UDC 525.855:621.1.016.4
IRSTI 32.39.01
RESEARCH ARTICLE

MODEL OF THERMAL BALANCE CHANGE IN LARGE CITIES AND SOURCES OF ITS EMERGENCE

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Abstract. *The article presents a model for the change in thermal pollution in large cities, caused by the impact of solar radiation and traffic flow. Two main regimes are considered: laminar and turbulent, which characterize different heat exchange conditions in the urban atmosphere. Special attention is given to the analysis of air pollution caused by changes in the thermal balance in the urban environment. Unlike traditional sources of pollution, such as transportation and industry, heat exchange processes occurring in road surface materials have a significant impact on thermal pollution. The model is focused on studying heat and mass exchange processes occurring in the layers of road structures, as well as heat dissipation from these structures into the urban air environment. The key aspects of the study are heat transfer by convection and thermal conductivity of the air medium, which play an important role in the spread of thermal energy and, accordingly, in the formation of thermal pollution. The proposed model allows for a deeper understanding of the mechanisms that influence the temperature regime in cities and assessing their impact on environmental quality. The article discusses both theoretical and practical aspects of thermal processes in the urban atmosphere, opening opportunities for more effective management of thermal pollution and minimizing its impact on the health of city residents.*

Keywords: *thermal balance, convective heat transfer, thermal conductivity, heat dissipation, laminar flow, turbulence, urban asphalt-concrete pavement.*

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https://doi.org/10.51488/1680-080X/2025.1-11
Received 03 December 2024; Revised 21 January 2025; Accepted 20 February 2025

ӘОЖ 525.855:621.1.016.4
ҒТАМР 32.39.01
ҒЫЛЫМИ МАҚАЛА

ҮЛКЕН ҚАЛАЛАРДАҒЫ ЖЫЛУЛЫҚ ТЕҢДЕСТІРУ МОДЕЛІ ЖӘНЕ ОНЫҢ ПАЙДА БОЛУ КӨЗДЕРІ

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Аңдатпа. *Мақалада ірі қалалардағы жылулық ластанудың өзгеруін күн радиациясының әсері мен көлік қозғалысының әсерінен қалыптасқан модель ұсынылған. Осылайша, мақалада бұл мәселе екі режимде қарастырылады: ламинарлық және турбулентті. Атмосфераның ластануына байланысты жылулық баланс өзгерістерін талдауға егжей-тегжейлі тоқталады. Қалалардағы ластанудың көздері тек көлік немесе өнеркәсіп қана емес, сонымен қатар жол жабындарының материалдарынан жылу алмасу әсері де айтарлықтай әсер етеді. Модельдің негізі жол құрылымдарының қабаттарында жылу мен масса алмасу процестерін зерттеуге және олардан ауаның қалалық ортаға жылу беруін зерттеуге бағытталған. Бұл жерде ауаның жылу өткізгіштігін ескере отырып, жылудың конвекциялық ауысымы кеңінен қарастырылады. Ұсынылған модель қала атмосферасындағы жылу алмасу механизмдерін тереңірек түсінуге және олардың қоршаған ортаға әсерін бағалауға мүмкіндік береді. Мақалада қалалық атмосферадағы жылу-техникалық процестердің теориялық және практикалық аспектілері қарастырылып, жылулық ластануды басқару мен оның қала тұрғындарының денсаулығына әсерін азайту бойынша тиімді шараларды жүзеге асыру мүмкіндіктері талқыланады.*

Түйін сөздер: *жылулық тепе-теңдік, жылудың конвекциялық таралымы, жылуөткізгіштік, жылу берілу, ламинарлық қозғалыс, турбуленттілік, қалалық асфальт бетоны.*

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https://doi.org/10.51488/1680-080X/2025.1-11
Алынды 03 желтоқсан 2024; Қайта қаралды 21 қаңтар 2025; Қабылданды 20 ақпан 2025

