

THE INFLUENCE OF RADIATION ON THE WIND REGIME FORMATION IN URBAN BLOCK

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Abstract This paper presents the findings of a numerical study investigating the impact of solar and thermal radiation under clear and cloudy sky conditions on the formation of the wind regime in an isolated urban block in Krasnoyarsk city. A numerical simulation was conducted based on the microscale mathematical model of the urban atmosphere. The area under investigation is a residential zone comprising high-rise buildings with single access points, situated among low-rise buildings, which are streamlined by a constant wind flow in winter and summer season. The findings of the numerical simulation have shown a correlation between the wind regime within the urban block and the daily dynamics of solar radiation.

Key words: CFD, urban environment, heat transfer, radiation.

AMS Mathematics Subject Classification: 76D05, 80A21.

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1 Introduction

The rapid growth of cities and the development of mathematical simulation methods have naturally led to the emergence of numerical studies of aerodynamics and heat transfer processes in the urban environment, whose main purpose is to improve the comfort level of urban residents. The research works address a number of phenomena, such as the urban heat island [1], the wind regime [2]; the spread of pollution [3]; the influence of urban development on the level of pedestrian comfort [4], heat and mass transfer in urban neighborhoods [3, 5]. The present paper considers the influence of solar and thermal radiation under clear and cloudy sky conditions on the formation of the wind regime, with the example of an isolated urban block of Krasnoyarsk city in winter and summer seasons.

The numerical simulation of the heat and mass transfer processes occurring within the specified urban block was conducted using a microscale model of the urban atmosphere, implemented in the SigmaEco software package [6].

2 Mathematical model

The microscale mathematical model of the urban atmosphere is based on the Reynolds-averaged Navier-Stokes (RANS) equations for incompressible flows in the anelastic

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approximation [6, 7]:

$$\nabla \mathbf{V} = 0,$$

$$\frac{d(\rho_h \mathbf{V})}{dt} = -\nabla p + \mathbf{g} \rho_h (\theta_h - \theta) / \theta_h + \nabla [(\mu + \mu_t) (\nabla \mathbf{V} + \nabla \mathbf{V}^T)],$$

$$\rho_h C_p \frac{d\theta}{dt} = \nabla \cdot \left[\left(\lambda + \frac{\mu_t C_p}{Pr_t} \right) \nabla \theta \right] + S_\theta,$$

where \mathbf{V} - velocity, m/s; ρ_h - hydrostatic density, kg/m³; θ - potential temperature, K; p - pressure, Pa; μ - dynamic viscosity, kg/(m·s); C_p - heat capacity, J/(kg·K); λ - conductivity, W/(m·K); S_θ - heat source, W/m³; μ_t - turbulent viscosity; Pr_t - the turbulent Prandtl number.

The two-parameter $k-\omega$ SST model [8], which includes additional terms to account for the impact of buoyancy forces on the generation and dissipation of turbulent kinetic energy, is employed to describe the turbulent characteristics. In order to describe the velocity profile near the wall, near-wall functions based on the aerodynamic roughness model proposed in [9] are employed.

The initial and boundary distributions of potential temperature, velocity, and turbulent characteristics describe a neutral atmosphere ($\theta_h = const$) [10].

A coupled heat transfer model, comprising a one-dimensional unsteady heat conduction equation, is employed to calculate the heat transfer of the atmosphere with the ground and buildings.

In order to describe the propagation of radiation in an urban environment, the radiative transfer equation (RTE) is employed, utilizing the 'gray' gas approximation, and solved based on the finite volume method. In the context of the meteorological model, the radiation field is subdivided into two distinct categories: short-wave solar radiation and long-wave atmospheric and ground surface radiation. A separate RTE is solved for each radiation. The model for calculating direct and diffuse solar radiation and atmospheric thermal radiation transport is presented in [6].

