Simulation Research on the Effects of Minor Disturbance on the Decrease of Surface-layer Temperature Inversion in Urumqi

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Abstract. The layer of temperature inversion hinders the vertical movement of air currents, especially in areas with mountainous terrain. In winter, when solar radiation is diminished, mountain breezes intensify the diurnal temperature inversion layer, which in turn restricts the dispersion of soot, pollutants, and condensed water vapor, worsening air quality. This research utilizes the FLUENT fluid simulation tool to investigate atmospheric interactions linked to the disturbance of the temperature inversion by introducing disruptions at its base, with a particular emphasis on the temperature inversion occurrence in Urumqi from December 20, 2017. The findings reveal that disruptions at the bottom of the temperature inversion layer can promote the exchange of cooler surface air with the warmer air above, shifting the atmospheric stability from a stable state to an unstable one. This induced upward motion boosts horizontal diffusion and creates a localized 'circulation.' The disturbance affects the temperature inversion across a diameter of roughly 1000 meters, effectively disrupting the inversion layer. The results of the simulation offer significant theoretical insight to support the implementation of artificial temperature inversion disruption as a means to alleviate and manage air pollution.

Keywords: Numerical simulation; Turbulence model; FLUENT; Destroy temperature inversion; Intensity change.

1 Introduction

The reduction in air quality is intricately linked to the meteorological factors that influence the spreading and dilution of air pollutants. Important meteorological elements, including temperature inversions and the depth of the mixing layer, impose significant limitations on the dispersion and dilution of these pollutants [6-8]. A temperature inversion takes place when air temperature stays constant or rises with elevation, reflecting a stable atmospheric stratification that greatly hampers vertical pollutant diffusion [9-10]. In the lower atmospheric layer, such inversions can hinder the timely dispersion of pollutants at high concentrations, resulting in severe air contamination that poses risks to human health and property [8]. Urumqi, positioned centrally

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within Xinjiang, lies in the Eurasian continent's interior, at the northern base of the Tianshan Mountains and the southern end of the Junggar Basin, encircled by mountains on three sides. The high occurrence of temperature inversions significantly contributes to the serious air pollution characterized in this city [1-5]. Especially in winter, when solar radiation decreases, the interplay of the valley-mountain breeze intensifies the urban temperature inversion layer, further hindering the dispersal of soot, pollutants, and vapor condensates, thereby worsening air pollution. At present, numerous studies have examined the suppression of air pollutant dilution and diffusion attributable to the temperature inversion layer in this area. Nonetheless, investigations into strategies to mitigate or eliminate temperature inversions are still quite limited. Current approaches mainly concentrate on modifying the atmospheric temperature and humidity distribution through methods like artificial precipitation enhancement [11].The artificial manipulation of cloud and fog dissipation [12] is intended to diminish or remove the temperature inversion layer. Although these techniques have shown effectiveness, their success is contingent upon suitable weather conditions. Additionally, the lack of supportive theoretical frameworks and numerical model simulations restricts the scientific insights available for the artificial reduction or removal of the temperature inversion, resulting in elevated costs and less than satisfactory results. In recent times, employing the computational fluid dynamics (CFD) simulation tool Fluent in meteorological studies has attracted increasing interest, especially in examining urban microscale wind patterns and pollution dispersion, where it has found extensive application [13-16]. In contrast to mesoscale models, Fluent provides comparatively high spatial resolution, with the potential for minimum horizontal grid spacing reaching around 10 meters. Deng Yuanchang et al. [17] utilized the Fluent fluid dynamics platform to assess how surface roughness affects wind fields in real landscapes, simulating the distribution of wind fields and validating it against observed wind speeds. Their research revealed that the root-mean-square error related to the wind speed acceleration ratio from the simulation was maintained within 6% on the windward slope. In a similar vein, Zhai Jianbo et al. [18] applied Fluent software to model wind speed distribution in the stope across various mining techniques. Additionally, Li Lei [19] noted that this field of research has also profited from the implementation of Fluent software for detailed simulations of wind fields in complex terrains. The program has effectively reproduced simulation results of surface-layer wind fields with improved resolution and precision in small-scale areas under elaborate surface conditions. Fluent provides a range of sophisticated turbulence models that can effectively simulate inviscid, laminar, and turbulent flows. Among these models are the Spalart-Allmaras model, various k-ω models, several k-ε models, the Reynolds stress model (RSM) group, the large eddy simulation (LES) model group, along with the latest detached eddy simulation (DES) and V2F models. In his research, Kim [20] performed simulations of the wind field at Askervein Mountain using several turbulence closure schemes grounded in the Reynolds-averaged Navier-Stokes (RANS) equations. He determined that the RNG k-ε turbulence closure scheme was effective in accurately calculating the average wind field velocity, as well as for analyzing the separation and re-entry of airflow, along with its turbulence characteristics. Conversely, Summer [21] contended that although the numerical simulation methods based on the RANS equations can reliably determine average wind field values, they struggle to predict the turbulence's fluctuating values. While the RNG k-ε turbulence closure scheme adequately describes airflow separation and re-entry, it does not effectively represent the intermittent structures of turbulence or the processes of vortex generation and transport, highlighting a limitation in the RANS equations concerning fluctuating motions. For flow fields in complex terrains, the LES model is preferred. Chow[22] indicated that the small-scale turbulence filtered by the sub-grid in the LES model exhibits greater isotropy, enhancing the reasonableness and accuracy of this approach. In China, studies utilizing Fluent to model the reduction or removal of temperature inversions are still quite limited. This paper aims to deeply examine the mechanisms behind the dissipation of temperature inversions and offers scientific insights and theoretical backing for real-world applications. To achieve this, the Fluent fluid mechanics model is employed to replicate the process of temperature inversion layer disruption by integrating low-altitude artificial disturbances into a representative temperature inversion situation observed in Urumqi. Additionally, this research investigates the practicality of deploying Fluent for simulating the breakdown of the temperature inversion layer.

