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(REVIEW ARTICLE)

Turbulent diffusion and air pollution: A comprehensive review of mechanisms, impacts, and modeling approaches

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Abstract

Turbulent diffusion is often a desirable phenomenon in many contexts, but it also presents significant challenges, particularly in the realm of air pollution. Air pollution, a universally recognized and frowned upon issue, degrades air quality and poses serious long-term health risks. Turbulent flows, characterized by chaotic and random fluid motions, give rise to turbulent diffusion, a process that acts as a transport mechanism for dispersing pollutants in the atmosphere. Despite its inherent complexities, the study of turbulent diffusion has advanced significantly, building on foundational concepts like Osborne Reynolds' decomposition in the 1850s and extending to Kolmogorov's length scale framework. These developments have enabled a deeper understanding of turbulent diffusion and its wide-ranging applications across various fields as new methods are continuously employed to broaden the scope of research and application.

Keywords: Turbulent diffusion; Atmospheric turbulence; Energy cascade; Air pollution; Pollutant dispersion; atmospheric turbulence; Environmental modeling

1. Introduction

1.1. Air Pollution: An Overview

Among multiple hazardous and health-compromising situations in the 21st century, air pollution is among the leading causes if not the most. The 21st century is the most industrialized era of Earth's history and the most polluting generation which could be observed by the degeneration of the Earth’s atmosphere (ozone inclusively) [1], leading to atmospheric instabilities across the globe. It is a critical environmental issue that poses significant risks to human health, ecosystems, and the climate, as harmful substances are released into the atmosphere including particulate matter (PM), nitrogen oxides (NOx), sulfur dioxide (SO2), carbon monoxide (CO), volatile organic compounds (VOCs), and greenhouse gases such as carbon dioxide (CO2) and methane (CH4). These pollutants originate from various sources, including industrial activities, vehicular emissions, agricultural practices, residential heating, and natural events like wildfires and volcanic eruptions[2]

1.2. Human Health Impact

Firstly, humans' major concern is that air pollution directly influences individual's health negatively through constant or regular exposure to air pollutants, leading to respiratory conditions such as asthma, bronchitis, and chronic obstructive pulmonary disease (COPD). It is also intricately linked to heart attacks, strokes, and premature deaths of the vulnerable such as children, and a high mortality rate among the aged[3][4].

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1.3. Environmental Impact

Environmental ecosystems are also impacted, as plants, animals, and aquatic life are affected by acid rain resulting from SO_2 and NOx emissions which leads to the damage of forests, soils, and water bodies [5]. Rapid climate change, global warming, fluctuating weather patterns, and rising sea levels are closely linked to poor atmospheric air quality [6].

2. The Significance of Understanding Turbulent Diffusion

2.1. Complexity of Atmospheric Dispersion

For the above phenomenon to come to fruition, the pollutants themselves must primarily undergo two phenomena that influences the behavior of the released pollutants namely natural spread or pollutant mass distribution as a result of common particle buoyancy and turbulent induced dispersion respectively, which is the complexity of atmospheric dispersion. It is variable as it is dynamic causing pollutants to be dispersed over large distances[7][8], secondly, it is turbulent where chaotic and irregular airflow is at work for dispersing the pollutants [9].

2.2. Turbulent Diffusion Mechanisms

Given the influential mechanism of the spread and transportation of the pollutants, turbulent diffusion is the culprit for it promotes mixing and dilution through chaotic air movements, its impact varies across different scales[10], from small eddies to large atmospheric currents which boost pollutant concentration and distribution patterns in multiple areas of interest[11].

2.3. Importance of understanding Turbulent Diffusion

Keen interest and understanding of turbulent diffusion for accurate predictions can help assess the impact of air quality and develop effective mitigation strategies, in turn reducing the adverse effects[12] [13]. Under regulatory compliance, effective air quality regulations require robust models to predict pollutant dispersion and to ensure compliance with environmental standards[14].

