,j,k+1} - 2P_{i,j,k} + P_{i,j,k-1}}{\Delta z^2} = 0$$

This equation can determine the desired value of $P_{i,j,k}$ in each difference cell:

$$P_{i,j,k} = \frac{\frac{P_{i+1,j,k} - P_{i-1,j,k}}{\Delta x^2} + \frac{P_{i,j+1,k} - P_{i,j-1,k}}{\Delta y^2} + \frac{P_{i,j,k+1} - P_{i,j,k-1}}{\Delta z^2}}{A},$$

where $A = \left(\frac{2}{\Delta x^2} + \frac{2}{\Delta y^2} + \frac{2}{\Delta z^2} \right)$.

The calculation according to this formula is terminated if the condition is met:

$$\left| P_{i,j,k}^{n+1} - P_{i,j,k}^{n} \right| \le \varepsilon,$$

where n is an iteration number (number of «time» steps); ε is a small number.

After calculating the velocity potential field, the components of the air velocity vector are calculated according to formulas (3.4).

3.4 Development of software packages for assessing the level of air pollution

On the basis of the considered difference schemes the following are developed:

1) software package (generic code) «Coal Dust Dispersion–A» – to calculate air pollution based on three-dimensional equations of aerodynamics and mass transfer (scale «Microscale» and «Local»);

2) software package «Coal Dust Dispersion–B» – to calculate air pollution based on two-dimensional equations of mass transfer and aerodynamics (scale «Microscale»).

Software packages are written in the FORTRAN algorithmic language. Before proceeding to the description of the developed codes, a description of the algorithm for solving the problem of assessing the level of air pollution during coal transportation is given. The solution algorithm consists of several stages:

– *The first stage*: the formation of a database for modeling.

At this stage, the user synthesizes the input data for numerical simulation, for example: the size of the calculation region, the shape of the gondola car, the size of the gondola car, the shape of the additional boards, their size, etc.

– *The second stage*: data entry.

At this stage, the user enters the input data into the output file using the keyboard.

– *The third stage*: calculation.

At this stage, the user runs the simulation code (for example, the code «Coal Dust Dispersion-A») and a numerical solving of the problem of aerodynamics and mass transfer is carried out. The solution determines the field of air flow velocity in the calculation area, the field of coal dust concentration.

– *The fourth stage*: analysis of simulation data.

At this stage, the user assess the level of air pollution on the bases of obtained results.

– *The fifth stage*: adjusting the input data to perform a new calculation.

At this stage, the user makes the necessary adjustments to the source file (for example, changes the shape of the additional boards) and the calculation is repeated again.

Consider the structure of modeling codes.

«Coal Dust Dispersion-A» code structure:

1) subprogram «POTSP» – solving the equation for the velocity potential;

2) subprogram «SPCAL» – calculation of air flow velocity field;

3) subprogram «DUST» – solving the equation of masstransfer (calculation of coal dust concentration in the atmospheric air);

4) subprogram «HQCAL» – hazard quotient calculation;

5) subprogram «CONCD» – developing of a concentration field for visualization of pollution zones.

DuS – data entry file

Functional particularities of «Coal Dust Dispersion-A» code:

1. Ability to calculate the spatial distribution of the concentration of coal dust in the air.

2. Ability to assess the level of air pollution under different conditions of atmospheric stability.

3. Ability to assess the level of air pollution taking into account the gravitational settling of coal dust.

4. Ability to assess the level of air pollution taking into account the shape of the gondola car.

5. Ability to assess the level of air pollution in the residential area.

6. Ability to account dependence the intensity of coal dust emissions in the gondola on the value of the local air flow rate.

The calculation time of one variant of the task on the basis of this code is approximately 10-15 s.

«Coal Dust Dispersion-B» code structure:

1) subprogram «POTS2» – solving the equation for the velocity potential;

2) subprogram «SPCA2» – calculation of the air flow velocity field;

3) subprogram «DS2» – solving the equation of mass transfer (calculation of the concentration of coal dust in the air);

4) subprogram «HQCA2» – calculation of hazard quotient;

5) subprogram «CONC» – developing of a concentration field for visualization of pollution zones;

DuS2 – data entry file.

The functional features of the code «Coal Dust Dispersion-B» are the same as for the code «Coal Dust Dispersion-A».

The calculation time of one variant of the task based on this code is approximately 3 s.

The results of testing the developed numerical models are given in Appendix A.

Conclusions to Chapter 3

1. The equations proposed in Chapter 2 for assessing the level of dust pollution of air during coal transportation take into account the most significant physical factors that cause the dispersion of coal dust from gondola cars, but these models allow only a numerical solution. Therefore, in practice it is very important to create such numerical models on the basis of modeling equations, which would be stable when conducting parametric studies of coal dust release from the gondola car.

2. The difference schemes used to numerically solve the equation describing the dispersion of coal dust in atmospheric air are given. An important feature of these difference schemes is that the solution of the problem is reduced to the sequential solution of equations of simple structure by an explicit formula. This approach provides a simple software implementation of numerical models.

3. The description of difference schemes which are used for calculation of a velocity potential field and velocity of an air flow near gondola cars with coal is resulted. The application of these difference schemes is reduced to the sequential solution of equations of simple structure, which allows a simple software implementation of difference operators.

4. On the basis of the considered difference schemes computer programs for assessing of atmospheric air pollution level during coal transportation in gondola cars are developed. These programs allow to conduct research on the process of air pollution in real time. The flexibility of software packages is based on the application of the modular principle during their development.

5. Created numerical models and computer programs are a new tool for parametric study of the process of air pollution during the coal transportation in gondola cars.

6. Developed numerical models and computer programs created on their basis take into account very significant physical factors that are not taken into account in the method OND-86, which is used nowadays as the main tool for studying the level of air pollution from man-made emissions.

CHAPTER 4
STUDY OF THE EFFICIENCY OF AERODYNAMIC METHODS OF PROTECTION AGAINST ATMOSPHERIC AIR POLLUTION DURING THE TRANSPORTATION OF COAL IN WAGON

This section presents the results of studies on the effectiveness of the use of additional boards and shields to protect the air from pollution during the transportation of coal. The organization of the research process took into account the experience of world leaders in the field of environmental protection during the transportation of coal in wagons [65, 80-82, 84].

4.1 Study of the intensity of coal dust removal

A set of laboratory experiments on the analysis of the intensity of coal dust removal during coal transportation in gondola cars was performed in the laboratory of the Department of Hydraulics and Water Supply of Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan. Based on the experience of specialists dealing with this problem [80-81, 84], studies were performed on models of gondola cars (Fig. 4.4).

The purpose of laboratory research was to test working hypotheses about the possibility of reducing the level of environmental pollution through the use of special additional boards or screens in gondola cars.

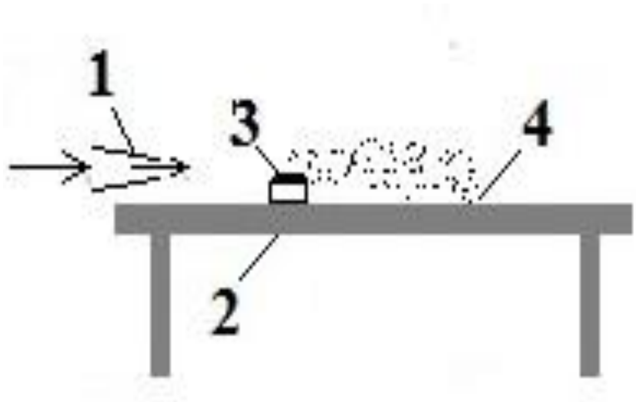
The experiments were performed in several stages. This section presents the results of the first stage of research - analysis of the intensity of coal removal from the research site. The purpose of this study is to determine the emission rate per unit area depending on the air flow rate. These data were later used to determine the intensity of coal emissions during computational experiments.

Coal from Mezhdurechenskaya CZF (humidity 4.6%) was used for laboratory tests. The particle size distribution of this coal is shown in table. 4.1.

Table 4.1 - Particle size distribution of coal

> 5 mm	5–3,15 mm	3,15–0,5 mm	0,5–0,25 mm	0,25–0,125 mm	0,125–0 mm
3–6%	4,5–11,25 %	21,5–53,75 %	5,0–12,8 %	3,5–8,75 %	5,5–13,75%

The scheme of the experimental setup is shown in Fig. 4.1.



1 – fan; 2 – table; 3 – model of a wagon car with coal; 4 – coal sedimentation zone

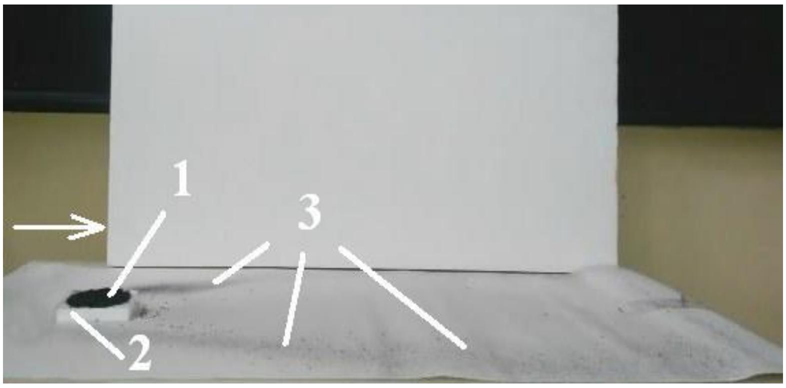
Figure 4.1 – Scheme of the experimental setup

The experiments were performed at an air temperature of29^0C–30^0C, the relative humidity was approximately 26%. Before the experiment, coal samples were placed in ovens brand 2B-151 for 3 hours and were there at a temperature 40^0C. The aim was to minimize the humidity of the experimental samples of coal to bring the experimental conditions closer to the conditions of Nigeria (the average annual temperature in the country is about 32^0C). Since coal wagons may not be transported for several hours while loading and forming a warehouse, the cargo in gondola cars stays for a long time in direct sunlight, heat, which leads to low humidity. If transportation is continued, the humidity will decrease even more.

At the first stage of research, the area with coal measuring 5 cm × 5 cm was blown (Fig. 4.2). The experiment was performed for the range of air flow velocity:

0.6 m/s – 14.3 m/s. A GM 8908 anemometer was used to measure the air flow rate. After purging (5 min), the removed coal dust was collected and weighed.

The results of the physical experiment are shown below. In fig. 4.2 shows the area of contamination that has formed near the site.



1 – coal; 2 – research site; 3 – pollution zone

Figure 4.2 – Removal of coal dust from the experimental site

The obtained experimental data were used to construct a graphical dependence $Q = f(V)$ (Q – the mass of coal dust removed from a unit surface per unit time, V – air flow rate). Next is the graphical dependence $Q = f(V)$ was approximated as follows:

$$Q=4.2*(V-V_{th}), \text{ mg/(m}^2\text{s)},$$

where V – air flow rate, m/s, V_{th} – «Threshold» value of the velocity, after which the separation of particles begins (the experimental value of this value V_{th}=1.58 m/s.).

This empirical model was used during computational experiments, when the task was to calculate the intensity of coal dust removal from different parts of the cargo surface in the wagon.

4.2 Investigation of air pollution in the case of loading coal with a "cap" in the wagon

In the second stage of research, the issue of coal removal from the gondola model in the case of loading it with a «cap» was studied, as in Nigeria such coal transportation is very common (Fig. 4.3). This method is considered to be extremely negative for the environment, because a significant area of the cargo surface is exposed to air flow, therefore, there is an intensive removal of dust from the wagon.

Figure 4.3 – «Cap» of the cargo exceeds the height of the board of the wagon [89]

During the research, a 12-1592 wagon car was chosen as the base. The length of the gondola is 12,800 mm, the height is 3 474 mm, and the width is 3 134 mm. The physical model of the gondola was made on a scale of 1:100 (Fig. 4.4). During the experiments, the Reynolds number was 10^4 - 10^5 (as a characteristic linear scale, the selected length of the car, the speed of the oncoming air flow). The maximum excess of the coal cap in the car model was 7 mm air temperature 30 ^{0}C.

Figure 4.4 – Model of a wagon with coal (loading with a «cap»)

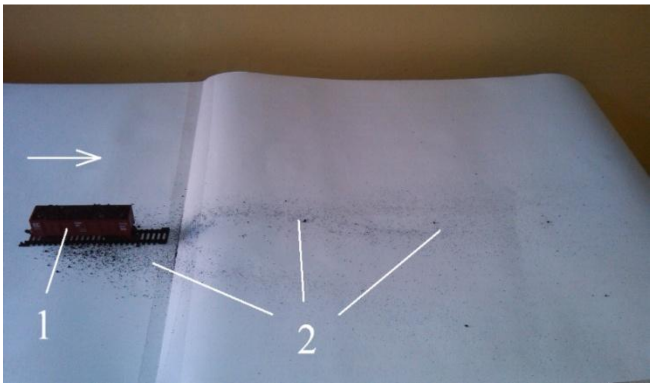
During the research were measured:

1. The mass of coal removed from the model of the gondola after the purge.

2. The size of the pollution area.

3. Dust concentration (PM2.5) at a certain distance from the model.

In fig. 4.5 shows a photo of the area of contamination near the model of the gondola in the case of loading it with a «cap» (air flow rate:13.6m/s – 14.3m/s).

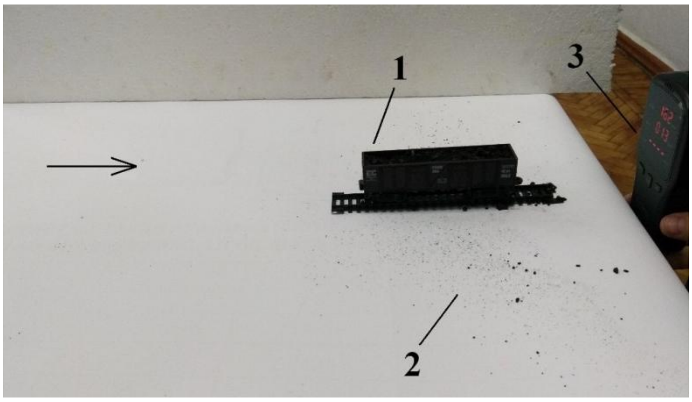


1 – model of wagon car; 2 – pollution zone

Figure 4.5 – The area of contamination in the absence of additional boards on the model of the wagon and in the presence of a «cap» of the cargo

As can be seen from the figure, a large area of contamination has formed near the gondola model, which completely «covers» a large area near the highway. The contamination zone has the form of a «cone». The length of the contamination area is almost 6 lengths of the gondola model, and the width is almost 4-5 lengths of the car model. The area of contamination is dark, especially near the model. This indicates a significant removal of coal from the wagon and a high level of contamination of the underlying surface. It is seen that from the model of the wagon there was a removal of different fractions of coal. Larger fractions fell near the wagon model. This experiment confirms that in the case of the use of wagon cars without additional sides and with the «cap» of the cargo is intense pollution of the environment according to the scheme: «car - air - the underlying surface».