УДК 525.855:621.1.016.4
МРНТИ 32.39.01
НАУЧНАЯ СТАТЬЯ

МОДЕЛЬ ИЗМЕНЕНИЯ ТЕПЛОВОГО БАЛАНСА В КРУПНЫХ ГОРОДАХ И ИСТОЧНИКИ ИХ ПОЯВЛЕНИЯ

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Аннотация. *В статье представлена модель изменения теплового загрязнения в крупных городах, вызванного воздействием солнечной радиации и движением транспортного потока. Рассматриваются два основных режима: ламинарный и турбулентный, которые характеризуют различные условия теплообмена в городской атмосфере. Особое внимание уделено анализу загрязнения атмосферного воздуха, обусловленного изменениями теплового баланса в городской среде. В отличие от традиционных источников загрязнения, таких как транспорт и промышленность, существенное влияние на тепловое загрязнение оказывают теплообменные процессы, происходящие в материалах дорожных покрытий. Модель ориентирована на изучение тепломассобменных процессов, происходящих в слоях дорожных конструкций, а также теплоотдачи от этих конструкций в воздушную среду города. Ключевыми аспектами исследования являются перенос тепла конвекцией и теплопроводность воздушной среды, которые играют важную роль в распространении тепловой энергии и, соответственно, в формировании теплового загрязнения. Предложенная модель позволяет более глубоко понять механизмы, которые влияют на температурный режим в городах, и оценить их влияние на качество окружающей среды. В статье рассматриваются как теоретические, так и практические аспекты теплотехнических процессов в городской атмосфере, что открывает возможности для более эффективного управления тепловым загрязнением и минимизации его воздействия на здоровье горожан.*

Ключевые слова:. *тепловой баланс, конвекционный перенос тепла, теплопроводность, теплоотдача, ламинарное движение, турбулентность, городское асфальтобетонное покрытие.*

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https://doi.org/10.51488/1680-080X/2025.1-11
Поступило 03 декабря 2024; Пересмотрено 21 января 2025; Принято 20 февраля 2025

ACKNOWLEDGEMENTS / SOURCE OF FUNDING

The study was conducted using private sources of funding.

CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ / ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

The growth of urban areas has led to their noticeable effect on atmospheric phenomena. The significant density of urban settlements and industrial facilities, as well as the increase in the area of transport highways, led to the appearance of an extensive heat zone within the city.

In rural flat areas, the sun's rays are mainly reflected; in the city, roofs and walls of houses, dark asphalt surfaces of roads and sidewalks absorb solar radiation to a much greater extent than the soil and vegetation outside the city, and then emit it. The increase in air temperature in the city is also due to heat loss by industrial enterprises and thermal power plants.

The increase in the thermal balance of cities is significantly influenced by the conditions of movement of vehicles, the thermo physical properties of road surfaces and squares, as well as their geographical location. Due to the low ventilation, the volume of the aerosol thermal dome over the city increases, which is formed at an altitude of 200-300 m and prevents vertical ventilation. Such phenomena are especially strong in the atmospheric environment of Almaty, Tekeli, Zaisan, Ust-Kamenogorsk, etc., because they are surrounded on all sides by mountains, which contribute to a sharp change in the microclimate of the air environment. For example, Table 1 shows that the microclimate of city streets, measured in Almaty and Ust-Kamenogorsk, differs significantly from the microclimate outside the city. The temperature difference between inside and outside the city in summer is +5-7 ° C, and in winter - +3-5 ° C.

Table 1
Microclimate of the Almaty and Ust-Kamenogorsk road network [15]

Cities	**The intersection of streets**	**Air temperature Temperature difference**	
		in summer, +°C	**in winter, –°C**
1	2	3	4
Almaty in the region: in summer= +35°C in winter=–2°C	Abay–Dostyk	42/+7	+4/+6
	Abay–Furmanova	41/+6	+4/+6
	Abay–Mate Zalka	41/+6	+3/+5
	Raimbek–Furmanov	42/+7	+3/+5
	Raimbek–Mate Zalka	40/+5	+3/+5
	Tole bi–Furmanova	41/+6	+3/+5
	Tole bi–Saina	40/+5	+4/+6
Усть-Каменогорск in the region: in summer =+30°C in winter =-16°C	Abay–Lenina	34/+4	-10/-6
	Abay–Voroshilova	35/+5	-10/-6
	Abay Bazhova	35/+5	-11/-5
	Karbysheva–Vinogradova	34/+4	-12/-4
	Lenin–Belinsky	34/+4	-12/-4
	Lenin–Metallurgov	35/+5	-13/-3

The mechanism of heat transfer is caused by the movement of microstructural elements of the body (from building materials) and depends on the physical properties of the medium.