2 Data and Methods

2.1 Data Processing

In this study, the second-level data collected from the Urumqi Meteorological Station at 20:00 on December 19, 2017, was chosen as the foundational dataset to model the degradation of the temperature inversion layer (mixing layer), aiming to render the sensitivity experiment as authentic as possible. Before initiating the simulation, a thorough sensitivity analysis of the parameters was performed to uncover which elements exerted the most significant influence on the outcomes. Physical properties and boundary conditions were selected according to practical necessities, and their values were established through an optimal strategy derived from numerous simulations. This methodology not only aids in refining the simulation framework but also contributes to improving the precision of the findings. In summary, the careful selection of the appropriate simulation duration, region, and parameters, along with conducting a sensitivity analysis, constitutes essential components in crafting the Fluent simulation experiment plan. Decisions ought to be made based on real-world conditions, integrating personal insights with specialized knowledge.To create the necessary three-dimensional data for Fluent simulation analyses, it is essential to carry out a three-dimensional gridding of the second-level sounding data obtained from the Urumqi National Benchmark Station. This dataset encompasses information regarding temperature, humidity, atmospheric pressure, and wind conditions. The designated simulation area is structured as a cuboid, measuring 1000 meters in length, 1000 meters in width, and 600 meters in height. The model consists of grid points arranged in a 100×100×60 configuration, leading to a resolution of 10m×10m×10m. In this study, a three-dimensional model is utilized, partitioning the grid into two distinct sections: an external fixed and immovable grid region, as well as an internal rotating grid area, which collectively contain around 12 million grids. The standard realizable k-ε turbulence model is employed for the simulations, and the movement of the wind column is achieved through the sliding grid technique. A no-slip condition is applied to the ground, while the upper boundary is characterized as a pressure-outlet condition, which is determined by a user-defined function (UDF). Additionally, the temperature at the upper boundary is defined via the UDF, along with the pressure and temperature conditions at the sides, all specified in the UDF file. This file facilitates the alteration of air pressure and temperature based on height. Within the internal grid area, a rotational speed of 0.75 RPM is set, and the simulation time step is configured at 0.01 seconds, with the possibility of extension after stabilization. The simulation ensures second-order accuracy for both turbulence terms and the energy equation. Li [22] illustrated the efficacy of this technique for detailed simulation of the meteorological conditions at the urban block scale, highlighting its ability to more accurately and realistically simulate ideal wind and temperature profiles as boundary conditions at this smaller scale.