The following figure shows how the dust concentration was measured in the laboratory according to the gondola model. To measure the concentration of dust PM2.5 on the model of the car used a laser meter WP6910 (Fig. 4.6). The measurement was performed at the height of the sides of the gondola model, and at the length *l* from model (*l* – the length of the car model).



1 – model of gondola car; 2 – pollution zone; 3 – device for measuring the concentration of dust WP6910

Figure 4.6 – Measurement of dust concentration according to the wagon model

At the next stage of research, a 3D computational experiment was conducted to assess air pollution near the highway. The experiment was performed on the basis of developed numerical models of aerodynamics and mass transfer. The scheme of the 3D model of the wagon is shown in fig. 4.7. Note that the X-axis is directed along the axis of the car. The shape of the «cap» of the cargo and the shape of the car are set in the numerical model using markers. Dust sedimentation rate is accepted 7.6×10^{-3} m/s, air flow rate 14.0 m/s. The purpose of the calculation was to assess the size, shape and intensity of the formed area of air pollution near the railway.

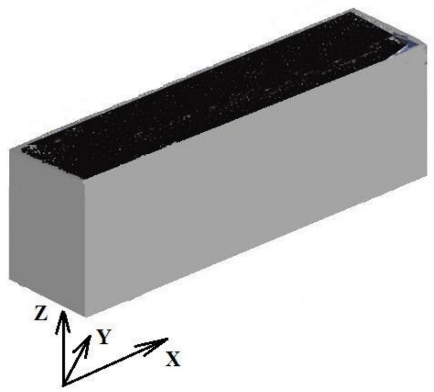
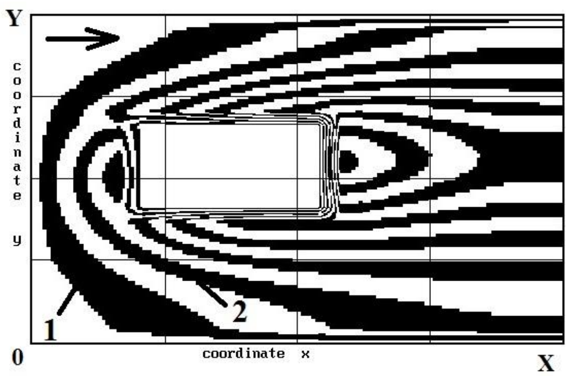


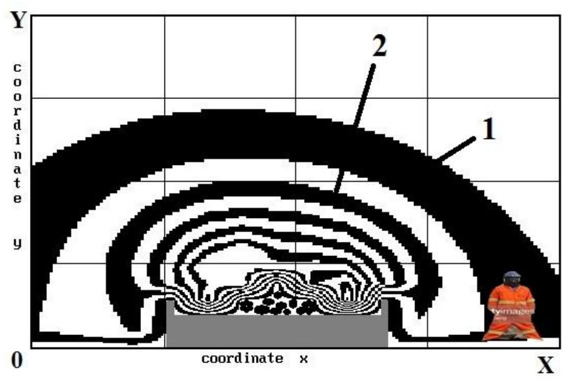
Figure 4.7– Scheme of the calculation area in 3D modeling

In fig. 4.8 and 4.9 show the concentration field of dust pollutant in two sections: respectively z = const (top view) and *x* = const (side view). Schematically, the location of a person is shown near the wagon (Fig. 4.8).



1 – C = 0,33 mg/m^3; 2 – C = 0.78 mg/m^3

Figure 4.8 – Contamination zone near the wagon (top view)

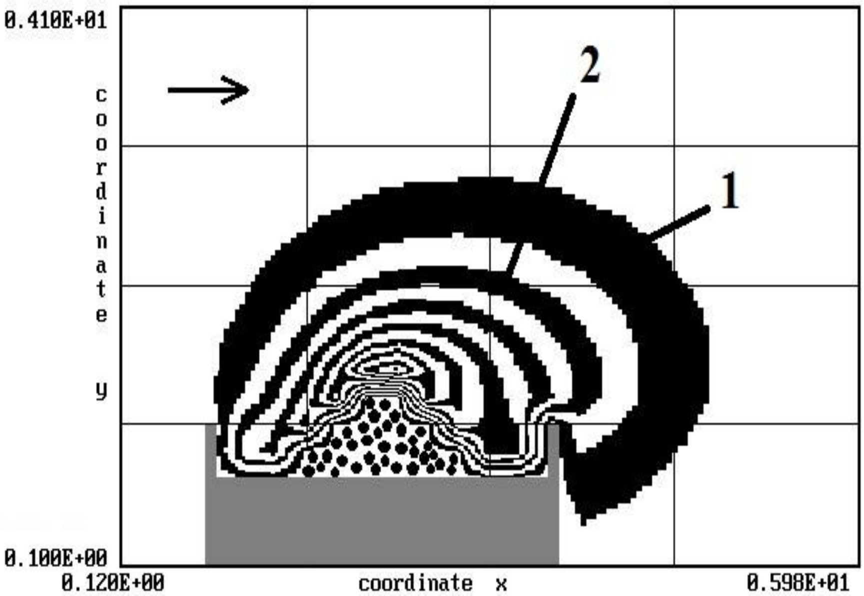


1– C = 2.1 mg/m^3 ; 2 – C = 10.2 mg/m^3

Figure 4.9 – Contamination zone near the gondola (side view)

As can be seen from these figures, the results of the computational experiment confirm the formation of a large area of contamination near the gondola. The calculation based on the developed three-dimensional model requires almost 1 minute of computer time.

In fig. 4.10 shows the distribution of the concentration of coal dust near the gondola, obtained on the basis of the developed 2D numerical model (calculated per 1 m of the length of the gondola). The calculation based on the developed two-dimensional model requires 10 s of computer time.



1 – C = 0.15 mg/m^3; 2 – C = 0.75 mg/m^3

Figure 4.10 – Zone of air pollution near the gondola loaded with a «cap» (calculation based on 2D numerical model)

As can be seen from the figure, the air flow removes coal dust from the gondola, which leads to contamination of areas near the highway. Some discrepancy in the distribution of dust concentration isolines in cross section (compared to 3D calculation) is explained by the fact that in the case of modeling based on a three-dimensional model takes into account the removal of dust along the entire length of the gondola, which leads to a wide area of contamination.

conducting a physical experiment. In the case of using a two-dimensional model, this effect is not taken into account.

To quantify the impact of coal dust removal from the gondola, the dust concentration at a height of 1.7 m and at different distances from the gondola was calculated. The hazard factor was determined in this area HQ [32]:

$$HQ = AC / RfC, \qquad (4.1)$$

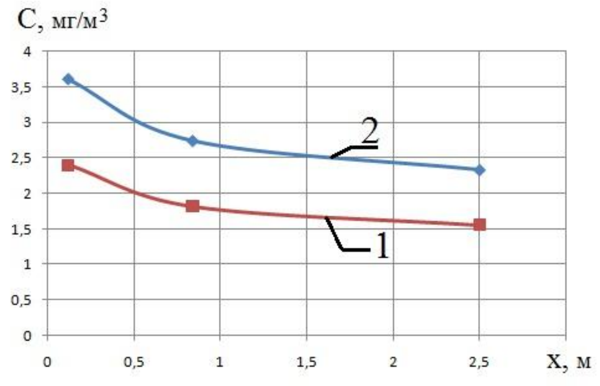
where *AC* – concentration of coal dust near the wagon; *RfC* – reference concentration.

It is known that the level of danger to humans depends on the value of this indicator, as shown in table. 4.2 [32].

Table 4.2 - Criterion of non-carcinogenic risk

Risk characteristics	Risk factor HQ
The risk of adverse effects is considered to be negligibly small	<1
A threshold that does not require urgent action but cannot be considered acceptable enough	1
The probability of adverse effects increases in proportion to the increase HQ	> 1

In the calculation of the hazard indicator as the value of *RfC* value is taken 1,5 mg/m^3 (maximum permissible concentration recommended by the NIOSH institute, the standard is valid from August 2016). The distribution of this indicator and the concentration of coal dust near the wagon is shown in Fig. 4.10.



1 –coefficient HQ; 2 – concentration of coal dust

Figure 4.11 – Distribution of coal dust concentration near the wagon and the value of the danger factor HQ (wagon with a «cap» of coal)

As can be seen from Fig. 4.11, in the case of loading coal into a car with a «cap» is quite intense air pollution near the highway, and the value of the HQ near the wagon is 1.5.

4.3 Study of the effectiveness of the use of additional boards such as "vertical wall" to protect the environment from dust pollution

At the next stage of research, a working hypothesis was put forward about the possibility of reducing the level of environmental pollution by installing additional boards on the gondola car of the «vertical wall» type, exceeding the «cap» of the cargo (Fig. 4.12).

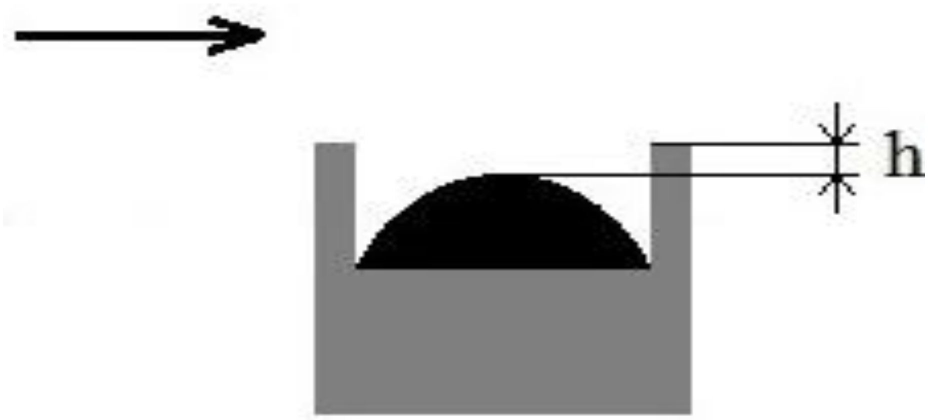
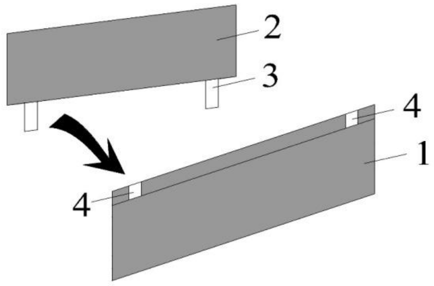


Figure 4.12 – Scheme of additional boards of the type «vertical wall»

The principle of installation of additional boards in a gondola car is shown in fig. 4.13: «lugs» are made on the sides of the wagon by welding, where the guide pins of the additional sides are installed. There is also a possibility when the boards are made holes for guide pins.



а

1 – the wall of the wagon; 2 – additional board; 3 – «guide pins»; 4 – holes for installation of additional boards

б

1 – mounting for the board; 2 – additional board (http://www.gerina.ru/poluvagon.jpg)

Figure 4.13 – The principle of placement of additional boards on the wall on the wagon mounting location (a) and a schematic view of the additional boards (b)

To test the working hypothesis, experimental studies were conducted to estimate the size of the contamination zone of the underlying surface in the case of installation in the gondola of such additional boards. The model of such gondola is shown in fig. 4.14. The sides (exceeding the coal cap by h = 6 mm) were made of cardboard and fixed to the walls of the gondola model. The experiment was performed for the air flow rate, as for the basic variant - that is, a car without sides.

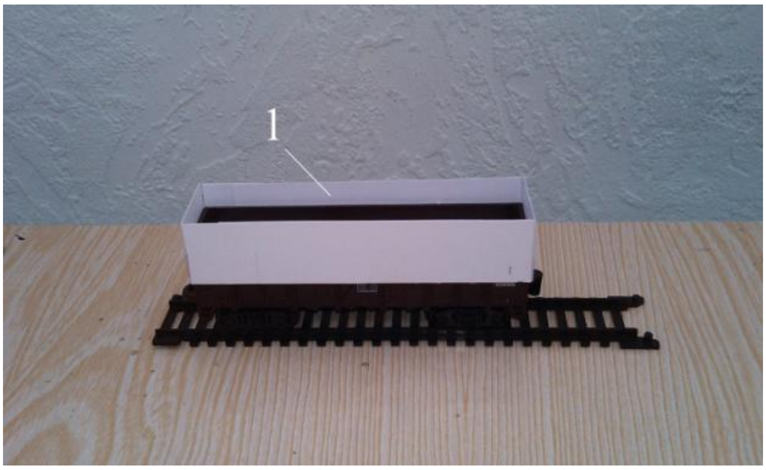
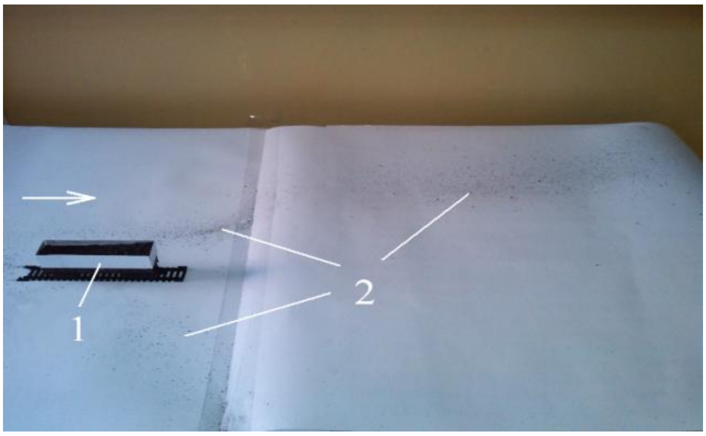


Figure 4.14 – Model of wagon with additional sides of the type «vertical wall»

In fig. 4.15 shows the area near the model of the wagon with additional sides of the type «vertical wall».