In urban air, energy transfer is carried out due to chaotic molecular motion, diffusion of molecules, the intensity of which is proportional to temperature (**Sakhin, 2014**). Due to the effect of the air flow during the movement of transport, the kinetic energies in the gas (air) atoms increase, which leads to a change in the thermal balance.

2 LITERATURE REVIEW

The issue of changing the heat balance in large cities is relevant in the context of global climate change and urbanization. Thermal pollution in cities is a complex process involving both natural and anthropogenic factors. This review examines key studies on heat balance models in urbanized areas, as well as various sources of heat pollution. **(Matveev, 2001).**

Models of heat balance in cities: classical and modern approaches

One of the first studies in the field of heat balance in cities is the work of Oke, who introduced the concept of an «Urban Heat Island» (UHI). According to his model, the heat balance in cities is disrupted by the concentration of building materials such as concrete and asphalt, which absorb solar radiation and then release heat into the atmosphere. Oke describes how various components of urban infrastructure (roads, buildings, green spaces) affect the microclimate in the city, creating a temperature difference between the city and its suburbs. **(Oke, 2002)**

Sailor, D.J. and Amir Baniassadi developed a model of thermal balance. They complement it with an analysis of the impact of climate change on the urban environment. Research shows how an increase in temperature in the urban environment caused by anthropogenic activity enhances the effect of global warming. The models developed by the researchers include not only traditional heat sources (transport, industry), but also the influence of solar radiation and heat exchange processes in road surface materials. (**Sailor et al., 2019**)

Transport and industry are traditionally considered sources of heat pollution in cities, but recent studies have indicated the need to take into account other factors, such as heat transfer in urban coating materials.

Brian Stone, Jason Vargo, and Dana Habeeb focused on the effect of covering streets and buildings on the heat balance, showing that asphalt and concrete have a high absorption coefficient of solar radiation and slowly release it as heat into the atmosphere, thereby creating elevated temperatures in the city. (**Stone et al., 2012**) In this context, Lili Somantri1 and Shafira Himayah proposed a new method for assessing thermal pollution, taking into account changes in the heat capacity and thermal conductivity of various types of coatings. Research also shows that in cities where black coatings are actively used, the effect of the "urban heat island" is particularly pronounced. (**Lili et al., 2024**)

Modeling of thermal processes in an urban atmosphere

Phelan Patrick and Keil Kalush focused on heat transfer models, including convective heat transfer and thermal conduction processes in the urban atmosphere. Their work has significantly expanded the understanding of the impact of vertical air flows on the distribution of thermal energy in cities, as well as how changes in traffic and energy supply affect the microclimate. Another important point in the research is the influence of turbulent flows in cities, which significantly increases the exchange of heat between different layers of the atmosphere. (**Phelan et al., 2016**)

Chuhui Shen,, Hao Ho, Yaoyao Zheng, Yuji Murayama, Ruci Wang, Tangao Hu conducted a comprehensive simulation of the heat balance in large metropolitan areas, taking into account both laminar and turbulent heat exchange modes. They showed that in larger cities with high density of buildings and traffic flows, the intensity of turbulent heat exchange increases, which leads to a more uniform temperature distribution, but at the same time increases the local phenomena of thermal pollution. (**Chuhui et al., 2022**)

Innovations in heat balance models

With the development of computing technologies in recent decades, heat balance models have become more complex and accurate. Qiao X, LiL, Di, Y L Gen, and A Y Hoy proposed new approaches to modeling heat balance using satellite observation data and machine learning algorithms. These models make it possible to more accurately predict temperature changes in cities, taking into account all possible sources of heat pollution and their interaction with climatic conditions. (**Qiao et al. 2018**)