2.2 Boundary Condition

The movement of air is regarded as a three-dimensional, steady, and incompressible flow. Due to the small scale of the simulation, the effect of the Coriolis force is considered negligible. Moreover, since the density of air remains nearly constant over a limited range, it is treated as a constant throughout this analysis. The dynamic viscosity of air, an essential parameter in fluid mechanics, is commonly represented by the symbol μ. This viscosity can be determined from temperature using the following equation: $\mu = 1.458\times10^{-6}\times T$^(3/2)/(T + 110.4), where T indicates the absolute temperature in Kelvin (K). Ground friction is not incorporated into this study, leading to a surface roughness of 0 m. A structured hexahedral grid is developed based on specific requirements, consisting of six faces (east, west, south, north, top, and bottom) for which boundary conditions need to be established. A no-slip fixed-ground boundary condition is applied to the ground. The temperature at the upper boundary is defined according to the User Defined Function (UDF), while the side pressure and temperature are similarly derived from the UDF file, facilitating the specification of pressure and temperature variations with elevation. Ultimately, the inlet boundary conditions are supplied through the Fluent UDF interface.

3 Analysis of Simulation Results

3.1 Initialization Data

The sounding diagram obtained from the Urumqi National Meteorological Benchmark Station at 20:00 on December 19, 2017, is depicted in Figure 1. The temperature curve is represented by the blue line, which shows the ground temperature at -10°C. As the altitude increases, temperature elevates to -8°C at a pressure of 914 hPa and continues to rise to -6°C at 905 hPa. Upon further ascent to 828 hPa, the temperature reaches 2°C. Importantly, the temperature remains constant at -6°C between the pressures of 905 hPa and 839 hPa. This information points to a notable temperature inversion, indicated by a Convective Available Potential Energy (CAPE) value of 0. The stability of the atmospheric layers is evident, and both the capabilities for horizontal diffusion and vertical exchange within the atmosphere are significantly limited, which creates difficulties for the dispersion of atmospheric pollutants.

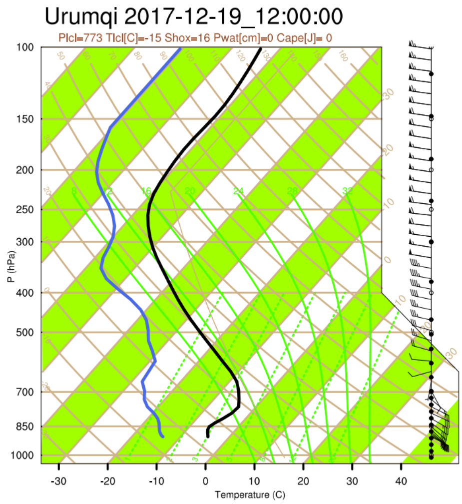

Fig. 1. Skew-T log-P diagram

The sounding data for temperature, air pressure, and humidity were utilized as the initial conditions in the Fluent model. Figure 2 demonstrates the horizontal non-uniformity of the temperature inversion layer in Urumqi, revealing variations in thickness across different areas. Generally, the pattern of temperature changes with altitude stays consistent. Within the simulated atmosphere of this sensitivity experiment, the lapse rate for temperature is notably steep, the air movement remains stable, and the overall atmospheric state is stable. The vertical stability plays a crucial role in the diffusion and transport of air pollutants throughout the atmosphere.