1 – model of wagon car; 2 – pollution zone

Figure 4.15 – Contamination zone near the wagon model with additional sides of the type «vertical wall»

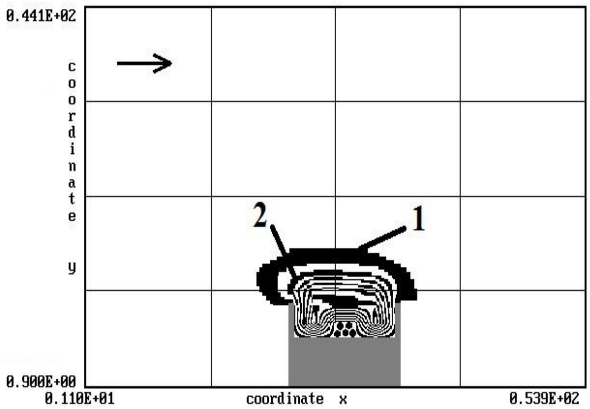
If we compare Fig. 4.15 from fig. 4.5 (model of the wagon without additional sides, loading with a «cap»), it is seen that the use of additional sides of this form has reduced the removal of large fractions from the wagon. This is evidenced by the color of the contaminated area - it is lighter than in the previous case (car without additional sides). This means that the use of additional sides reduced the local velocity near the surface of the cargo and the kinetic energy of the air flow near the surface of the cargo was only enough to «tear off» small particles of cargo.

The length of the contamination zone near the wagon model was approximately four car lengths, and the width was approximately 3-5 model lengths. The angle of divergence of the «cone» of the contamination zone is greater than in the previous case, it is obvious that there was a removal of smaller fractions and there is a removal of a smaller mass of cargo. At the end of the experimental studies, the mass of coal that settled on the surface of the installation was determined (coal was collected and weighed). These data were compared with the mass of coal that settled on the surface of the installation for the basic version - the model of the wagon without additional sides (see Fig. 4.5). The same procedure was performed for other options for additional boards and screen, which are discussed below.

For this variant, the emission of coal dust decreased by approximately 13% - 15% compared to the base version, ie - in the absence of sides.

At the next stage of research on the basis of the developed numerical models calculations on an estimation of efficiency of application of such additional boards on the real car were executed. The intensity of coal dust emission from the cargo surface is calculated from the obtained experimental dependence, given earlier. The results of these computational experiments are shown below (air flow velocity 14.0 m/s).

In fig. 4.16 shows the area of contamination (the cross section corresponds to the middle of the car), obtained when using a three-dimensional numerical model.

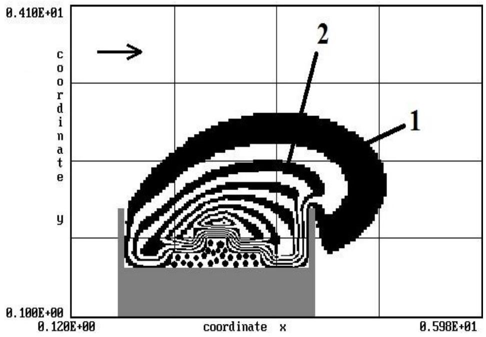


1 – C = 3.2 mg/m^3; 2 – C = 16.5 mg/m^3

Figure 4.16 – Contamination zone near the wagon with additional sides of the type «vertical wall», section x = const (calculation based on 3D numerical model)

If you compare this figure with Fig. 4.9 (calculation also on the basis of 3D CFD model), it is possible to be convinced that application of additional boards allows to reduce the sizes of a pollution zone that «catches» the developed numerical model. The calculation based on the constructed 3D numerical model showed that for such a variant the emission of coal dust decreased by 17%.

In fig. 4.17, and shows the contamination zone obtained when using a two-dimensional numerical model.



a)

б)

Figure 4.17 – Contamination zone near the wagon with additional sides of the type «vertical wall», calculation based on 2-D numerical model (a) and in the case of removal of dust from the trailer (b):
1 – C = 0,11 mg/m^3; 2 – C = 0,58 mg/m^3

As can be seen from the figure, an area with a large gradient of coal dust concentration is formed above the surface of the cargo. It is also seen that the wind flow captures the dust and carries it through the board of the gondola in the direction of wind flow. It is also seen that under the action of gravity dust particles move down along the wall of the wagon.

In fig. 4.17, b shows the removal of dust from the trailer. This is an experiment that was conducted on the territory of DNUZT. The emission of dust was created by dropping a container with construction debris on the floor of the trailer, ie the emission source was semi-continuous. Next, a photograph of the formed contamination zone was taken. The wind speed at the level of the trailer side was almost 2.7 - 3.3 m/s. Comparing fig. 4.17, and Fig. 4.17, b, we see a qualitative agreement on the shape of the real pollution zone and calculated according to the developed numerical model.

In fig. 4.18 shows the value of the concentration of coal dust near the car (calculation based on 2D numerical model, height 1.7 m).

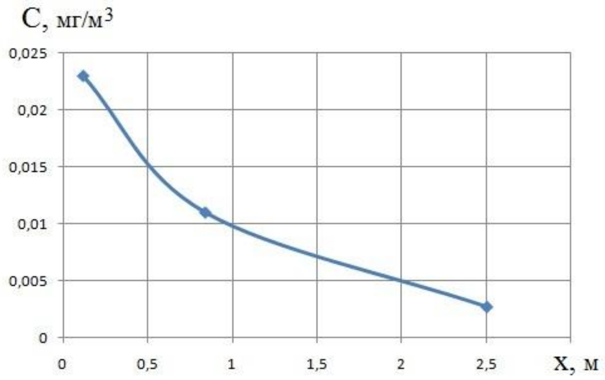


Figure 4.18 – Distribution of coal dust concentration in atmospheric air (car with additional sides of the type «vertical wall»)

As can be seen from Fig. 4.18, installation of additional vertical boards «vertical wall» allows to reduce the level of air pollution: the concentration of coal dust anywhere in this area does not exceed the limit value *RfC* = 1.5 mg/m^3.

4.4 Study of the effectiveness of the use of additional wings of the «wing» type to protect the environment from pollution

At the next stage of research, a working hypothesis was put forward that it is possible to reduce the intensity of the environment near the railway line, if you use additional «wing» type, having a L-shape (Fig. 4.19). To confirm this working hypothesis, a physical experiment was performed, the results of which are given below. In fig. Figure 4.20 shows a model of a gondola car with additional sides of the "wing" type (H = 5 mm, angle 45^0). The experiment was performed for the air flow rate, as for the basic variant – that is, a car without sides.

In fig. 4.21 shows the results of an experiment to assess the contamination zone of such a wagon.

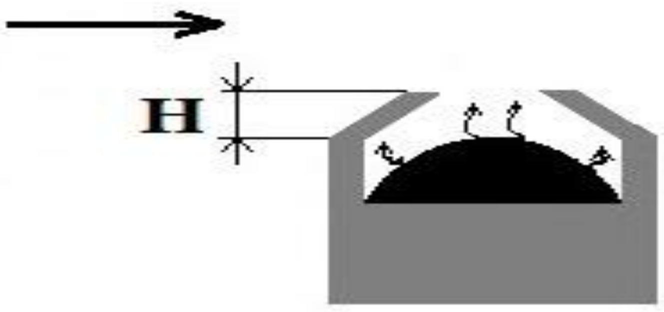


Figure 4.19 – Scheme of additional Г-shaped «wing» side boards

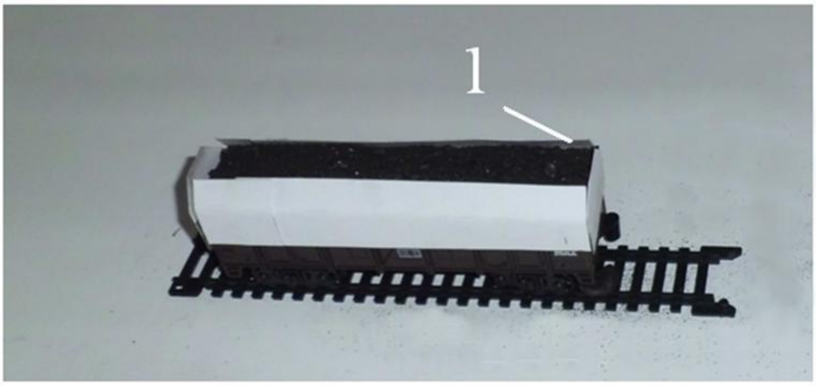


Figure 4.20 – Model of gondola with additional sides of the type «wing» Г-shaped (1)

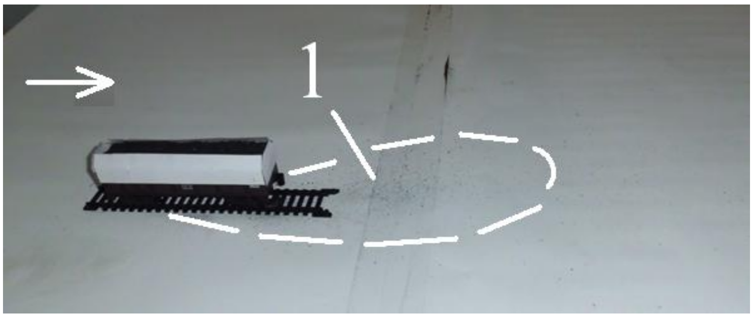
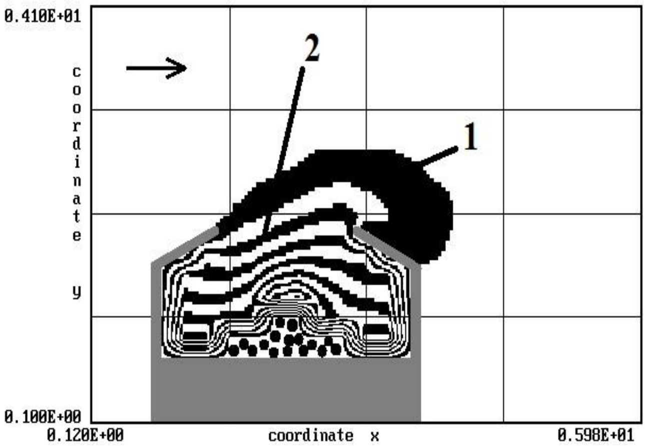


Figure 4.21 – Contamination zone (1) near the wagon model with additional Г-shaped «wing» sides

If we compare Fig. 4.21 from fig. 4.5 (model of the wagon without additional sides), it is seen that the use of additional sides of this form has significantly reduced the size of the contamination area near the model of the wagon. The contaminated area has the shape of a «drop». The length of this zone is almost equal to the length of the wagon, the width is less than the length of the wagon model. From the figure it is also clear that in the case of using additional sides of this form there was a decrease in the mass of coal taken out of the wagon compared to the car without additional sides, the color of the contamination zone is not as saturated as in the previous two cases. This indicates a decrease in the local velocity of the air flow near the surface of the cargo. For this protection option, the emission of coal dust decreased by approximately 19% - 21% compared to the base version (no additional sides).

At the next stage of research, calculations were performed on the basis of the developed 2D CFD model to assess the effectiveness of the use of additional Γ-shaped sides mounted on a real wagon. The intensity of coal dust emission from the cargo surface is calculated according to the obtained experimental dependence given earlier, ie it was taken into account that the emission intensity depends on the local air flow velocity (ground flow velocity 14.0 m/s).

Figure 4.22 shows a picture of air pollution near the gondola with coal for this scenario.



1 – C = 0.045 mg/m^3 ; 2 – C = 0.224 mg/m^3

Figure 4.22 – Contamination zone near the wagon in the presence of additional Γ-shaped sides

The figure shows that the installation of additional boards leads to a change in the intensity and shape of the dust pollution zone compared to the scenario when there are no additional boards. In this case there is a partial containerization of cargo. Isolines of dust concentration inside the wagon repeat the shape of the «wing». Dust comes out of the hole between the «wings» and is carried away by air flow on the «wing» in the area adjacent to the car airspace.

In the second stage of research, the concentration of dust in the air near the real wagon was calculated. These data are shown in Fig. 4.23 (level 1.7 m).

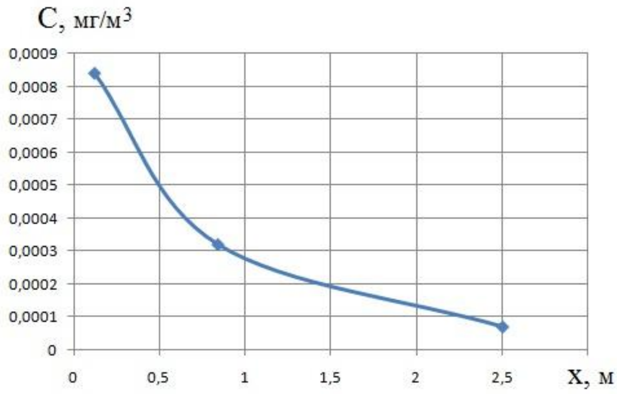


Figure 4.23 – Distribution of coal dust concentration in atmospheric air (car with additional Г-shaped sides of the «wing» type)

As can be seen from the figure, the installation of additional sides of the type "wing" can significantly reduce the level of air pollution. The concentration of coal dust nowhere in this area does not exceed the limit value RfC = 1,5 mg/m^3. Based on the performed computational experiment, it was found that the emission of coal dust decreased by approximately 22% compared to the base version (no additional boards).

4.5 Study of the effectiveness of the use of additional boards such as «inner wing» to protect the environment from pollution

At the next stage of research, a working hypothesis was put forward that it is possible to reduce the intensity of contamination of the working area near the highway in the case of installation in the wagon of additional boards such as «inner wing». The scheme of such board is shown in fig. 4.24.

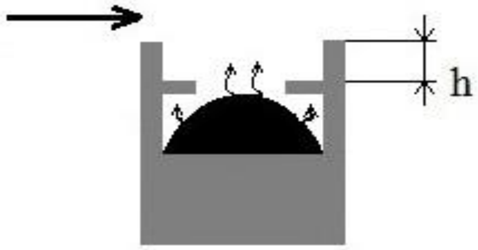
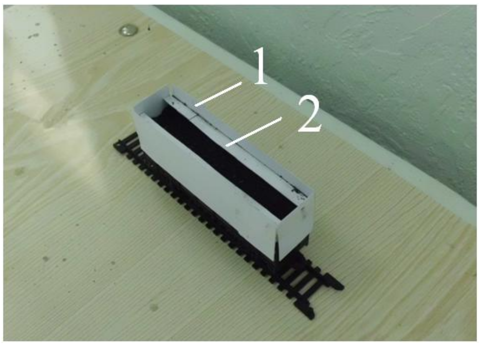


Figure 4.24 – Scheme of additional boards of the type «inner wing»

A physical experiment was performed to test the working hypothesis. In fig. 4.25 shows a model of a wagon car with additional sides of the «inner wing» type (length of the «inner wing» 57 mm, height h = 4 mm). The experiment was performed for the air flow rate, as for the basic variant – that is, a car without sides.