Rosa Cafaro, Barbara Cardone, Valeria D'Ambrosio, Ferdinando Di Martino, Vittorio Miraglia used methods of geographic information systems (GIS) to model thermal pollution at the level of individual city blocks. In their study, attention is paid not only to the materials of road surfaces, but also to the nature of urban development, as well as interaction with natural ecosystems. (**Rosa et al., 2024**)

Forecasting and minimizing the effects of thermal pollution

Amid the growing interest in issues of sustainable development and adaptation to climate change, Shanshan Chen, Dagmar Haase, Salman Qureshi, Mohammad Karimi Firozjaei have proposed new strategies to minimize thermal pollution. Among their proposals are the improvement of thermal insulation of buildings, the introduction of "green roofs", the increase of green areas in cities, as well as the use of innovative materials for covering road and sidewalk surfaces. (**Scherer et al., 2020**)

Thus, studies of changes in the heat balance in large cities show that thermal pollution is a complex and multifaceted process in which both traditional heat sources (transport, industry) and the materials from which road surfaces and buildings are built are important. Modern heat balance models include integrated approaches using satellite data, GIS, and machine learning methods, which allows for more accurate consideration of all factors affecting the urban microclimate. The topic of thermal pollution requires further research and the development of effective solutions to improve the urban environment and resilience to climate change.

3 MATERIALS AND METHODS

The process of heat exchange in the air environment of large cities is closely related to the air temperature, the total area of urban roads and squares, traffic flow, etc. In the air, the process of substance transfer is carried out by moving microparticles of gas (for example, exhaust gases from vehicle exhaust pipes) and dust from the road surface. This process, which often occurs at intersections of the urban road network, is called convection heat transfer in gases. This process differs from thermal conductivity in that the heat carriers here are the macroscopic elements themselves, whose dimensions are many times greater than the free path of the gas (dust) in the air. Heat transfer by convection is always accompanied by thermal conductivity of the medium. The heat flow in the air is carried out in two modes: laminar and turbulent.

In the laminar regime, all particles of gas (or liquid) move parallel to each other, without mixing along the normal direction of motion. Therefore, heat transfer in this direction is carried out only due to thermal conductivity (λ). Therefore, when calculating heat transfer processes, the Fourier equation is used. (**1-2 formula**):

$$Q = \int q dF = -\int \gamma \left(\frac{\Delta t}{\Delta n}\right) dF = -\gamma \left(\frac{\Delta t}{\Delta n}\right) F, \tag{1}$$

$$q = \frac{dQ_\tau}{dF d_\tau} = -\gamma \left(\frac{\Delta t}{\Delta n}\right) = -\gamma grad \cdot t \tag{2}$$

where Q – the amount of heat, W;

γ – coefficient of thermal conductivity of the medium, W/(mK);

F – surface area, м^2;

q – heat flow density, W/m^2.

Formulas (1) and (2) determine the coefficient of thermal conductivity in pavement materials:

$$\gamma = \frac{[q]}{[grad \cdot t]} = -\frac{Q}{\left[F \cdot \left(\frac{\Delta t}{\Delta n}\right)\right]} \tag{3}$$

As the temperature increases, the heat flow in the urban environment increases. Among them, helium and hydrogen stand out sharply, the thermal conductivity of which is 5-10 times greater due to their low molecular weight and, consequently, a higher rate of molecular diffusion, which contributes to a dramatic change in the microclimate of the city.

Building materials with a porous structure, such as bricks, concrete, curbstones, and others, have low thermal conductivity coefficients (0.02-3.0 W/(mK)), which makes them good thermal insulators. However, this indicator largely depends on the ratio of the mass of the skeleton of the material and the air pores, and therefore on its bulk mass. When using such materials in cities, it is important to take into account that as the temperature rises, their thermal insulation properties deteriorate. In addition, the degree of moisture content of the material significantly affects the thermal conductivity. With increasing moisture in the material, thermal conductivity increases, since the coefficient of thermal conductivity of water is 25 times higher than that of air filling the pores of the material. As a result, when the water in the material is moistened or frozen, its thermal conductivity can increase by almost 100 times, which significantly changes the thermal balance in the urban environment. (**Kiyalbai et al, 2022**)

A high degree of development and asphalting (up to 50% in some cities of Kazakhstan) leads to an increase in water runoff, even with light rains. These hydrological changes are caused by changes in the meteorological regime. During the periods between rains in cities, the amount of moisture required for evaporation is lower than in rural areas, which leads to the accumulation of thermal energy in the air, which is usually consumed by the evaporation process (600 calories per 1 g of water).