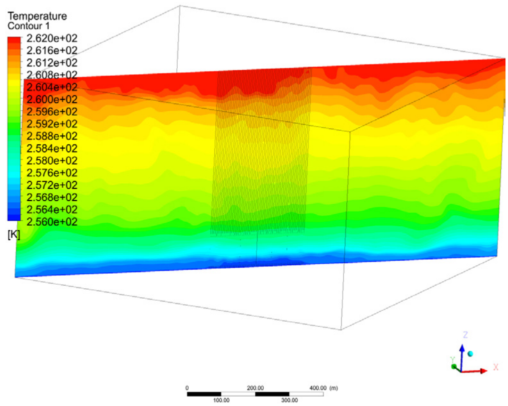

Fig. 2. Air temperature varies with height

A disturbance was introduced at the base of the temperature inversion layer using the Fluent fluid model. This disturbance functions similarly to an agitator in a washing machine, with a rotation speed set to one revolution every 80 seconds, as illustrated in Figure 3 below. In the analysis conducted by Chen Haining et al. [23] on the air-volume attenuation of air-conditioning centrifugal fans, it was observed that traditional fans exhibit negligible air-volume attenuation, whereas full-high-pressure fans may experience air-volume losses of up to 20%, leading to a corresponding reduction in the affected area. Consequently, to increase the rotation speed of the bottom disturbance, additional air columns can be incorporated instead of merely increasing the rotation speed. The air outlet diameter was established at 1 meter, with an air-outlet velocity set at 90 m/s. Four air columns were utilized in the simulation. By incorporating more air columns, the rotation speed of the bottom disturbance was effectively increased. Notably, doubling the velocity of the low-level disturbance did not affect the attenuation of the air columns, while simultaneously enhancing the air-outlet velocity to broaden the affected area. The parameters for this sensitivity experiment, including the air-outlet velocity and the air-outlet diameter of the fans, were determined based on data provided by the fan manufacturer, ensuring a realistic approach and offering a practical reference for future field applications.

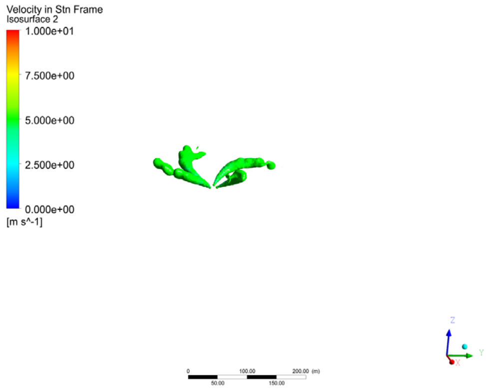

Fig. 3. Bottom disturbance simulation diagram

3.2 Analysis of Simulation Results

Introducing a disruption at the base of the temperature inversion layer enables the exchange of colder air in the near-surface layer with the warmer air situated above the inversion. This interaction between cold and warm air generates atmospheric instability, which drives vertical airflow diffusion, subsequently facilitating horizontal diffusion as depicted in Figure 4a. After one hour of the disturbance, the cold air in the lower layer starts to diffuse, while the warmer air from the upper layer moves downward toward the surface. As a result, the cold air is pushed toward the edges, leading to considerable changes in the configuration of the temperature inversion layer. The warm air from above cascades down towards the lower layer in a funnel-like fashion. By altering the initial conditions of the temperature inversion layer through the introduction of a disturbance and applying external forces, the stable structure's initial state is modified, which affects the potential temperature distribution. Changes made to the pressure parameters of this stable structure also have an impact on the energy distribution within the stable stratification, influencing the potential temperature profile further. The original integrity of the temperature inversion layer is weakened, resulting in alterations to the vertical stability structure of the atmosphere. Figure 4b presents the effects recorded after two hours of disturbance, at which time the temperature inversion layer is completely disrupted. As the air near the ground becomes warmer, the atmosphere attains a state of instability, facilitating an unrestricted exchange between the atmospheric layers above and below.

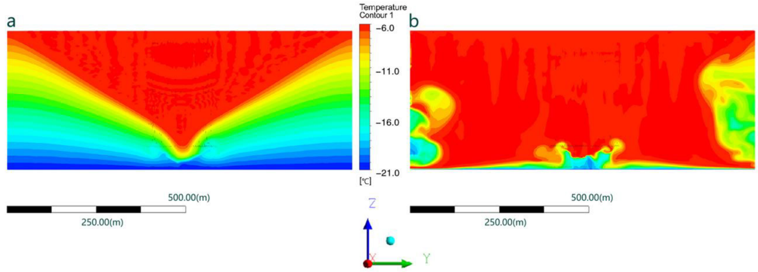

Fig. 4. A Effect image after one hour of disturbance b Effect image after three hours of disturbance

Remarkably, the shifts in vertical temperature resulting from disturbances lasting one hour and two hours lead to a diameter of the affected area surpassing 1 kilometer. Considering that temperature inversion is the main driver of air pollution in Urumqi, measures for energy conservation and emission reduction are only supplementary. However, with the city's development and the rising population, depending exclusively on these strategies proves inadequate for effectively addressing air pollution. Therefore, breaking the temperature inversion layer becomes the most immediate and efficient solution for controlling air pollution.