In fig. 4.26 shows the results of an experiment to assess the contamination zone for such a wagon.



1 – additional board; 2 – «inner wing»

Figure 4.25 – Model of a gondola car with additional sides of the type «inner wing»

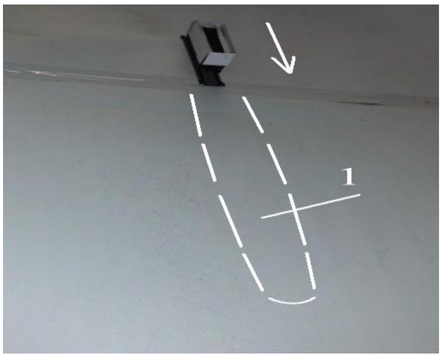


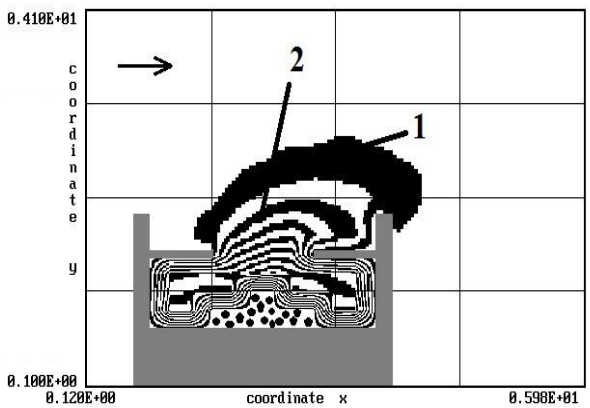
Figure 4.26 – Contamination zone (1) in the case of the use of additional boards of the type «inner wing»

Comparing fig. 4.26 from fig. 4.5, we see that the area of contamination that is formed is much smaller in both area and intensity than in the case of using a wagon without additional sides. Here, the shape of the contamination zone has the appearance of an elongated «rectangle». It is also seen that in contrast to the option, when there are no additional boards, there was a removal of small fractions, as evidenced by the color of this zone. The length of the contamination zone is approximately 3 model lengths, the width is almost one model length.

Thus, the results of the experiment confirm the proposed working hypothesis about the possible minimization of the removal of coal dust from the wagon by using additional boards such as «inner wing». For this option, the removal of coal from the wagon has decreased by approximately 22% - 24%.

At the next stage of research, a computational experiment based on the 2-D CFD model was performed to numerically determine the concentration of coal dust in the air in the case of using additional boards such as «inner wing» for a real car. The intensity of coal dust emission from the cargo surface is calculated according to the obtained experimental dependence given earlier. The air flow velocity is 14 m/s.

In fig. 4.27 shows a picture of air pollution near the wagon with coal for this scenario.



1 – C = 0.044 mg/m^3 ; 2 – C = 0.222 mg/m^3

Figure 4.27 – Contamination zone near the wagon in the presence of additional sides of the type «inner wing»

The figure shows that the installation of additional boards leads to changes in the intensity and shape of the contaminated area, and there is a partial containerization of cargo. An area with a high dust concentration gradient is formed under the «inner wing». Dust is removed through the hole between the «inner wing». The calculation based on the constructed numerical model showed that for such a variant the emission of coal dust decreased by 26%.

Next, the concentration of dust in the air near the wagon was calculated. These data are shown in Fig. 4.28 (level 1.7 m).

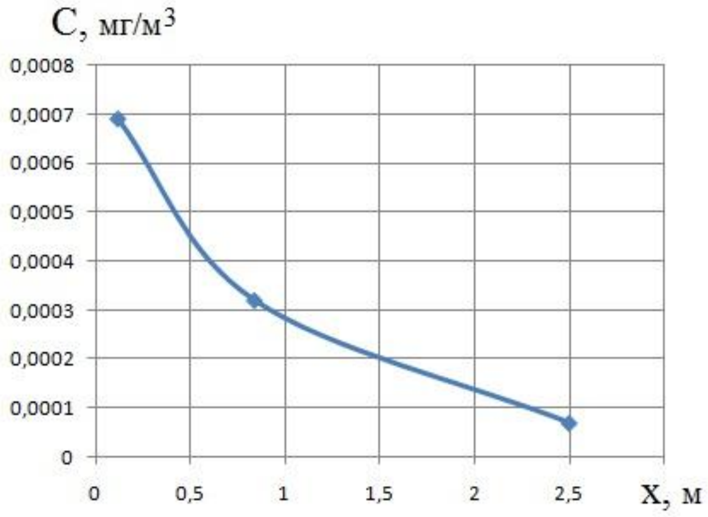


Figure 4.28 – Distribution of the concentration of coal dust in the air (car with additional sides of the type «inner wing»)

As can be seen from the figure, the installation of additional sides of the type «inner wing» allows, as in the previous scenario, to significantly reduce air pollution. The concentration of coal dust nowhere in this area does not exceed the limit value *RfC* = 1,5 mg/m^3.

It should be noted that the manufacture of additional boards (material: wood, plastic, etc.) does not require significant material costs. So, the cost of additional boards from a tree makes approximately 8 euros, installation of fastenings on the car for additional boards – almost 2 euros.

4.6 Study of the effectiveness of the installation of the screen in the wagon car to protect the environment from pollution

To reduce the intensity of coal dust removal from the wagon, it is proposed to use the installation of a screen in the wagon, which is placed across the car (Fig. 4.31). This screen type «barrier» is an obstacle that «runs» the air flow, as a result of its inhibition, and thus reduce the flow rate over the load.

To test the working hypothesis that the installation of the screen will reduce the intensity of removal of coal dust from the wagon, a physical experiment was conducted. Initially (Fig. 4.29), the experiment was conducted for a model of a wagon without a screen. In contrast to previous cases, here the height of the «cap» of the cargo was lower than in previous cases. That is, it was also a «poorly loaded car», but with a smaller height «cap» of the cargo. Air flow rate: 13.4 m/s – 14.1 m/s.

Figure 4.29 – Model of wagon with cargo (no screen)

In fig. 4.30 shows the contamination area near the model of the wagon without a screen.

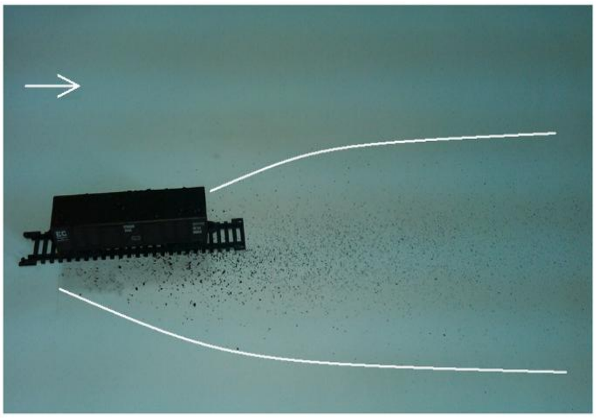


Figure 4.30 – Contamination zone (truncated lengthwise) in the absence of a screen

The contamination zone for this scenario has the form of a cone. The length of the contamination area is approximately 5 lengths of the wagon model, and the width is approximately 4 lengths of the wagon model. The area of contamination has a dark color, especially near the model, which indicates a significant removal of coal from the model of the wagon. Large fractions fell both near the wagon model and in the trail.

In fig. Figure 4.31 shows a model of a wagon car with a screen (screen height 1 cm, the screen is located at a distance of 15 mm from the end wall of the car).

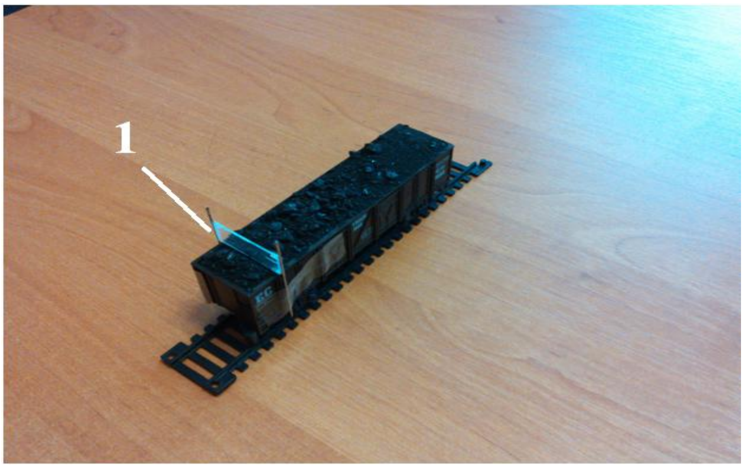


Figure 4.31 – Model of wagon with screen (1)

In fig. 4.32 shows the contamination zone near the model of the wagon with a screen.

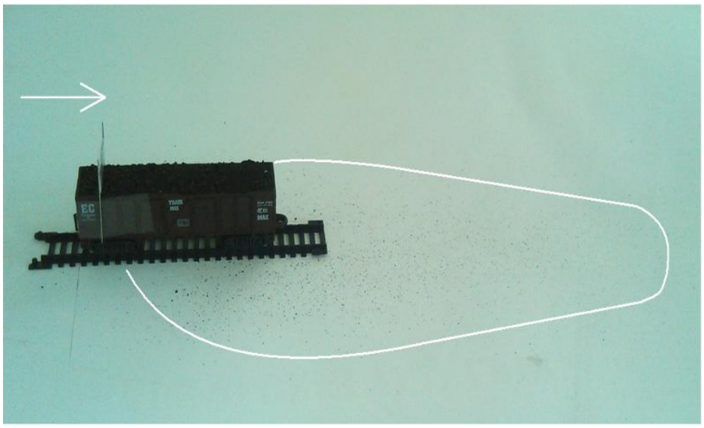


Figure 4.32 – Contamination area when using the screen

Comparing fig. 4.32 from fig. 4.30, we see that in the case of using the screen, the contamination zone has become smaller in size. Here the shape of the contamination zone has the shape of a bottle. In contrast to the option when there is no screen, there was a removal of small fractions, as evidenced by the «light» color of the contaminated area. The length of the contamination zone is approximately 2.5 model lengths, and the width is approximately 1 model length.

Based on the analysis of this information, it is possible to qualitatively assess the effectiveness of the use of the screen on the wagon with bulk cargo. For this variant of the experiment, the removal of coal dust decreased by approximately 11% - 12%. The calculation based on the constructed 2D numerical model (air flow velocity 14 m/s) showed that for such a variant the emission of coal dust was reduced by 14%.

Thus, the results of the experiment confirmed the correctness of the working hypothesis about the possible use of screens in the wagon car to minimize the level of environmental pollution.

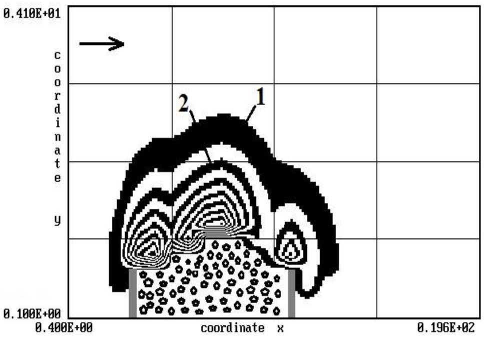
Below, in table. 4.3 shows the data on the average value of the dust concentration $PM_{2.5}$ behind the model of the wagon when installing different types of protection.

Table 4.3 – The value of the concentration of dust $PM_{2.5}$ behind the model of the wagon, mkg/m^3

Type of protection	No protection	Board «vertical wall»	Board «wing»	Board «inner wing»	Screen
Dust concentration behind the model	38	15	12	12	19

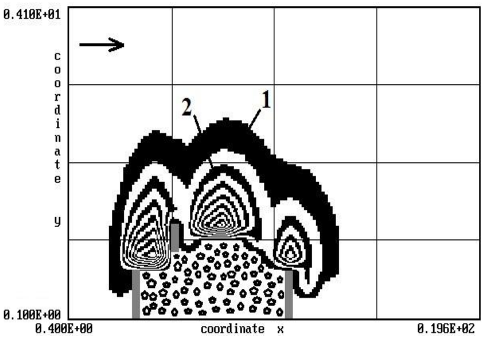
Analyzing the data from table. 4.3, it can be argued that the use of the proposed additional boards, the screen can reduce the intensity of dust pollution.

In fig. 4.33 and 4.34 show the data of numerical modeling of the zone of air pollution without a screen and in the case of using a screen on a real car. Here is the distribution of impurity concentration along the gondola.



1 – C = 0,21 mg/m^3; 2 – C = 0,64 mg/m^3

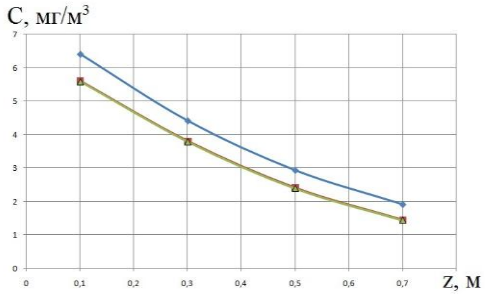
Figure 4.33 – Contamination zone above the wagon without a screen



1 – C = 0,16 mg/m^3 ; 2 – C = 0,53 mg/m^3

Figure 4.34 – Contamination area above the wagon when using the screen

In fig. Figure 4.35 shows the calculated values of the concentration of dust in the air at different heights from the «cap» of the cargo. The section corresponding to the middle of the wagon is selected. The calculation for the «screen» scenario was performed on two grids: 25 × 21 nodes and 50 × 42 nodes.



◆ – wagon without screen; ☐ – car with one screen (grid 25 × 21 knots);

Δ – wagon car with screen (grid 50 × 42 knots)

Figure 4.35 – Distribution of dust concentration in the air over the car

As can be seen from Fig. 4.35, the use of the screen can reduce the level of air pollution.