2.4. Challenges in Modeling Turbulent Diffusion

In various scientific fields, turbulence remains one of the most rigorous and challenging phenomena, primarily because it is governed by complex mathematical equations such as Navier-Stokes equations [15][16]. Turbulent diffusion is further complicated by environmental conditions where atmospheric variables and pollutant sources are often coupled with limited data[17][18].

2.5. Purpose of the Review

This review introduces the fundamental mechanisms of turbulent diffusion and various methods for predicting mean concentration distributions in selected engineering applications. The focus is solely on turbulent diffusion, which involves the spreading of a scalar quantity due to irregular turbulent velocity fluctuations. The Combined effects of diffusion and shear mean velocity (shear-flow dispersion), the impacts of buoyancy from density differences between the discharged and receiving fluids are not considered, nor are the suppressions of turbulence due to density stratification. A review of turbulent flows serves as the starting point, emphasizing aspects crucial to turbulent diffusion, next, an exploration of the mechanisms by which turbulence induces rapid mixing, the derivation of the time-averaged equations of species conservation, and present methods for estimating the resulting turbulent diffusion coefficients. Following this, application, challenges and limitations of future directions are explored.

3. Fundamentals of Turbulent Diffusion

3.1. Basic principles and definitions

In any case involving turbulence, it is essential to first establish the basic principles and definitions related to the fundamentals of turbulent diffusion. In a general sense, turbulent diffusion is the process by which a scalar quantity such as temperature, pollutant concentration, or any other properties spread within a fluid medium due to chaotic and irregular fluid velocity fluctuations [19]. Turbulence itself is a flow regime characterized by chaotic, stochastic property changes, including rapid variations in pressure and flow velocity in both space and time, typically occurring at high Reynolds numbers and involving eddies, vortices, and apparent randomness[20][21].

Diffusion refers to the process by which particles spread from areas of high concentration to areas of low concentration in a medium or within different mediums [22], whereas mean concentration can be determined as the average concentration of a scalar quantity over a given time or spatial domain, used in predicting distributions. Turbulent Diffusion Mechanisms include eddy diffusion which is caused by turbulent eddies that mix scalar quantities[23](a physical quantity that has only magnitude and no direction, such as temperature or concentration) across different regions of the fluid, enhancing the spread much faster than molecular diffusion. Turbulent mixing entails the rapid and irregular movement of fluid particles leading to an effective blending of scalar quantities, promoting uniformity in concentration[24].

Due to the highly unpredictable nature of turbulent flows, statistical approaches are necessary when solving equations that describe the average behavior of a scalar quantity over time[25][26], smoothing out the rapid fluctuations and employment of turbulent diffusion coefficients that quantify the rate at which a scalar quantity spreads due to turbulence, often derived from empirical or theoretical models [27][28] [29].

4. Historical Development

4.1. Key milestones in the study of turbulent diffusion in the atmosphere

The study of turbulent diffusion in the atmosphere has been shaped by successive key developments, beginning with Osborne Reynolds' pioneering work on turbulent flows which laid the groundwork for understanding turbulent diffusion by introducing the concept of Reynolds decomposition, which separates a turbulent flow into mean and fluctuating components in the 1880s [30][31][32], this was followed by Albert Einstein's theory of Brownian motion in 1905 that provided a statistical framework for understanding diffusion processes, influencing the study of atmospheric turbulence in 1905[33]. Lewis Fry Richardson formulated the famous $l \propto t^{\frac{3}{2}}$ scaling law for turbulent diffusion, describing how the separation distance between particles in a turbulent flow increases over time in 1926 [34][32]and followed by Andrey Kolmogorov in 1941 when he developed the theory of local isotropic turbulence, introducing the Kolmogorov scaling laws which are fundamental to understanding energy distribution in turbulent flows and energy cascades[30][35][36]. The 1950s and 1960s saw the introduction of Gaussian plume models for predicting the dispersion of pollutants in the atmosphere whereby these models assumed a normal distribution of pollutant concentrations and became standard tools in environmental engineering [37][38]. Over the years, advancements measurement techniques emerged, including Doppler Radar, LIDAR, and the introduction of harmless tracers whose behavior was modeled and analyzed using computational fluid dynamics (CFD) and numerical methods [39][40]. Ongoing, there is an increase in integrated assessment models through artificial intelligence and the utilization of high-resolution satellite data and drone-based measurements to provide more detailed and comprehensive data on atmospheric turbulence and pollutant dispersion [41] [42][43].