The disruption occurring at the base of the temperature inversion layer generates a radial velocity in the cold air within the near-surface layer. As this cold air at the lower level spreads radially, the warm air above it begins to descend. Simultaneously, when the cold air can no longer disperse horizontally, it begins to rise, as illustrated in Figure 5, which showcases a diagram of velocity streamlines simulated with the Fluent fluid mechanics model. The streamlines resulting from the disturbance after a duration of two hours include both vertical and horizontal aspects. An examination of these streamlines reveals a strong correlation with the predicted results from the initial sensitivity experiment design. When the fluid experiences disturbance, its streamlines adjust accordingly. The findings indicate that the exertion of external pressure prompts the atmosphere to initially expand radially, followed by an upward movement, a flow towards the center at greater heights, and finally, a downward flow influenced by gravitational forces. By intentionally introducing a disturbance, a large-scale vortex emerges, disrupting the stable temperature inversion layer, also known as the mixing layer. The sensitivity experiment conducted on the disruption of the temperature inversion elucidates the structure and evolution of the disturbance streamlines, thus improving the comprehension of fluid motion dynamics. This approach offers a theoretical basis as well as experimental evidence beneficial for both engineering design and scientific inquiry.

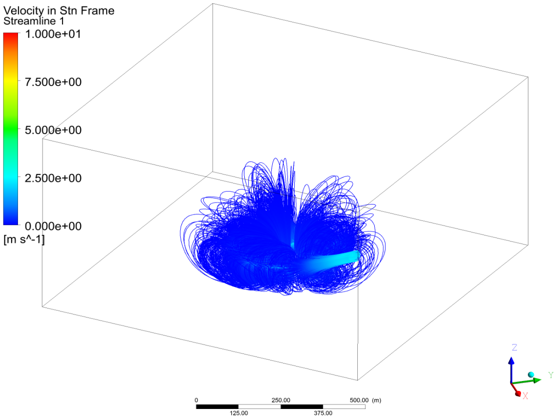

Fig. 5. Disturbance streamline

4 Conclusion

In this study, initial field data from Urumqi (actual observations) were employed to model the disruption process of the temperature inversion layer by initiating a disturbance at its base. The aim was to offer scientific and theoretical insights for the implementation of artificial methods to disrupt temperature inversions, thereby alleviating air pollution. The key findings are summarized as follows:

1. By initiating a disturbance at the base of the temperature inversion layer, a notable exchange occurred between the cold air from the near-surface layer and the warm air from above the inversion. This interaction resulted in atmospheric instability, facilitating vertical and horizontal diffusion of the airflow. As the cold air from the lower layer spread out, the warm air from the upper layer began to descend to the ground, culminating in the total destruction of the temperature inversion layer. With the heating of ground air, the atmosphere experienced increasing instability, which enabled free exchanges between the upper and lower layers. The area influenced by the disturbance extended beyond 1 kilometer.

2. This research represents the inaugural application of the Fluent fluid model for detailed simulation studies concentrating on the breakdown of the temperature inversion layer (mixing layer). The findings from the simulation indicate that Fluent is exceptionally proficient in performing fine-scale simulations of small-scale wind fields, presenting clear advantages over mesoscale models in accurately depicting complex streamlines within restricted areas. Certain principles employed in Fluent, including the unstructured grid technology and the finite volume method for modeling intricate geometric configurations, are of substantial reference value for meteorologi-

cal models, especially those related to boundary-layer meteorology. The incorporation of these technologies has the potential to significantly improve the simulation capabilities of meteorological frameworks.

In this investigation, while Fluent was used to model the breakdown of the temperature inversion layer, other beneficial factors, including solar radiation and mountain-valley airflow, were excluded from consideration. Factoring in these elements post-destruction of the temperature inversion layer could improve the simulation outcomes as well as the breadth of the impacted area. The phenomenon of temperature inversion plays a crucial role in contributing to air pollution in Urumqi. While energy conservation and measures to reduce emissions act as additional strategies, they alone are inadequate. In light of the city's urban development and population increase, dependence solely on these measures is unlikely to successfully manage air pollution levels. As a result, the breakdown of the temperature inversion layer is identified as the most straightforward and effective strategy for alleviating air pollution.

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