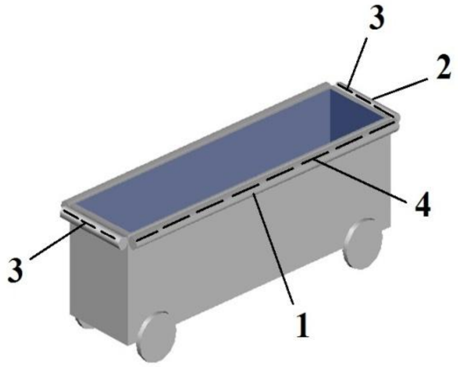
Now determine the additional resistance of the wagon when installing the screen. Assuming that the height of the screen is approximately h=1 m, width b=3m, air density 1,2 kg/m^3, screen resistance coefficient 1,1 (flat plate), train speed 60 km/h, then this resistance can be calculated from the known dependence on aerodynamics [41]

$$F_x = C_x \rho S \frac{V^2}{2},$$

where C_x – coefficient of resistance; $S = h \cdot b$ – screen area; ρ – air density; V – speed of movement.

The calculation shows that the additional resistance for 1 wagon with a screen will be almost 60 kg. The weight of the wagon with coal is approximately 82 tons, ie the additional resistance introduced by the screen is negligible. Also note that the cost of a wooden screen is almost 3 euros, the installation of mounts on the car for the screen – about 1 euro.

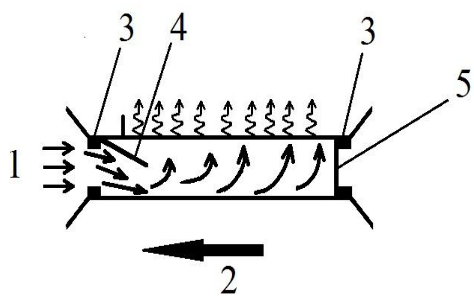
At the end of this section, consider another version of the screen – the air curtain. To reduce the intensity of removal of coal dust from the wagon, it is proposed to use such a curtain. The idea of this curtain is as follows. Along the perimeter of the car in its upper part there are air ducts, which have a perforation on top for air outlet. The layout of the air ducts is shown in Fig. 4.36. The ends of each air duct are open, but have a non-return valve, as, for example, for the air duct located on the sides of the wagon (Fig. 4.36).



1 – air duct located along the side wall of the wagon; 2 – air duct located on the end walls of the wagon;3, 4 – perforation in air ducts

Figure 4.36 – Layout of air ducts on the body of the wagon

During the movement of the wagon, air begins to flow to the end of the air duct, which is directed in the direction of train movement.

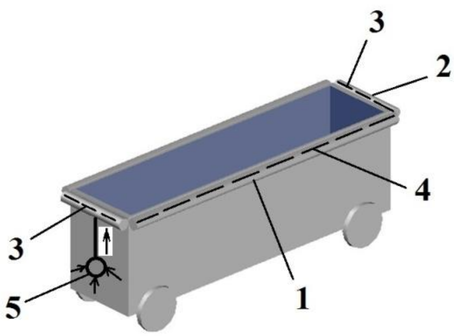


1 – air flow inlet; 2 – the direction of movement of the wagon; 3 – valve seat; 4, 5 – valves

Figure 4.37 – Scheme of the air duct

The flow of air entering the air duct opens the valve 4 (Fig. 4.37), while the valve 5 – closes. The incoming air moves out through the perforation (slit). This process is conventionally shown in the figure by wavy arrows. Thus, during the movement of the car there is a vertical air stream, which, like a screen located on the perimeter of the wagon, prevents the removal of coal dust and thus reduces environmental pollution. The use of such a «screen» is possible only on the end walls of the wagon.

Varying the area of the inlet openings of the air duct, the area of its cross section, the area of perforation, based on the aerodynamic calculation is determined by the air flow velocity in the air curtain and its value, depending on the speed of the train. Another approach may be to use a blower placed on the body of the car to supply air to the perforated ducts (Fig. 4.38).



1 – air duct located along the side wall of the wagon;

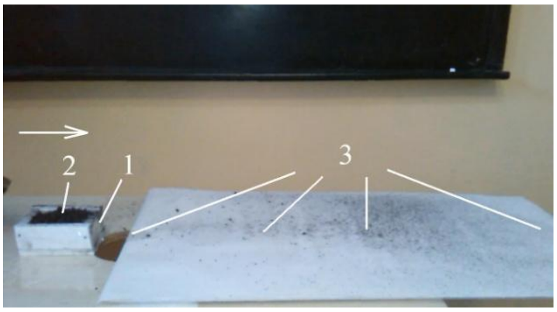
2 – air duct located on the end walls of the wagon;

3,4 – perforation in air ducts; 5 – fan

Figure 4.38 – Layout of the blower on the body of the wagon

To confirm the working hypothesis about the possibility of using an air curtain to minimize the removal of coal dust from the gondola, a physical experiment was conducted. For this purpose the installation shown in fig. 4.39. The car was modeled with a vessel made of foam (dimensions: 12cm * 12cm * 7cm), filled with coal. According to this model of the gondola, a hole was made in the table, from where the air from the blower came vertically upwards. The speed of the main air flow was 7.2 m/s – 8.6 m/s, flow rate in the air curtain 11.6 m/s – 13.8 m/s. The results of the physical experiment are given below.

In fig. 4.39 shows the area of contamination near the model in the absence of an air curtain.

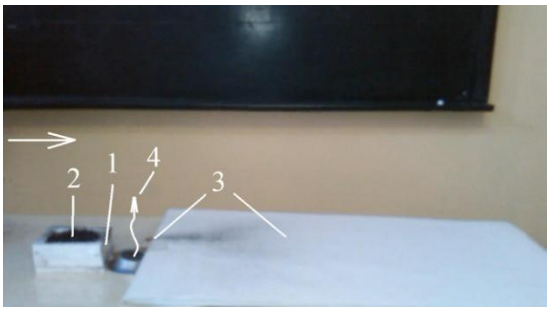


1 – wagon car model; 2 – coal; 3 – pollution zone

Figure 4.39 – Pollution zone according to the model in the absence of a vertical curtain

From fig. 4.39 it is clear that a large and intense zone of dust pollution has formed near the car model. The length of the zone is about 6 lengths of the model, the width is almost 4-5 lengths of the model.

In fig. 4.40 shows the area of contamination in the presence of an air curtain near the model.



1 – wagon car model; 2 – coal; 3 – pollution zone 4 – air curtain stream

Figure 4.40 – Pollution zone according to the model in the presence of an air curtain

Comparing fig. 4.40 and 4.39, we see that the use of an air curtain has dramatically reduced the size and intensity of the pollution zone near the model.

Thus, the results of the experiment confirmed the correctness of the working hypothesis about the possible use of an air curtain to minimize the level of environmental pollution. Further research is needed to implement this idea on a real wagon.

4.7 Modeling of air pollution in the residential area during the movement of a train with coal

Based on the developed 3D numerical model and the code "Coal Dust Emission", the calculation of air pollution in the residential area near the Enugu station during the movement of the coal train was performed. In fig. 4.41 arrow shows the direction of movement of the train. It is believed that coal is loaded into wagon cars with a «cap».

Figure 4.41 – View of the settlement area (residential area near Enugu station, Nigeria) (Google image)

In this region, the residential area is located at a distance of about 10 m – 12 m from the highway. The forecast is based on the developed three-dimensional numerical model of mass transfer. The movement of a train consisting of 10 cars with coal is considered. The surface area of the cargo in each car is taken as $50m^2$; train speed is 18 km/h, air speed is 4 m/s, wind direction is north-west. Each coal car is modeled by a point source of dust pollution using the Dirac delta function. But as the car moves, its coordinates change into delta functions. The intensity of coal dust emissions from the car is calculated on the basis of the empirical formula given in paragraph 4.1.

In fig. 4.42, 4.43 shows the area of dust pollution (level z = 3.5 m) for different points of time during the passage of the train.

1 – C = 0,43 mg/m^3; 2 – C = 0,82 mg/m^3

Figure 4.42 – Dust pollution zone near Enugu station during coal train operation (t = 4 s)

1– C = 0,47 mg/m^3 ; 2 – C = 0,88 mg/m^3

Figure 4.43 – Dust pollution zone near Enugu station during coal train operation (t = 8 s)

As can be seen from the figures, a large area of dust pollution is formed during the movement of the train. Structures near the railway are affected by the source of dust emissions.

In the table. 4.4 shows the calculated data on the concentration of coal dust near the highway for the time t = 9 s (in Fig.4.41 position, along which shows the distribution of dust concentration, indicated by the dashed line). This table shows the data of a similar calculation, but if the gondola cars will be installed additional boards such as «inner wing».

Table 4.4 – Concentration of dust in the air at different distances from the highway (concentration is given in dimensionless form)

Distance *Y*, m	Concentration, mg/m^3	
	«Badly » loaded wagon car	Wagon car with board «inner wing»
2	10.63	5.12
4	3.73	1.64
6	0.87	0.31
11	0.46	0.07

As can be seen from table. 4.4, the use of additional boards has led to a significant reduction in air pollution.

The following figures show the area of contamination after the passage of the train with coal for several points in time (ie without the presence of a source of coal dust).

1– C = $0.81 \cdot 10^{-4}$ mg/m^3 ; 2 – C = $1.7 \cdot 10^{-4}$ mg/m^3

Figure 4.44 – Dust pollution zone near Enugu station after passing a train with coal (t = 14 s)

$1 – C = 0.12 \cdot 10^{-8}$ mg/m^3 ; $2 – C = 0.23 \cdot 10^{-6}$ mg/m^3

Figure 4.45 – Dust pollution zone near Enugu station after passing a train with coal (t = 24 s)

As can be seen from the figures, the cloud of dust formed in the atmosphere during the passage of the train is carried away by the wind flow and covers the residential area, ie the process of air pollution and the underlying surface after passing the train with coal continues.

Conclusions to Chapter 4

1. For the first time, the results of physical experiments are presented, which confirm the proposed working hypotheses about the possibility of reducing the level of environmental pollution through the use of additional sides or screen on coal wagons. The results of the experiments showed that the use of additional boards and screen in the gondola leads to a decrease in the removal of dust from it and thus minimizes the level of environmental pollution.

2. With the help of the developed numerical models and created codes the research on an estimation of level of pollution of atmospheric air at coal transportation in wagon cars with additional boards and the screen is carried out for the first time. The results of these studies confirmed that the use of such protection methods leads to a decrease in the concentration of coal dust in the air.

3. The results of research show that the constructed numerical models allow for the first time to quickly determine the level of air pollution, taking into account the movement of a freight train with coal.

4. The results of computational experiments indicate that the use of the developed codes allows to obtain predictive information about the level of air pollution, taking into account a range of important physical factors influencing the process of scattering of coal dust. Therefore, according to their capabilities, the proposed numerical models are close to the capabilities of modern physical experiment.

CONCLUSIONS

The dissertation contains the results obtained by the author, which together solve the scientific and practical problem of reducing the level of environmental pollution during the transportation of coal in wagon cars. The research performed in this work allows us to draw the following conclusions:

1. The analysis of factors influencing the removal of coal dust during coal transportation in wagons showed that the most important factor causing the removal of coal dust is the value of the local air flow rate near the cargo, therefore, to prevent large-scale dust emissions from the gondola to reduce the local air flow rate near the surface of the coal.

2. Based on a systematic analysis of scientific papers on environmental pollution during coal transportation in wagon cars, it is established that existing methods of environmental protection from pollution are high cost, not always effective, require the use of additional equipment at loading stations. To solve this problem, new approaches have been developed to minimize the level of environmental pollution during coal transportation.

3. The analysis of models and methods used in practice to assess the level of environmental pollution during coal transportation, shows that they have significant limitations and do not allow to determine the effectiveness of different methods of environmental protection from pollution during coal transportation, which requires improvement of models and methods , which take into account the movement of the train with coal, weather conditions, the trajectory of the train, the types of protection used on wagon cars.

4. On the basis of the performed experimental researches it is established that application in wagon cars of additional boards like «vertical wall» allows to reduce removal of coal dust from a wagon car by 13% –15%; the use of additional boards of the «wing» type allows to reduce the removal of coal dust from the wagon by 19% - 21%; the use of additional boards such as «inner wing» can

reduce the removal of coal dust from the wagon by 22% - 24%; the use of the screen allows to reduce the removal of coal dust by 11% -12%.

5. The possibility of using a new approach has been shown experimentally, namely the use of an air curtain on a wagon car, which allows to reduce the level of environmental pollution during coal transportation.

6. To estimate the intensity of coal dust emission from the surface of the cargo, an empirical model was obtained that allows to calculate the mass of dust entering the atmosphere at different local air velocities near the coal surface.

7. A set of numerical models has been developed to predict the dustiness of atmospheric air during coal transportation in wagon cars, taking into account the shape of the car and the shape of the additional sides and screen. Verification of the developed numerical models confirmed their adequacy.

8. The method of determining the level of air pollution during coal transportation has been improved, which allows to take into account the trajectory of train movement, meteorological conditions, train speed with coal when estimating the level of pollution.

9. Developed numerical models and methods of environmental protection are used in LLC "Energoservice-KR" to develop technology to protect air from pollution during transportation of iron ore and coal, as well as in the educational process of the Dnieper National University of Railway Transport named after Academician V. Lazaryan.

REFERENCES

1. Абрамовський Є. Р., Гринчишин Ю. Л., Єгоров Є. В., Загній О. А. Методи розрахунку концентрації повітряних забруднень на міській території : навч. посіб. Дніпропетровськ : Наука і освіта, 2010. 223 с.

2. Аргучинцев В. К., Аргучинцев А. В. Моделирование мезомасштабных гидротермодинамических процессов и переноса примесей в атмосфере и гидросфере региона оз. Байкал. Иркутск : Изд-во Иркутского гос. ун-та, 2007. 255 с.

3. Белолипецкий В. М., Костюк В. Ю., Шокин Ю. И. Математическое моделирование течений стратифицированной жидкости. Новосибирск : Наука, 1991. 116 с.

4. Беляев Н. Н., Карпо А. А. Моделирование процесса сноса угольного концентрата из полувагонов. *Наук. вісн. буд-ва* : зб. наук. пр. / Харк. нац. ун-т буд-ва та архітектури. Харків, 2016. № 1 (83). С. 196–199.

5. Беляев Н. Н., Коренюк Е. Д., Хрущ В. К. Методы экспресс расчета уровня загрязнения атмосферы. Днепропетровск : Наука и образование, 2002. 192 с.