In calculating the transport of thermal radiation, it is assumed that the medium is absorbing. Water vapor functions as both an absorbing and radiating gas. The WSGG model proposed in [11] is employed for the calculation of the absorption coefficient of a gas mixture by banded method.

3 Problem statement

The residential block of Krasnoyarsk city comprised eight single-access high-rise buildings with a height of 73 m, which dominate the surrounding low-rise buildings, is considered (Fig. 1).

The presented calculation options are associated with changing seasons and cloud conditions (Table 1). The wind flow characteristics were assumed in accordance with the data presented in [12]. The mean maximum and minimum air temperatures of the warmest and coldest months were employed as the surface temperature of the incident wind flow, respectively. In this study, the speed and direction of wind and temperature were assumed to be constant. In accordance with the established normative require-

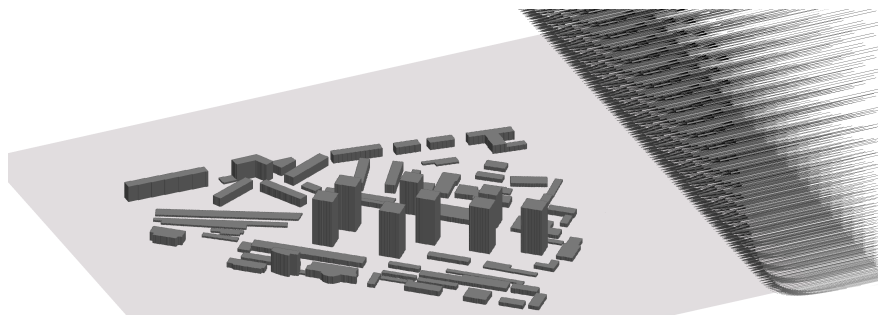


Figure 1: Geometry of the calculation domain.

Table 1: Calculation options for different meteorological conditions

Option	Month	Cloudiness	Wind speed, m/s	Temperature, °C	Water pres- sure, hPa
1	June	clear	2.5	25	12
2	June	cloudy	2.5	25	12
3	February	clear	2.5	-23	1.8
4	February	cloudy	2.5	-23	1.8

ments, the thermal resistance coefficient for walls of buildings in Krasnoyarsk is $3.62 \text{ m}^2/(\text{K}\cdot\text{W})$, while that for windows is $0.6 \text{ m}^2/(\text{K}\cdot\text{W})$. In consideration of the regulatory standard for glazing in residential buildings, which is 18 %, the average thermal resistance coefficient for walls was assumed in the calculations to be $3 \text{ m}^2/(\text{K}\cdot\text{W})$. The temperature inside the buildings was assumed to $25 \text{ }^\circ\text{C}$ for all options. The albedo for the brick walls of buildings was assumed to be 0.25, while for roofs – 0.1, and for ground – 0.15. The emissivity factor for all surfaces was assumed to be 1. The roughness of the ground was 0.05 m.

The calculation domain was oriented in accordance with the prevailing wind direction and had sizes $1000\text{m}\times 850\text{m}\times 450\text{m}$. (Fig. 1). The discretization of the computational domain for the study urban district was represented by an unstructured orthogonal grid, with additional horizontal detailing in the building area, where the cell size reached 1 m. The minimum vertical cell size in the surface region was 0.35 m. Total cells of grid is 4 900 000.

4 Results and discussion

One peculiarity of high-rise urban development in relation to solar radiation is the prevalence of extensive areas exhibiting shading effects (Fig.. 2). The geographical location and remoteness of Krasnoyarsk city from the equator (56° N) serve to amplify this effect. In June, the Sun reaches its highest point in the sky relative to the horizon. Consequently, the primary radiation flux is concentrated on horizontal surfaces, reaching a maximum of over $800 \text{ W}/\text{m}^2$) between 10 a.m. and 2 p.m. (Fig. 2a). During the morning and evening hours, shading areas can occupy a considerable portion of the city

block. The presence of cloud cover has the effect of reducing both the total amount of incident solar radiation and the gradient between shaded and unshaded areas due to an increase in the proportion of diffuse radiation (Fig. 2a, b). In the winter months, the solar radiation intensity decreases, and position of the Sun in the sky is much lower than it is in June (Fig. 2a, b). This results in the primary radiation flux being directed towards vertical surfaces of buildings, rather than horizontal surfaces. Therefore, the area of shading increases, while the maximum intensity of radiation on the horizontal surface decreases by approximately twice that observed in June.