In areas of heavy traffic, the air is saturated with dust and exhaust fumes. Although dust reflects the sun's rays, it also makes it difficult to transfer heat to the atmosphere, contributing to the accumulation of heat in the city. In addition, in cities, unlike the surrounding areas, there are changes in the aerodynamic regime. This is partly due to the presence of tall buildings that change the vertical profile of air flows, reducing wind speed near the ground, but at the same time accelerate the flow of air along the streets, especially in the surface layer.

If we consider Ust–Kamenogorsk, the main industrial city of Kazakhstan, with a total area of over 203 km^2, as an example, then industry and warehouse areas occupy about 27 km^2 (about 13.3%) on its territory. The length of the city's backbone network is 116.6 km within the city limits. The density of streets and roads is 1.84 km per 1 km^2 of the area. The planning structure of the road network is a mixed type of rectangular and radial layout. The main industrial pollutants of the city's air are TMK, CCS, condenser plant, motor transport enterprises, boiler houses of thermal power plants, etc. They emit about 200 thousand tons of emissions per year into the city's air environment, which is a source of energy pollution of the urban environment. As a result, an artificial stratospheric layer is created over the city, which in turn leads to a significant change in the thermal balance.

The Russian physicist G. Richman was the first to comprehensively analyze the cooling processes of heated objects (for example, cooling road surfaces in the air) and demonstrated that they depend not only on the temperature difference, but also on the surface area and volume of the object. It has been proven that in the process of heat exchange, the amount of heat transferred from or to an object is directly related to the surface area of the body F, the temperature difference between the body and the environment, the characteristics of its movement, as well as the shape of the object and its geometric parameters. **(Lazarev, 2005)**

For elementary area and elementary time, the process is described by the equation (**formula 4**):

$$dQ_t = \alpha(t_в - t_{ст})dFd\tau, \tag{4}$$

where ($t_в$–$t_{ст}$) – temperature pressure;

α – heat transfer coefficient, W/(m^2·K).

For a stationary heat exchange process at the UDS of cities at a constant ambient temperature and surface area, the heat flow is equal to:

$$Q = \alpha(t_в - t_{ст})F\ , \tag{5}$$

and the density of the heat flow:

$$q = \frac{Q}{F} = \alpha(t_в - t_{ст}). \tag{6}$$

From equations (5) and (6) we have:

$$\alpha = \frac{q}{(t_в - t_{ст})}. \tag{7}$$

The heat transfer coefficient determines the degree of intensity of heat transfer between the surface of the body and the environment, taking into account the specific conditions in which this process occurs. Since α depends on the velocity of motion of the medium ω, the shape of the surface of the body F, its linear dimensions, and the temperature pressure ($t_в$–$t_{ст}$), ambient temperatures $t_в$ and etc. The most significant influence on α is exerted by the thermo physical properties of materials used in the construction of urban roads, territories, buildings and structures: thermal conductivity coefficient λ, specific heat capacity C, density p, dynamic viscosity μ and coefficient of volumetric expansion β. (**Kiyalbaev et al., 2004**)