6. Беляев Н. Н., Берлов А. В., Машихина П. Б. Моделирование нестационарных процессов аварийного загрязнения атмосферы: монография. Днепропетровск : «Акцент ПП», 2014. 127 с.

7. Беляев Н. Н., Гунько Е. Ю., Росточило Н. В. Защита зданий от проникновения в них опасных веществ : монография. Днепропетровск : «Акцент ПП», 2013. 136 с.

8. Беляев Н. Н., Оладипо Мутиу Олатойе. Минимизация интенсивности выноса пыли из полувагона при транспортировке угля. *Електромагнітна сумісність та безпека на залізничному транспорті :* науковий журн. Дніпро : Дніпропетр. нац. ун-т залізн. трансп. ім. акад. В. Лазаряна, 2016. № 11. С. 93–100.

9. Беляев Н. Н., Оладипо М. О. Модели оценки уровня загрязнения атмосферы при транспортировке сыпучих грузов. *Наука та прогрес транспорту. Вісн. Дніпропетр. нац. ун-ту залізн. трансп. ім. акад. В. Лазаряна.* 2016. Вип. 5 (65). С. 22–29.

10. Беляев Н. Н., Оладипо М. О. Проблема уноса угольной пыли. *Наука та прогрес транспорту. Вісн. Дніпропетр. нац. ун-ту залізн. трансп. ім. акад. В. Лазаряна.* 2016. Вип. 6 (66). С. 17–24.

11. Беляев Н. Н., Оладипо М. О. Расчет динамики загрязнения примагистральной территории при перевозке угля. *Наука та прогрес транспорту. Вісн. Дніпропетр. нац. ун-ту залізн. трансп. ім. акад. В. Лазаряна.* 2016. Вип. 1 (67). С. 18–26.

12. Беляев Н. Н., Оладипо Мутиу Олатойе. Математическое моделирование уноса угольной пыли. *Інформатика, управління та штучний інтелект. Матеріали третьої міжнарод. науково-техн. конф. студентів, магістрів та аспірантів.* Харків : НТУ «ХПІ», 2016. С. 6.

13. Беляев Н. Н., Оладипо Мутиу Олатойе. Экологические проблемы транспортировки сыпучих грузов железнодорожным транспортом. *Диференціальні рівняння та проблеми аерогідромеханіки й тепломасо-переносу* : тези доп. Всеукраїнської наукової конф. (28-30 вересня 2016 р., Дніпро). Дніпро : Дніпропетр. нац. ун-т, 2016. С. 62.

14. Беляев Н. Н., Оладипо Мутиу Олатойе. Теоретическое и экспериментальное исследование уноса угольной пыли. *Теоретичні та практичні аспекти розвитку науки (частина II)* : матеріали II Міжнародної науково-практ. конф. (м. Київ, 29-30 листопада 2016 року). Київ : МЦНД, 2016. С. 15–16.

15. Беляев Н. Н., Оладипо Мутиу Олатойе. Компьютерно-информационная система анализа уноса угольной пыли. *Современные информационные и коммуникационные технологии на транспорте, в промышленности и образовании* : тезисы X Международной научно-

практ. конф. (Днепр, 14-15 декабря 2016 г.). Днепр : ДИИТ, 2016. С. 90–91.

16. Беляев Н. Н., Оладипо Мутиу Олатойе. Моделирование загрязнения окружающей среды при транспортировке сыпучих грузов железнодорожным транспортом. *Комп'ютерне моделювання та оптимізація складних систем (КМОСС-2016)* : матеріали II Всеукр. науково-техн. конф. з міжнародною участю (м. Дніпро, 1-3 листопада 2016 р.) / Міністерство освіти і науки України, Державний вищий навчальний заклад «Український державний хіміко-технологічний університет». Дніпро : ДВНЗ УДХТУ, 2016. С. 26–27.

17. Беляев Н. Н., Оладипо Мутиу Олатойе, Гыркало А. В. Прогнозирование уровня загрязнения рабочих зон возле железнодорожной магистрали. *Строительство. Материаловедение. Машиностроение. Сер.: Энергетика, экология, компьютерные технологии в строительстве.* Днепр : ГВУЗ «Приднепр. гос. акад. стр-ва и архитектуры», 2017. Вып. 98. С.61–67.

18. Беляев Н. Н., Оладипо М. О., Кириченко П. С. Защита окружающей среды при транспортировке угля. Кривой Рог : Изд. : Р. А. Козлов, 2018. 92 с.

19. Беляев Н. Н., Козачина В.А., Оладипо М. О. Защита атмосферного воздуха от загрязнения при перевозке угля: эксперимент, математическое моделирование. *79 Міжнародна науково-практична конференція «Проблеми та перспективи розвитку залізничного транспорту»*, 16-17.05.2019, Дніпро. Дніпро : ДНУЗТ, 2019. С. 293-294.

20. Беляев Н. Н., Якубовская З.Н., Козачина В.А., Оладипо Мутиу Олатойе. Математическое моделирование загрязнения транспортного коридора при перевозке угля. *Комп'ютерне моделювання та оптимізація складних систем (КМОСС-2018)* : матеріали IV Міжнародної науково-техн. конф. «Комп'ютерне моделювання та оптимізація складних систем» (м. Дніпро, 1-2 листопада 2018 р.) /

Міністерство освіти і науки України, Державний вищий навчальний заклад «Український державний хіміко-технологічний університет». Дніпро : ДВНЗ УДХТУ, 2018. С. 38.
21. Берлянд М. Е. Прогноз и регулирование загрязнения атмосферы. Ленинград : Гидрометеоиздат, 1985. 273 с.
22. Бруяцкий Е. В. Теория атмосферной диффузии радиоактивных выбросов. Киев : Ин-т гидромеханики НАН Украины, 2000. 443 с.
23. Вамболь С. О., Вамболь В. В., Кондратенко О. М., Міщенко І. В. Критеріальне оцінювання рівня екологічної безпеки процесу експлуатації енергетичних установок : монографія / НУЦЗ України. Харків : ФОП Бровін О.В., 2018. 320 с.
24. Вамболь С.О., Строков О. П., Вамболь В. В., Кондратенко О. М. Сучасні способи підвищення екологічної безпеки експлуатації енергетичних установок : монографія / НУЦЗ України. Харків : ФОП Бровін О. В., 2015. 212 с.
25. Воробйов Є. О., Ніколенко М. О., Худякова І. О. Запобігання забруднення повітря пилом під час транспортування вугілля. *Вісті АДІ ДВНЗ «ДонНТУ»*. Горлівка, 2005. № 1. С. 34–38.
26. Генихович Е. Л. К вопросу о применимости гауссовой модели для расчета загрязнения воздуха. *Тр. ГГО*. 1982. Вып. 450. С. 35–40.
27. Голинько В. И. Рудничная пыль, динамика, контроль концентрации и пылеотложений. *Уголь Украины*. 1994. № 4. С. 58–59.
28. Голінко В.І., Савельєв Ю.В., Чеберячко І.М., Пустовий Д.С. Зниження концентрації дрібнодисперсного пилу при проходці гірничих виробок з використання енергії вибуху. *Зб. наук. пр. Нац. гірнич. ун-ту*. 2019. № 57. С. 169–178.
29. Гусев Н. Г., Беляев В. А. Радиоактивные выбросы в биосфере. Москва : Энергоатомиздат, 1991. 257 с.
30. Закон України про охорону навколишнього природного середовища. *Відомості Верховної Ради (ВВР)*. 1991. № 41. Ст. 546.

31. Запорожець О. І. Проект концепції управління ризиками надзвичайних ситуацій техногенного та природного характеру. *Безпека життєдіяльності*. 2007. № 4. С. 2–4.

32. Зберовский А. В. Математическое моделирование загрязнения атмосферы при аварийном выбросе химически опасного вещества. *Зб. наук. пр. Нац. гірнич. ун-ту.* 2012. № 37. С. 305–310.

33. Іконнікова Н. А., Юрченко А. А., Іконніков М. Ю. Экспериментальные исследования коэффициента захвата железорудной пыли каплями воды при ее орошении. *Зб. наук. пр. Нац. гірнич. ун-ту*. 2018. № 54. С. 363–377.

34. Калабин Г. В., Бакланов А. А., Амосов П. В. Метод расчета аэрогазодинамики камерообразных выработок на основе математического моделирования. *ФТПРПИ*. 1990. № 1. С. 74–88.

35. Колесник В. Е., Головина Л. А. , Богуцкая В. В. Математическое моделирование процесса рассеивания промышленной пыли в атмосфере. *Зб. наук. пр. Нац. гірнич. ун-ту.* 2006. № 26, т. 2. С. 120–130.

36. Колесник В. Е., Головина Л. А., Левченко М. В. Пылевой выброс вентилятора главного проветривания угольной шахты: экологическая опасность, способы снижения или локализация : монография. Днепропетровск : Нац. горн. ун-т, 2011. 125 с.

37. Кострюков В. А. Основы гидравлики и аэродинамики. Москва : Высшая шк., 1975. 220 с.

38. Кошик Ю. Й. Розробка технології боротьби з пилом при перевезенні гірничої маси залізничним транспортом : автореф. дис. … канд. техн. наук. Кривий Ріг, 2003. 20 с.

39. Лаврентьев М. А. Проблемы гидродинамики и их математические модели. Москва : Наука, 1977. 407 с.

40. Логачев И. Н., Логачев К. И. Аэродинамические основы аспирации. Санкт-Петербург : Химиздат, 2005. 659 с.

41. Лойцянский Л. Г. Механика жидкости и газа. Москва : Наука, 1978. 735 с.

42. Марчук Г. И. Математическое моделирование в проблеме окружающей среды. Москва : Наука, 1982. 320 с.

43. Беляев Н. Н., Якубовская З. Н., Козачина В. А., Оладипо Мутиу Олатойе. Математическое моделирование загрязнения транспортного коридора при перевозке угля. *Комп'ютерне моделювання та оптимізація складних систем (КМОСС-2016)* : матеріали IV Міжнародної науково-техн. конф. « Комп'ютерне моделювання та оптимізація складних систем» (м. Дніпро, 1-2 листопада 2018 р.) / Міністерство освіти і науки України, Державний вищий навчальний заклад «Український державний хіміко-технологічний університет». Дніпро : ДВНЗ УДХТУ, 2018. С. 38.

44. Оцінка ризику для здоров'я населення від забруднення атмосферного повітря : метод. рекомендації : наказ МОЗ України від 13.04.2007 р. № 184. URL: https://zakon.rada.gov.ua/rada/show/v0184282-07#Text (Accessed 05.09.2020).

45. Методика расчета концентрации в атмосферном воздухе вредных веществ, содержащихся в выбросах предприятий. Ленинград : Гидрометеоиздат, 1987. 93 с.

46. Озмидов Р. В. Горизонтальная турбулентность и турбулентный обмен в океане. Москва : Наука, 1968. 204 с.

47. Оладипо М.О. Анализ загрязнения атмосферного воздуха при перевозке угля в полувагонах**.** Результаты лабораторных исследований и математического моделирования. *Науковий симпозіум «Тиждень еколога–2019»* (ДДТУ, Кам'янське, 7-10.10.2019). Кам'янське, 2019. С. 17.

48. Оладипо Мутиу Олатойе. Оценка уровня загрязнения воздушной среды возле железнодорожных магистралей с помощью информационной системы анализа уноса угольной пыли из вагонов.

Доклады междунар. научн. симпозиума «Неделя эколога – 2017», 10-13 апреля 2017 г. Каменское : ДГТУ, 2017. С. 35.

49. Оладипо Мутиу Олатойе. Экспертная оценка загрязнения рабочих зон при перевозке угля. *Материалы 77-й Международной научно-практ. конф. «Проблемы и перспективы развития железнодорожного транспорта»*, 11-12 мая 2017 г., Днепр. Днепр : ДНУЖТ, 2017. С. 242.

50. Отделкин Н. С. Теоретические основы оценки потерь сыпучих грузов и защиты окружающей среды от пылеобразования при перегрузке и хранении в портах : дис. … д-ра техн. наук. Н. Новгород, 2009. 301 с.

51. Пененко В. В., Алоян А. Е. Модели и методы для задач охраны окружающей среды. Новосибирск : Наука, 1985. 257 с.

52. Пляцук Л. Д., Бойко В. В. Аналіз методів математичного моделювання розповсюдження забруднюючих речовин в атмосфері. *Вісн. КНУ імені Михайла Остроградського.* 2010. Вип. 6. С. 1–4.

53. Полянин А. Д., Вязмин А. В., Журов А. И., Казенин Д. А. Справочник по точным решениям уравнений тепло- и массопереноса. Москва : Факториал, 1998. 368 с.

54. Пономарьова С. Д., Юрченко В. О., Аксьонова О. Ф. Розсіювання дрібнодисперсного пилу кондитерського підприємства за межами санітарно-захисної зони. *Харчова наука і технологія.* 2018. Вип. 1 (27). С. 344 – 355.

55. Роуч П. Вычислительная гидродинамика. Москва : Мир, 1980. 616 с.

56. Рудаков Д. В. Модель рассеивания примеси в приземном слое атмосферы над поверхностью со сложным рельефом. *Вісн. ДНУ. Сер.: Механіка*. 2004. Вип. 8. № 6. т. 1. С. 89–97.

57. Самарский А. А., Михайлов А. П. Математическое моделирование. Москва : Физматлит, 2001. 320 с.

58. Самарский А. А. Теория разностных схем. Москва : Наука, 1983. 616 с.

59. Серебреніков Е. В. Розробка методики визначення концентрації пилу на ділянках робочих зон кар'єрів при перевантаженні гірничої маси: автореф. дис. канд. техн. наук. Кривий Ріг, 2010. 20 с.

60. Способы и средства борьбы с пылью на добычных участках угольных шахт. Экспресс-информ / ЦНИЭИуголь. Москва, 1978. 40 с.

61. Степаненко С. Н., Волошин В. Г., Типцов С. В. Решение уравнения турбулентной диффузии для стационарного точечного источника. *Український гідрометеорологічний журн*. 2008. № 3. С. 13–24.

62. Уорк К., Уорнер С. Загрязнение воздуха. Источники и контроль. Москва : Мир, 1980. 539 с.

63. Численное моделирование распространения загрязнения в окружающей среде / Згуровский М. З., Скопецкий В. В., Хрущ В. К., Беляев Н. Н. Київ: Наук. думка, 1997. 368 с.