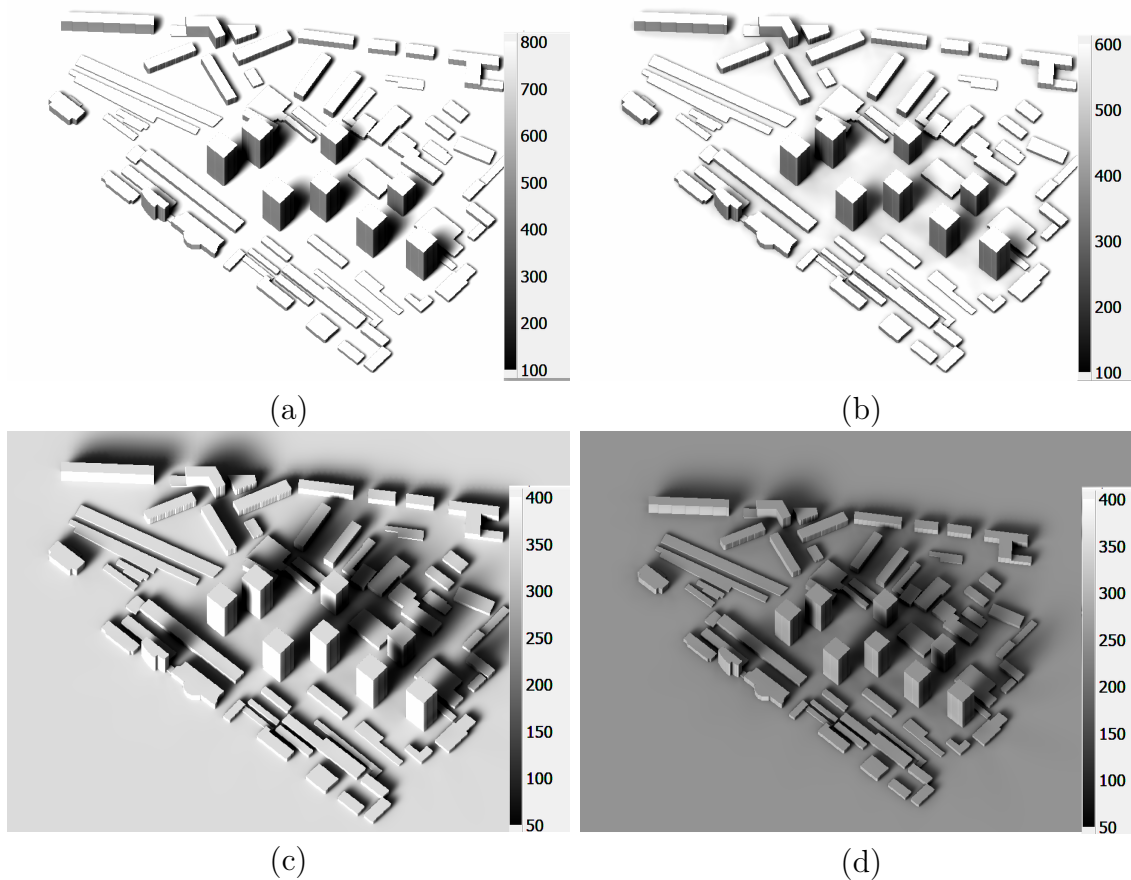


Figure 2: The incident solar radiation flux at noon, W/m^2 . Options: 1 (a), 2 (b), 3 (c), 4 (d).