5. Mathematical Foundations

5.1. Introduction to the equations and models used to describe turbulent diffusion

Consider a fluid (air) that carries a tracer gas at a rate dependent on its concentration, c, and the fluid velocity, u. However, the fluid velocity u alone cannot fully describe the movement of the tracer because it does not account for the motion of molecules that have different directions and speeds from u. *Molecular diffusion* accounts for the difference or captures the discrepancy between the actual movement of individual molecules (u_m) and the simplified way that motion is often represented in fluid dynamics models (u).

$$\Delta u = u_m - u \qquad \ldots\ldots\ldots\ldots\ldots\ldots 1$$

The mass flux due to this velocity difference becomes:

$$J = \Delta u. c \qquad \ldots\ldots\ldots\ldots\ldots\ldots 2$$

Now applying Fickian Law, molecular diffusion transport is proportional to the concentration gradient.

$$J_m \propto \Delta u. c. \frac{\partial c}{\partial x} \ldots\ldots\ldots\ldots\ldots\ldots 3$$

$$J_m = -D_m \frac{\partial c}{\partial x} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 4$$

Where: $D_m = constant\ of\ proportinality\ (molecular\ diffusivity)$

Now considering *advection* by mean motion:

$$J_x = cu - D_m \frac{\partial c}{\partial x} \quad \text{…………..5}$$

Substituting into the mass conservation equation yields the 2D advection-diffusion equation as:

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} = D_m \frac{\partial^2 c}{\partial x^2} + D_m \frac{\partial^2 c}{\partial y^2} \qquad \text{…………6}$$

Where:

$\frac{\partial c}{\partial t}$ =time rate of change of concentration at a point

$u\frac{\partial c}{\partial x}$ =advection of the tracer with the fluid (by mean motion)

$D_m \frac{\partial^2 c}{\partial x^2} + D_m \frac{\partial^2 c}{\partial y^2}$ =molecular diffusion (by Velocity fluctuation)

Turbulent flows are induced by fluctuations in velocity, as a result let's look at the velocity changes under Reynolds Averaged Navier Stocks Equation.

Navier Stocks equation:

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + v\frac{\partial^2 u_i}{\partial {x_j}^2} \qquad \text{…………7}$$

Decomposition of velocity:

$u_i = \overline{u_i} + u_i{}'$ or $u_j = \overline{u_j} + u_j{}'$

u_i= Instantaneous

$\overline{u_i} + u_i{}'$ =Mean + fluctuating

Substitute decomposition of velocity into Navier stocks equation:

$$\frac{\partial(\overline{u_i}+u_i{}')}{\partial t} + \left(\overline{u_j} + u_j{}'\right)\frac{\partial\left(\overline{u_i}+u_i{}'\right)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + v\frac{\partial^2(\overline{u_i}+u_i{}')}{{x_j}^2} \qquad \text{………..8}$$

$$\frac{\partial\overline{u_i}}{\partial t} + \frac{\partial u_i{}'}{\partial t} + \left(\overline{u_j}\right)\frac{\partial\overline{u_i}}{\partial x_j} + \left(u_j{}'\right)\frac{\partial\overline{u_i}}{\partial x_j} + \left(\overline{u_j}\right)\frac{\partial u_i{}'}{\partial x_j} + \left(u_j{}'\right)\frac{\partial u_i{}'}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + v\frac{\partial^2\overline{u_i}}{{x_j}^2} + v\frac{\partial^2 u_i{}'}{{x_j}^2} \text{……….9}$$