Currently, entrepreneurs are carrying out various construction works in order to open retail outlets and other services. For the construction of such structures within the city, they acquire various building materials with different thermophysical properties, for example, for:

reinforced concrete – λ=1,5 W/(m·K)., C=0,84 kJ/(kg·K), p=2,2 t/m^3;

asphalt concrete – λ=0,64-0,72 W/(m·K), C=1,7 kJ/(kg·K), p=1,2-1,4 t/m^3;

gypsum concrete – λ=0,37-0,56 W/(m·K), C=0,80 kJ/(kg·K), p=1,0-1,3 t/m^3;

loamy soil – λ=1,49 W/(m·K), C=1,15 kJ/(kg·K), p=1,96 t/m^3;

silicate bricks – λ=0,81 W/(m·K), C=0,84 kJ/(kg·K), p=1,9 t/m^3;

quartz sand – λ=0,44-0,81 W/(m·K), C=0,75-0,92 kJ/(kg·K), p=1,32-1,52 t/m^3,

coarse-grained river sand – λ=0,28-0,51 W/(m·K), C=0,80-1,02 kJ/(kg·K), p=1,46-1,50 t/m^3,

cinder block – λ=0,67 W/(m·K), C=0,75 kJ/(kg·K), p=1,5 t/m^3;

rubble stone – λ=1,28 W/(m·K), C=0,88 kJ/(кг·К), p=2,0 t/m^3 and etc.

However, they do not pay the necessary attention to how heat exchange processes occur in these materials and how they affect the disturbance of the thermal balance in the habitat. (**Pshembayev et al., 2023**)

In large non-industrial cities (this is especially true in Almaty), the level of heat balance changes significantly depends on the intensity, composition, density and traffic conditions of traffic flows.;

geometric parameters, type of road surfaces, territories of squares, their landscaping and street layout; the quality of the contents and the level of their cleaning;

locations along the transport network of various kinds of industrial, commercial and service points.

4 RESULTS AND DISCUSSION

The results of the theoretical calculation of the thermal effects on changes in the microclimate of the roadside environment will be presented at the next stage of these studies (in 2022), and the methodology for assessing changes in the microclimate of the roadside environment from exposure to thermal (solar) energy is included in the sections.

To measure the temperature in the layers of the pavement, diodes were placed at different depths of the pavement. Measurements were carried out every hour, therefore, with the help of a rheostat, it was necessary to maintain a constant current. Based on the measurement results obtained, a calibration curve (graph of the dependence of voltage variation on temperature) was constructed, which was used in field experiments to determine the temperature of the road surface at different depths and the air temperature above the road surface at different heights using a semiconductor diode. The calibration curve is shown in **Figure 1.**

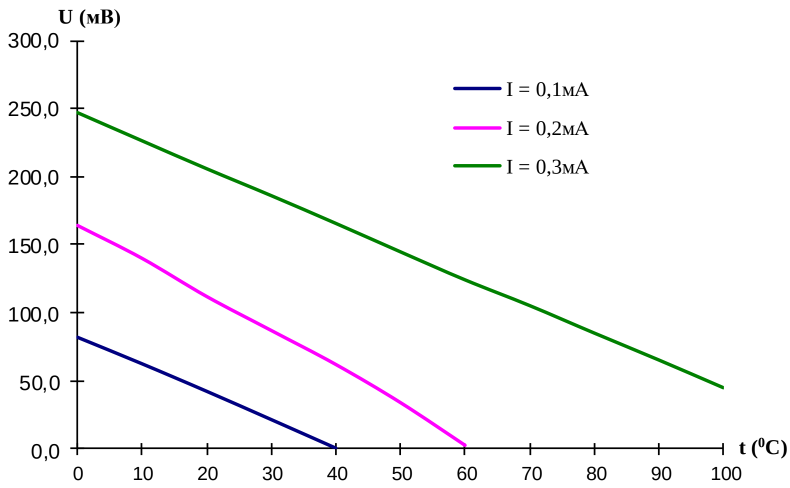

Figure 1. Is a graph of the dependence of the voltage at the ends of the diode on the temperature at a current of 0.1, 0.2 and 0.3 MPa (**author's materials**).

As can be seen from **Figure 2**, when a 0.1 mA current flows through a semiconductor diode, it can only be used in the temperature range from 0 to 40 ° C, at a current of 0.2 mA – up to 60 ° C and at a current of 0.3 mA – up to 100 °C. Therefore, when conducting field experiments to determine the temperature in the layers of pavement, it was necessary that a constant current of 0.3 mA pass through the diode.