Thermal radiation on a surface is primarily determined by temperature (Fig. 3). It is also affected by atmospheric radiation and radiation from adjacent surfaces such as walls of buildings. In clear summer weather during the daytime hours, the level of thermal radiation from the ground surface in the urban block is lower than outside, which is due to the shielding of solar radiation. On a clear summer day, heat losses due to thermal radiation from the surface can reach $100 W/m^2$. However, in shaded areas, on the contrary, the heating of surfaces by thermal radiation may occur due to the radiation from surfaces with higher temperatures. The presence of clouds enhances atmospheric radiation and distributes solar radiation more evenly, resulting in a reduction in the discrepancy in heat loss from the ground surface between ur-

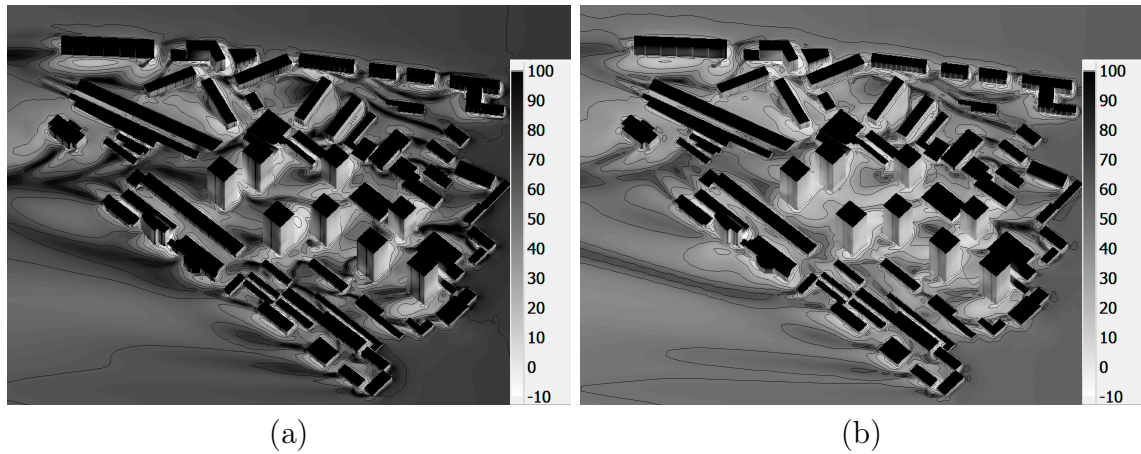


Figure 3: Thermal radiation flux at noon, W/m^2 . Options: 1 (a), 2 (b)

ban neighborhoods and the surrounding area (Fig. 3b). In February, as temperatures decline, the thermal radiation emitted from the surface also decreases.