64. Шмандий В.М. Научно-методические принципы исследования состояний техногоннной безопасности в регионе. *Вісник КДПУ*. 2002. Вип. 5(16). С. 19–24.

65. Alan J. Cimorelli et al. Aermod: Description Of Model Formulation / EPA-454/R-03-004, September, 2004. P. 91.

66. Alvarez J. T., Alvarez I. D.&Lougedo S. T. Dust barriers in open pit blasts. Multifase Computitional Fluid Dynamics (CFD) simulations. *WIT Transactions on Ecology and the Environment, Air Pollution* XVI, Vol 116. 2008. P. 85-93.

67. Aurizon. *South West System Coal Dust Management Plan*. URL: https://www.aurizon.com.au/-/media/project/aurizon/files/sustainability/south-west-system---coal-dust.pdf (Last accessed: 20.07.2020)

68. Belayev N. N., Khrutch V. K. An engineering approach to simulate the 3-d wind flows over buildings. *Proceedings of the Fourth Intern. Colloquium on Bluff Body Aerodynamics & Applications*, Ruhr-Universitat. Volume of Abstracts. Bochum (Germany), Sept. 11–14, 2000. P. 471–475.

69. Best Practices for Dust Control in Coal Mining. *Information Circular*/ Jay F. Colinet et al, IC 9517, Department of Health and Human Services, Pittsburgh, PA, Spokane,WA, January 2010. 30 p.

70. Biliaiev M. Numerical Simulation of Indoor Air Pollution and Atmosphere Pollution for Regions Having Complex Topography. *Air Pollution Modeling and its Application XXI*, Springer, 2012. P. 87–91.

71. Biliaiev M. M., Kozachyna V. A., Oladipo M. O. Dust from coal trains: reducing of environmental pollution in work places near railway. *Науковий вісн. будівництва*. 2017. № 2 (88), С. 268–271.

72. Biliaiev M. M, Kozachyna V. A., Oladipo M. O. Numerical analysis of atmosphere pollution from coal train. *East European Scientific Journal*. 2019. Vol 3(43). P. 10–15.

73. Biliaiev M. M., Kozachyna V. A., Oladipo M. O. Reducing of environmental pollution during coal transportation. *Collection of Research Papers of National Mining University*. 2017. № 52. P. 325–329.

74. BNSF Railway Company and United Pacific Railroad Company (UP). *Summary of BNSF/UP Super Trial 2010*. Online resource: http://www.bnsf.com/customers/pdf/coal-super-trial.pdf (Last accessed: 01.08.2020)

75. Calvin E. and Emmitt G. D. A Rail Emission Study: Fugitive coal dust Assessment and Mitigation, Simpson Weather Associates, Inc. D13066-6 - NSW Environment Protection Authority – Literature Review of Coal Train Dust Management Practices - Final December 2014 Page 84. URL: https://powerpastcoal.org/download/coal-dust-a-rail-emission-study-fugitive-coal-dust-assessment-and-mitigation/#) (Last accessed: 16.08.2020)

76. Chatwin P. C. Quantitative Models of Environmental Pollution: a Review. *College on Atmospheric Boundary Layer and Air Pollution Modelling*.16 May–3 June. 1994. № SMR / 760–18.

77. Coal dust emissions: From environmental control to risk minimization by underground transport. An applicative case-study B.

Fabiano, F. Currт, A. P. Reverberi, E. Palazzi. *Process Safety and Environmental Protection*. 2014. 92. P. 150–159.

78. Dukic M., Planner J. H. Dust Emissions from Coal Wagons: Reducing Emissions from the Surface of Coal, Bulk Solids Handling Online article, accessed [2011]: https://forum.bulk-online.com/showthread.php?31729-Dust-Emissions-from-Coal-Wagons-Reducing-Emissions-from-the-Surface-of-Coal-(M-%C4%90 (Last accessed: 06.09.2020).

79. Dust Control Hand Book for Industrial Mineral Mining and Processing / Andrew B. Cecala et al, DHHS (NIOSH). Pittsburg, PA, 2012. № 112. P.186.

80. Ferreira AD, Viegas DX, Sousa ACM. Full-scale measurements for evaluation of coal dust release from train wagons with two different shelter covers. *Journal of Wind Engineering and Industrial Aerodynamics*. 91(10), P. 1271–1283

81. Ferreira, AD, Vaz P. A. Wind tunnel study of coal dust release from train wagons. *Journal of Wind Engineering and Industrial Aerodynamics*. 2004. 92. P. 565–577.

82. Final Report Environmental Evaluation of Fugitive Coal Dust Emissions from Coal Trains Goonyella, Blackwater and Moura Coal Rail Systems Queensland Rail Limited, 31 March, 2008, Reference H327578-N00-EE00.00

83. Final Report on the Independent Review of Rail Coal Dust Emissions Management Practices in the NSW Coal Chain. *NSW Chief Scientist & Engineer*. August, 2016. URL: https://www.chiefscientist.nsw.gov.au/__data/assets/pdf_file/0008/89864/160805-FINAL-Coal-Dust-Report.pdf (Last accessed: 06.08.2020)

84. Franc de Bree Diffuse PM10 Emission Measurements Some Case Studies. URL: http://buroblauw.nl/wp-content/uploads/2008/11/debree_nl_abs_diffusive_pm10_em.pdf (Last accessed: 04.09.2020).

85. Hanna S. Air Quality Modelling over. Short Distances. *College on Atmospheric Boundary Layer and Air Pollution Modelling.* 1994. 16 May–3 June. № SMR/760–2. P. 712–743.

86. Hanna S., Chang J. Hybrid Plume Dispersion Model (HPDM) Improvements and Testing. *College on Atmospheric Boundary Layer and Air Pollution Modelling.* 1994. 16 May–3 June. № SMR/760–4. P. 1491–1508.

87. Initial Report on the Independent Review of Rail Coal Dust Emissions Management Practices in the NSW Coal Chain November 2015.

88. Kirk Winges, Richard Steffel Coal Dust from Rail Transport. Ramboll Environ US Corporation , 19020 33rd Avenue, Suite 310, Lynnwood, Washington 98036, 425-412-1800, 14 p.

89. Literature Review of Coal Train Dust Management Practices. *NSW Environment Protection Authority.* Milton, Australia. 1 December 2014. 112 p.

90. Model Evaluation Report on UDM Version 6.0. Cambridge Research Consultants Ltd., Cambridge CB2 1SJ UK, Ref. No. SMEGIS/00/9/E, 2002. P. 51.

91. Modeling of the atmosphere pollution from coal trains / Mykola Biliaiev, et al. *MATEC Web of Conf. EOT-2019*. Lviv, 2019. Vol. 294. 6 p. URL: https://doi.org/10.1051/matecconf/201929402007

92. Mrinal K. Ghose Emission factors for quantification of dust in Indian coal mines. *Journal of Scientific @ Industrial Research*. September 2004. Vol. 63. P. 763–768.

93. Murakami S., Mochida A., Yoshihiko H. Comparison of *“k-ε”* model, ASM and LES with wind tunnel test for flow field around cub c model. *8th Intern. conf. on Wind Engineering. Western Ontario*. 1991. № 12–3.

94. Nozawa K., Tamura T. Large eddy simulation of the flow around a low-rise building immersed in a rough – wall turbulent boundary layer. *Proceedings of 3rd European & African Conference on Wind Engineering.*

Eindhoven University of Technology. The Netherlands. 2001. July 2–6. P. 185–192.

95. NSW EPA. (2014a). Environment compliance report: Compliance audit of coal train loading and unloading facilities. NSW Environment Protection Authority. Retrieved from https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/epa/148597-comp-audit-coal-train.pdf (Last accessed: 13.08.2020).

96. QR Network, *Coal Dust Management Plan*, Coal Loss Management Project, Version DRAFT V10D, Date: 23rd May 2019. URL: https://www.aurizon.com.au/-/media/project/aurizon/files/sustainability/coal-dust-management-plan-revised-2019---for-consultation.pdf (Last accessed: 17.07.2020)

97. Qu Y., Millez M., Musson-Genon L., Carrissimo B. Development of building resolving atmospheric CFD code taking into account atmospheric radiation in complex geometric. *Conference Abstracts of 31st NATO* / SPS International Technical Meeting on Air Pollution Modelling and it’s Application, 27 September–01 October, Torino, Italy. 2010. № P. 1.5.

98. Reed W. R. Significant Dust Dispersion Models for Mining Operations. *DHHS (NIOSH) Publication*. Pittsburgh, PA, 2005. 138. P. 24.

99. De Faveri et al. Reduction of the environmental impact of coal storage piles: a wind tunnel study. *Atmospheric Environment.* Год??Vol. 24A, No. 11. Pp. 2787-2793.

100. Review of Dust from Coal Trains in Queensland, report to Senate Standing Committee on Community Affairs Inquiry: ”The impact on health of air quality in Australia”, Queensland Resources Council, March 2013, Prepared by Katestone Environmental Pty Ltd, Australia 4064. URL: http://www.aph.gov.au/DocumentStore.ashx?id=9f473c91-f005-43bf-9a2b-a0c67d277115 (Last accessed: 23.09.2020).

101. Revision of Emission Factors for AP-42, Section 11.9. Western Surface Coal Mining: Revised Final Report. *EPA Contract 68-D2-0159, MRI Project № 4604-02*, September 1998. P. 350.
102. Robert Kotchenruther. Fugitive Dust from Coal Trains^ Factors Effecting Emissions & Estimating $PM_{2.5}$, *EPA Region 10, NW –AIRQUEST*, 2013. URL: http://lar.wsu.edu/nw-airquest/docs/201306_meeting/20130606_Kotchenruther_coal_trains.pdf (Last accessed: 20.08.2020)
103. The Senate. Community Affairs Committee Secretariat. Impacts on health of air quality in Australia – August 2013, Commonwealth of Australia, Parliament House, Canberra, URL: https://www.aph.gov.au/parliamentary_business/committees/senate/community_affairs/completed_inquiries/2010-13/airquality/report/~/media/wopapub/senate/committee/clac_ctte/completed_inquiries/2010-13/air_quality/report/report.ashx (Last accessed: 17.07.2020)
104. Diego I., Pelegry A., Torno S., Torano J., Menendez M. Simultanious CFD evaluation of wind flow and dust emission in open storage piles. *Applied Mathermaticl Modelling*. 2009. 33. P. 3197–3207.
105. Storms B., Salari K. and Babb A. Fuel Savings and Aerodynamic Drag Reduction from Rail Car Covers, US Department of Energy – Office of Heavy Vehicle Technology. 2010. URL: https://ntrs.nasa.gov/api/citations/20090026079/downloads/20090026079.pdf (Last accessed: 27.08.2020)
106. South West System Coal Dust Management Plan. 2013. November. Australia, 48 p.
107. The Human Health Effects of Rail Transport of Coal Through Multnomah County, Oregon. A Health Analysis and Recommendations for Further Action, February 2013.

108. Tripathy D. P., Dash T. R., Badu A., Kanungo R. Assessment and Modelling of Dust Concentration in Open Cast Coal Mine in India. *Global Nest Journal*. 2015. Vol. 17, № 4. P. 825–834.

APPENDIX A

Verification

The results of test calculations confirming the adequacy of the constructed numerical models are given below. To perform these calculations, test problems known in the scientific literature are selected.

Test problem 1. To test the numerical method used to solve the two-dimensional equation (3.12), use the analytical solution of the first boundary value problem for a nonstationary equation of thermal conductivity, which in appearance coincides with equation (3.12), when the value of the coefficient a = 1 [53]. Problem conditions: a given rectangular region, where the initial temperature is equal to 400˚C. The calculation is performed for the region: 20 m × 15 m. At the boundaries of the region for the temperature set the boundary condition: T0 = 0 ˚C. The calculation determines the value of the temperature at the point: x = 1 m, y = 1 m for different points in time.

The process of temperature change in the region is described by the following equation (analytical solution) [53]:

$$T = T_0 \operatorname{erf}\left(\frac{x}{2\sqrt{at}}\right) \operatorname{erf}\left(\frac{y}{2\sqrt{at}}\right).$$

In the table A.1 shows the temperature calculation data according to the developed numerical model and based on the analytical solution.

Table A.1 - Estimated values of temperature

Time *t*, s	Analytical solution	Numerical model
2	54,76 ^oC	55,11 ^oC
4	29,16 ^oC	29,23 ^oC
6	19,71 ^oC	20,12 ^oC

As can be seen from the table, there is a satisfactory agreement between the numerical results and the analytical solution of the problem.

Test problem 2. The first boundary value problem for the three-dimensional equation of thermal conductivity, which has the form (3.14), is considered. For a rectangular domain, this equation has an analytical solution [53] for the following conditions: determination of temperature in the region $0 \le x < \infty$, $0 \le y < \infty$, $0 \le z < \infty$ under boundary conditions T =0 ^{0}C at the boundaries x = 0, y = 0, z = 0 and under the initial condition $T = T_0$, where T_0=300 ^{0}C. The modeling equation for this problem has the form

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right).$$

As we can see, this equation is similar to the equation for the velocity potential (3.14). The analytical solution of this problem is written as follows [53]:

$$T = T_0 erf\left(\frac{x}{2\sqrt{at}}\right) \cdot erf\left(\frac{y}{2\sqrt{at}}\right) \cdot erf\left(\frac{z}{2\sqrt{at}}\right).$$

The calculation is performed for the point: x = 1 m, y = 1 m. The dimensions of the calculation area: 12 m x 12 m x 12 m.

In the table A.2 shows the data of temperature calculation according to the developed numerical model and on the basis of the analytical solution for the case when the thermal conductivity coefficient a = 1.

Table A.2 - The value of the temperature at the point for different points in time

T, c	Analytical solution	Numerical solution
2	15,19 ^{o}C	15,24 ^{o}C
4	5,90 ^{o}C	6,01 ^{o}C
6	3,28 ^{o}C	3,33 ^{o}C

Comparing the data given in table A.2, we see that there is a satisfactory agreement.

Test problem 3. The test problem from work [2] is considered: scattering of passive impurity from a point source of emission. The analytical solution of this problem is written as follows [2, 22]:

$$C = \frac{M}{4\pi x\sqrt{k_y k_z}} \exp\left(-\frac{Wy^2}{4kyx}\right) \times \left\{ \exp\left[-\frac{W(z+H)^2}{4k_z x}\right] + \exp\left[-\frac{W(z-H)^2}{4k_z x}\right]\right\}.$$

Initial data [2]: W = 4 м/с; $K_{\text{у}}$ = 500 м^2/с; Y = 0; H = 120 м; Z = 120 м estimated level M = 106 мг/с; Kz = 5 м^2/с.