Based on the overall measurement results, a graph of changes in pavement temperature depending on air temperature is constructed (**Figure 1**) and a map of heating of road surfaces in the hot season by regions of Kazakhstan (**Figure 2**).

The graph shows that as the air temperature increases, the coating temperature increases in direct proportion. This is especially noticeable in the coating body (curve 1). At the same time, the temperature difference ranges from 3.5 ° C (at an air temperature of +20 ° C) to 22 ° C (at an air temperature of +53 ° C). There is also a significant increase in the temperature difference on the coating surface (curve 2): from 2 °C to 10.2 °C in the same temperature range.

The heating temperature of the coatings also has a significant effect on the human condition. At an altitude corresponding to the breathing level of the passenger car and truck driver above the pavement, i.e. at an altitude of 1.0 m (curve 3) and 1.5 m (curve 4), the temperature difference is 0.9 and 1.2 °C at an air temperature of +20 °C and 2.3 and 4.1 °C at an air temperature of +53 ° C.

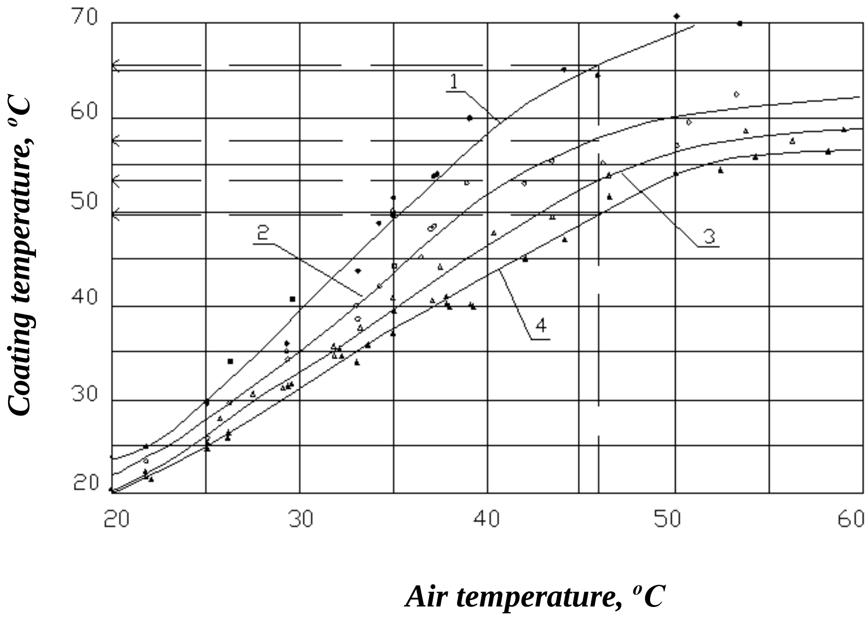

Figure 2 – Temperature change on asphalt concrete pavements depending on the air temperature: 1 – at a depth of 4-5 cm in the coating body; 2 – on the surface of the coating; 3 – at a height of 1.0 m above the coating; 4 – at a height of 1.5 m above the coating (**author's materials**).

5 CONCLUSIONS

During the construction of areas and territories, limit the occupied areas covered with materials with a high degree of porosity, such as asphalt concrete, cement concrete, etc.

On sidewalks laid in squares, parks, etc. in cultural and recreational areas, coatings can be laid from fine homogeneous crushed stone, no higher than 3-5 mm in size, or from stone seeding. The heat transfer of such materials is low due to the non-monolithic nature of the product.

It is impractical to locate retail and service outlets in the area of congested intersections. As a result, the mode of movement of vehicles becomes more complicated and the turbulence of the air flow increases dramatically.

During very warm periods of the year, when maintaining roads and streets, the technological operation should not include washing the carriageway and sidewalks with ordinary water. In such cases, it is advisable to spray air 2-3 times during the day on the green areas of the adjacent road area. As a result of such technological operations, the movement of atoms in the gas composition is sharply reduced and heat transfer to the city's air environment is significantly reduced.

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