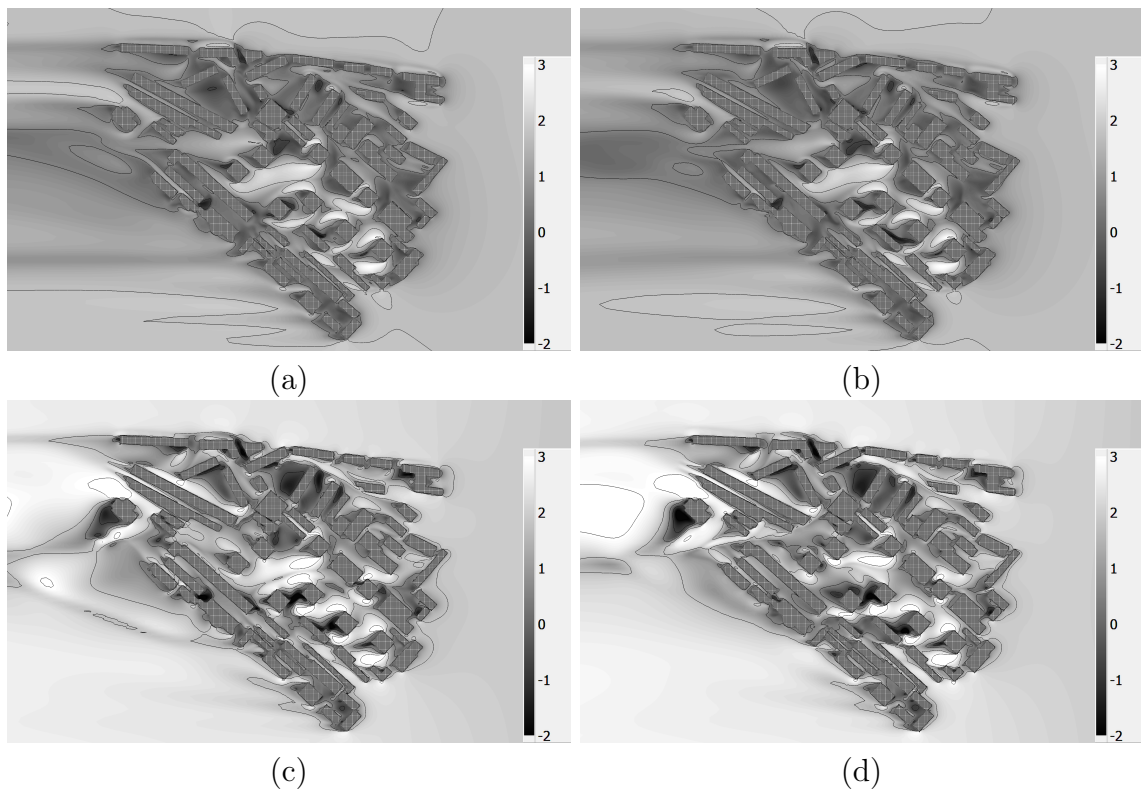


Figure 4: Velocity component field along the wind direction at a height of 2 m, m/s; at 1 p.m., options 1 (a), 3 (b); at noon, options 2 (c), 1 (d).

At night, since the inlet velocity profile is the same in all options, the velocity fields for all options are quite close. The discrepancies are attributable to variations in radiative heat exchange with the atmosphere, whereas during the winter months, the presence of a heat flux from buildings (Fig. 4 a,b). contributes an additional effect. At night, in urban areas, the airflow on average decelerates due to the presence of

buildings. However, in local areas, the flow may accelerate with respect to the wind speed, particularly when flowing around the first row of high-rise buildings. The high-rise buildings situated in the rear position do not constitute areas of localized flow acceleration upon entering the region of reverse flows, which is created by the initial high-rise buildings.

The most notable transformation in airflow is observed in June on days with maximal solar radiation flux, which occurs when the atmosphere is clear. As a consequence of the heating of the ground surface, the air flow accelerates in the region of the ground surface, both within and beyond the urban development (Fig. 4c). In urban development, the inhomogeneity of the velocity field increases due to intensification of the flow. The areas of flow acceleration near high-rise buildings increase in both the magnitude and the extent of the affected area, as well as new such regions emerge. The intensity and number of large vortex zones, which arise from the flow around medium- and low-rise buildings, increase. The emergence of cloudiness results in a slight reduction in velocity and an enhancement in the homogeneity of the flow field (Fig. 4c, d).

In the central part of the urban neighborhood, between high-rise buildings, a stable area of increased velocities is formed, which is preserved in all calculation options. It is influenced by the daily dynamics of solar radiation, which changes the size of this stable area and flow velocity, however, not destroying it completely.