The values of the impurity concentration at different distances from the source are given in table. A.3.

Table A.3 - The value of the impurity concentration

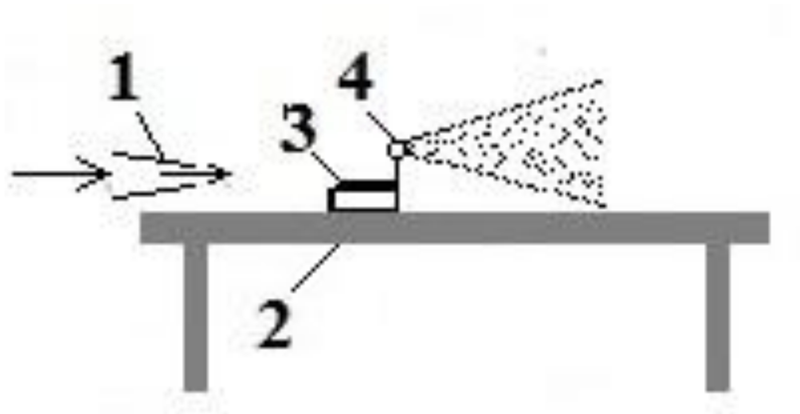
X, km	1	2	3	4
З, mg/m^3 (analytical solution) [2]	1,59	0,79	0,54	0,42
З, mg/m^3 (calculation according to the developed model / calculation according to the Crank-Nicholson scheme [2])	1,75 / 1,8	0,86 / 0,9	0,58 / 0,6	0,47 / 0,5

Analyzing the data from table. A.3, we see that there is a satisfactory agreement of the results.

Test problem 4. It is known that the scattering of ions in the air relates to the problem of mass transfer of impurities, so to verify the developed numerical model (3D model of potential flow and mass transfer equation) a physical experiment was performed, which consisted of measuring the concentration of negative ions from the ionizer. which was placed on the model of the gondola. Then the calculation was performed on the basis of the created numerical model and the experimental and numerical results were compared.

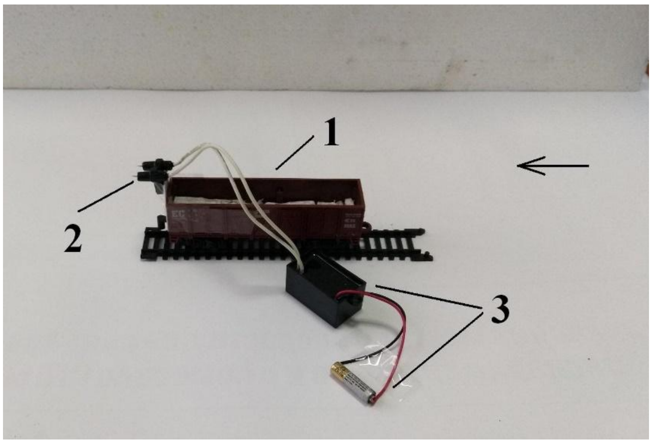
The scheme of the experimental setup is shown in Fig. A. 1. The model of the gondola was made on a scale of 1: 100. The AirNASA KJF03 ionizer was placed on the end wall of the model (at a height of h = 5 cm), the emission intensity was 10 × 106 particles / s. The air flow was created due to the operation of the blower, the air flow velocity left 0.47 - 0.54 m / s. A GM 8908 anemometer was used to measure the air flow velocity. A velocity of 0.5 m / s was used in the calculations.

Measurement of the number of negative ions was performed using the counter AIR ION TESTER KT-401. The ion concentration was measured at a height of 5 cm and at different distances from the end wall of the model.



1 - blower; 2 - table; 3 - gondola model; 4 - ionizer

Figure A.1 - Scheme of the experimental setup



1 - model of gondola car; 2 - nozzle of the air ionizer; 3 - power supply

Figure A.2 - General view of the experimental setup

The results of measurements and calculations are shown in table. A.4.

Table A.4 - Experimental and calculated value of ion concentration

Distance, *x*	Experiment	Estimated value
6 cm	(1,39-1,45)×104 ion / cm^3	1,43×104 ion / cm^3
9 cm	(1,29-1,35)×104 ion / cm^3	1,31×104 ion / cm^3
18 cm	(1,17-1,26)×104 ion / cm^3	1,13×104 ion / cm^3

Data from table. A. 4 show that there is a satisfactory agreement between experimental and calculated data.

APPENDIX B

Implementation of results

Міністерство освіти і науки України
Дніпровський національний університет залізничного транспорту
імені академіка В. Лазаряна

ЗАТВЕРДЖУЮ

Проректор з науково- педагогічної,
економічної роботи, перспективного та
іноваційного розвитку
д.т.н., проф. Радкевич А.В.

«12» 09 20 19 р.

АКТ ВПРОВАДЖЕННЯ

результатів дисертаційної роботи Оладіпо Мутіу Олатойе

Чинним актом підтверджується те, що результати дисертаційної роботи аспіранта Оладіпо Мутіу Олатойе використовуються в навчальному процесі Дніпровського національного університету імені академіка В. Лазаряна при підготовці студентів, які навчаються за спеціальністю «Будівництво та цивільна інженерія». Матеріали дисертаційної роботи, алгоритми та пакети програм використовуються при проведенні лекційних та практичних занять з дисциплін «Охорона природного середовища від забруднення промисловими підприємствами», «Екологічна безпека», що дозволило підвищити ефективність навчального процесу та якість викладання матеріалу при вивченні вказаних дисциплін.

Начальник навчального відділу — Л.Є. Андрашко

Зав. каф. «Гідравліка та водопостачання», д.т.н., проф. — М.М. Біляєв

ЗАТВЕРДЖУЮ
Директор ТОВ « Енергосервіс-КР»
Ольферт О.Ю.
«__16__»________________

АКТ

про впровадження результатів дисертаційної роботи Оладіпо Мутіу Олатойє

В дисертаційній роботі Оладіпо Мутіу Олатойє розроблено методи зменшення рівня забруднення атмосферного повітря при транспортуванні вугілля в напіввагонах. В дисертаційній роботі розроблені математичні моделі та спеціалізоване програмне забезпечення для оцінки ефективності використання додаткових спеціальних бортів, що встановлюються на борта вагонів для зменшення виносу вугільного пилу. Ці математичні моделі побудовані на фундаментальних рівняннях аеродинаміки та масопереносу. Запропоновані математичні моделі дозволяють прогнозувати динаміку забруднення атмосферного повітря при транспортуванні вугілля в напіввагонах. Особливістю розроблених моделей є те, що вони враховують швидкість руху потягу, геометричну форму додаткових бортів, атмосферну дифузію, вплив локальної швидкості повітря на інтенсивність виносу вугільного пилу. Тобто побудовані моделі враховують такі важливі параметри, що не враховуються в існуючих моделях, які використовуються для оцінки рівня забруднення атмосферного повітря при транспортуванні вугілля в напіввагонах.

Розроблені математичні моделі, пакети програм та запропоновані методи зменшення виносу вугільного пилу з напіввагонів було використано в ТОВ «Енергосервіс-КР» при розробці технології захисту атмосферного повітря від забруднення при транспортуванні залізної руди та вугілля.

директор

ТОВ «Енергосервіс-КР» Ольферт О.Ю.

APPENDIX C
Publications of the Author

Publications in Ukrainian Journals

Статті в наукових фахових виданнях України

1. Беляев Н. Н., Оладипо Мутиу Олатойе. Минимизация интенсивности выноса пыли из полувагона при транспортировке угля. *Електромагнітна сумісність та безпека на залізничному транспорті* : Науковий журн. 2016. № 11. С. 93–100. *(Видання включено до міжнародної наукометричної бази Index Copernicus).*

2. Беляев Н. Н., Оладипо М. О. Модели оценки уровня загрязнения атмосферы при транспортировке сыпучих грузов. *Наука та прогрес транспорту. Вісн. Дніпропетр. нац. ун-ту залізн. трансп. ім. акад. В. Лазаряна.* 2016. Вип. 5 (65). С. 22–29. *(Видання включено до міжнародної наукометричної бази Index Copernicus).*

3. Беляев Н. Н., Оладипо М. О. Проблема уноса угольной пыли. *Наука та прогрес транспорту. Вісн. Дніпропетр. нац. ун-ту залізн. трансп. ім. акад. В. Лазаряна.* 2016. Вип. 6 (66). С. 17–24. *(Видання включено до міжнародної наукометричної бази Index Copernicus).*

4. Беляев Н. Н., Оладипо М. О. Расчет динамики загрязнения примагистральной территории при перевозке угля. *Наука та прогрес транспорту. Вісн. Дніпропетр. нац. ун-ту залізн. трансп. ім. акад. В. Лазаряна.* 2016. Вип. 1 (67). С. 18–26. *(Видання включено до міжнародної наукометричної бази Index Copernicus).*

5. Biliaiev M. M., Kozachyna V. A., Oladipo M. O. Reducing of environmental pollution during coal transportation. *Collection of Research Papers of National Mining University.* 2017. № 52. P. 325 –329.

6. Biliaiev M. M., Kozachyna V. A., Oladipo M. O. Dust from coal trains: reducing of environmental pollution in work places near railway. *Науковий вісн. будівництва.* 2017. № 2 (88). С. 268–271.

7. Беляев Н. Н., Оладипо Мутиу Олатойе, Гыркало А. В. Прогнозирование уровня загрязнения рабочих зон возле железнодорожной магистрали. *Строительство. Материаловедение. Машиностроение. Сер.: Энергетика, экология, компьютерные технологии в строительстве.* 2017 . Вып. 98. С. 61–67.

- *Scientific Book*:

8. Беляев Н. Н., Оладипо М. О., Кириченко П. С. Защита окружающей среды при транспортировке угля. Кривой Рог : Изд.: Р. А. Козлов, 2018. 92 с.

Foreign publications

Статті у закордонних наукових періодичних виданнях

9. Biliaiev M. M., Kozachyna V. A., Oladipo M. O. Numerical analysis of atmosphere pollution from coal train. *East European Scientific Journal*. 2019. Vol 3(43). P. 10–15.

10. Modeling of the atmosphere pollution from coal trains / Mykola Biliaiev, Vitalii Kozachyna, Viktorолaiia Biliaieva, Mutiu Olatoye Oladipo and Kateryna Chernyatyeva. *MATEC Web of Conf. EOT-2019*. Lviv, 2019. Vol. 294. 6 p. https://doi.org/10.1051/matecconf/201929402007

Abstracts of Conferences

Публікації у виданнях, які засвідчують апробацію матеріалів дисертації

11. Беляев Н. Н., Оладипо Мутиу Олатойе. Математическое моделирование уноса угольной пыли. *Інформатика, управління та штучний інтелект. Матеріали третьої міжнарод. науково-техн. конф. студентів, магістрів та аспірантів.* Харків : НТУ «ХПІ», 2016. С. 6.

12. Беляев Н. Н., Оладипо Мутиу Олатойе. Экологические проблемы транспортировки сыпучих грузов железнодорожным транспортом. *Диференціальні рівняння та проблеми аерогідромеханіки й тепломасо-переносу : тези доп. Всеукр. наук. конф.* (28-30 вересня 2016 р., Дніпро). Дніпро : Дніпропетр. нац. ун-т, 2016. С. 62.

13. Беляев Н. Н., Оладипо Мутиу Олатойе. Теоретическое и экспериментальное исследование уноса угольной пыли. *Теоретичні та практичні аспекти розвитку науки (частина ІІ) : матеріали ІІ Міжнародної науково-практ. конф.* (м. Київ, 29-30 листопада 2016 року). Київ : МЦНД, 2016. С. 15–16.

14. Беляев Н. Н., Оладипо Мутиу Олатойе. Компьютерно-информационная система анализа уноса угольной пыли. *Современные информационные и коммуникационные технологии на транспорте, в промышленности и образовании : тезисы Х Международной научно-практ. конф*. (Днепр, 14-15 декабря 2016 г.). Днепр : ДИИТ, 2016. С. 90–91.

15. Беляев Н. Н., Оладипо Мутиу Олатойе. Моделирование загрязнения окружающей среды при транспортировке сыпучих грузов железнодорожным транспортом. *Комп'ютерне моделювання та оптимізація складних систем (КМОСС-2016) : матеріали ІІ Всеукр. науково-техн. конф. з міжнародною участю* (м. Дніпро, 1-3 листопада 2016 р.). Дніпро : ДВНЗ УДХТУ, 2016. С. 26–27.

16. Оладипо М. О. Оценка уровня загрязнения воздушной среды возле железнодорожных магистралей с помощью информационной системы анализа уноса угольной пыли из вагонов. *Международный научный симпозиум «Неделя эколога – 2017»* (ДДТУ, Каменское, 10-13.04.2017). Каменское, 2017. С.35.

17. Беляев Н. Н., Якубовская З. Н., Козачина В. А., Оладипо Мутиу Олатойе. *Математическое моделирование загрязнения транспортного коридора при перевозке угля. Комп'ютерне моделювання та оптимізація*

складних систем (КМОСС-2018) : матеріали IV Міжнародної науково-техн. конф. (м. Дніпро, 1-2 листопада 2018 р.). Дніпро : ДВНЗ УДХТУ, 2018. С. 38.

18. Беляев Н. Н., Козачина В. А., Оладипо М. О. Защита атмосферного воздуха от загрязнения при перевозке угля: эксперимент, математическое моделирование. *79-та Міжнародна науково-практ. конф. «Проблеми та перспективи розвитку залізничного транспорту»*, 16-17.05.2019, Дніпро. Дніпро : ДНУЗТ, 2019. С. 293–294.

19. Оладипо М. О. Экспертная оценка загрязнения рабочих зон при перевозке угля. *77-ма Міжнародна науково-практ. конф. «Проблеми та перспективи розвитку залізничного транспорту»*, 11-12.05.2017, Дніпро. Дніпро: ДНУЗТ, 2017. С. 252.

20. Оладипо М. О. Анализ загрязнения атмосферного воздуха при перевозке угля в полувагонах. Результаты лабораторных исследований и математического моделирования. *Науковий симпозіум «Тиждень еколога – 2019»* (ДДТУ, Кам’янське, 07-10.10.2019). Кам’янське, 2019. С. 17.