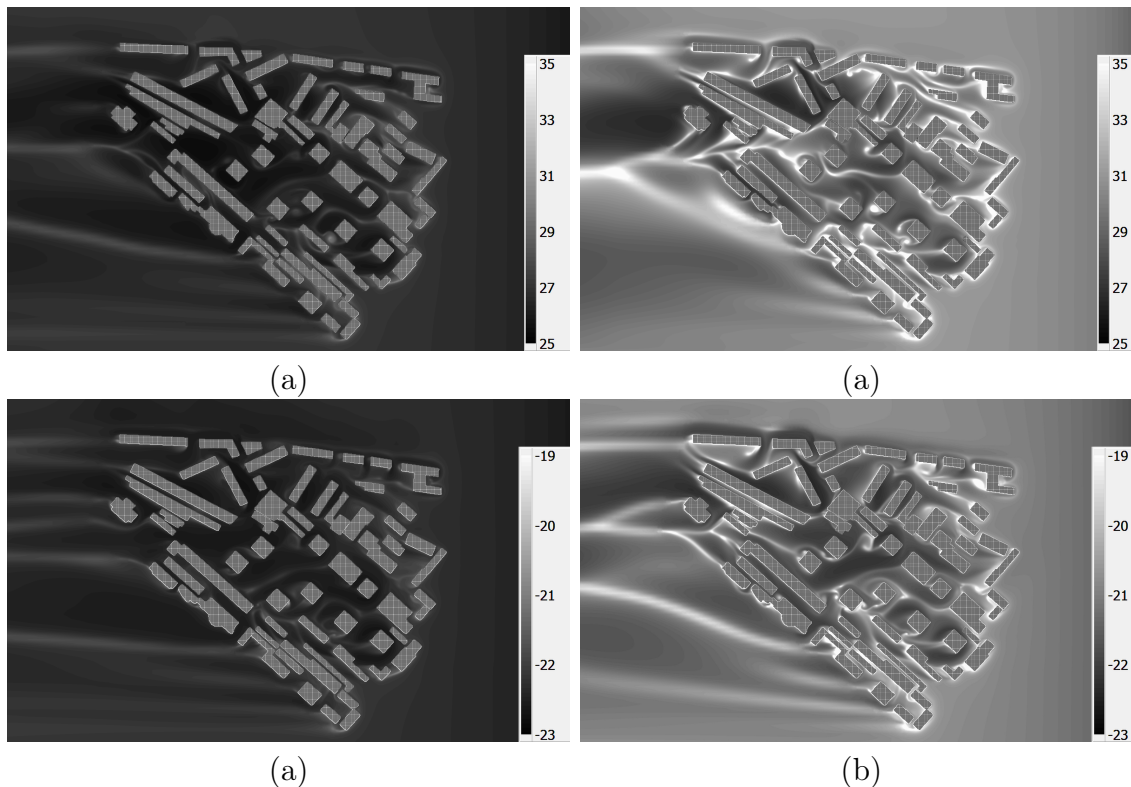


Figure 5: Temperature field at a height of 2 m , $^{\circ}\text{C}$. Option : 1 - 6 a.m. (a), 1 - at noon (b), 3 - 9 a.m. (c), 3 - 1 p.m. (c).

As the sun ascends, the ground begins to warm and the temperature in the surface near the ground begins to rise in relation to the incoming flow temperature (Fig. 5).

In June, local overheating at a height of 2 m can reach 10 °C and above. In February, the magnitude of overheating is significantly reduced (up to ~ 4 °C) in comparison to other months, as well as the duration of this effect. This gives rise to the formation of thermal plumes, which are elongated areas exhibiting elevated temperatures (Fig. 5).

4 Conclusions

The results of the numerical simulation of heat and mass transfer processes in the Krasnoyarsk city area during the winter and summer seasons under both clear and cloudy sky conditions have demonstrated that the aeration regime in urban development is non-stationary and is primarily influenced by the daily dynamics of solar radiation, which is dependent on the season of year and cloud cover. In particular, during the summer months, thermal radiation acts during the day time as a mechanism for removing solar heat, thereby reducing the heating of surfaces.

The distinctive feature of this area is the prevalence of dominant structures comprising high-rise single-unit buildings, which contribute to the formation of local zones of increased air velocities. In the event that the high-rise buildings fall within the aerodynamic shadow caused by the wind streamlined high-rise buildings that precede them, the areas of increased velocity may not occur.

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