Applying Reynolds averaging, then:

$$\frac{\partial\overline{\overline{u_i}}}{\partial t} + \frac{\partial\overline{u_i{}'}}{\partial t} + \frac{\partial\overline{(\overline{u_i}.\overline{u_j})}}{\partial x_j} + \frac{\partial\overline{(\overline{u_i}.u_j{}')}}{\partial x_j} + \frac{\partial\overline{(u_i{}'.\overline{u_j})}}{\partial x_j} + \frac{\partial\overline{(u_i{}'.u_j{}')}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial\bar{P}}{\partial x_i} + v\frac{\partial^2\overline{\overline{u_i}}}{{x_j}^2} + v\frac{\partial^2\overline{u_i{}'}}{{x_j}^2} \text{……..10}$$

The final equation becomes:

$$\frac{\partial\overline{u_i}}{\partial t} + \left(\overline{u_j}\right)\frac{\partial\overline{u_i}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + v\frac{\partial^2\overline{u_i}}{{x_j}^2} + \frac{\partial(u_i{}'.u_j{}')}{\partial x_j} \quad \text{…….11}$$

$\frac{\partial\overline{u_i}}{\partial t}$ =local derivative

$\left(\overline{u_j}\right)\frac{\partial\overline{u_i}}{\partial x_j}$ = Convective part

$\frac{1}{\rho}\frac{\partial P}{\partial x_i}$ =Pressure

$v\frac{\partial^2\overline{u_i}}{{x_j}^2}$ =viscosity

$\frac{\partial({u_i}'.{u_j}')}{\partial x_j}$ =Reynolds stress

Using the same analogy for both velocity and concentration combined. Decompose velocity and concentration into mean and fluctuation and neglecting the i and j.

$$u = \bar{u} + u' \qquad \text{.........12}$$

$$c = \bar{c} + \ c' \ (assume\ only\ fluctuation\ in\ y - direction) \ \text{........13}$$

$$v = v'$$

$$\bar{u}\ and\ \bar{c}\ are\ time\ averaged\ values$$

Where:

$$\bar{u} = \ \frac{1}{T}\int_0^T udt\ and\ \ \bar{c} = \ \frac{1}{C}\int_0^C cdt \qquad \text{........14}$$

Advection Equation is,

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + \ v\frac{\partial c}{\partial y} = D_m\frac{\partial^2 c}{\partial x^2} + D_m\frac{\partial^2 c}{\partial y^2} \qquad \text{..........15}$$

Substitute ($u = \bar{u} + u'$) and ($c = \bar{c} + \ c'$) into advection equation

$$\frac{\partial(\bar{c}+ c')}{\partial t} + \frac{\partial(\bar{u}+u')(\bar{c}+ c')}{\partial x} + \frac{\partial v'(\bar{c}+ c')}{\partial y} = D_m\frac{\partial^2(\bar{c}+ c')}{\partial x^2} + D_m\frac{\partial^2(\bar{c}+ c')}{\partial y^2} \text{........16}$$

$$\frac{\partial\bar{c}}{\partial t} + \frac{\partial(\bar{u}.\bar{c})}{\partial x} = D_m\frac{\partial^2\bar{c}}{\partial x^2} + D_m\frac{\partial^2\bar{c}}{\partial y^2} - \frac{\partial c'}{\partial t} - \frac{\partial(\bar{u}.c')}{\partial x} - \frac{\partial(\bar{c}.u')}{\partial x} - \frac{\partial(u'.c')}{\partial x} - \frac{\partial(v'.\bar{c})}{\partial y} - \frac{\partial(v'.c')}{\partial y} + D_m\frac{\partial^2 c'}{\partial x^2} + D_m\frac{\partial^2 c'}{\partial y^2} \quad \text{..........17}$$

Integrate w.r.t time (apply Reynolds averaging method)

$$\frac{\partial\bar{\bar{c}}}{\partial t} + \frac{\partial\overline{(\bar{u}.\bar{c})}}{\partial x} = \overline{D_m\frac{\partial^2\bar{c}}{\partial x^2}} + \overline{D_m\frac{\partial^2\bar{c}}{\partial y^2}} - \overline{\frac{\partial c'}{\partial t}} - \overline{\frac{\partial(\bar{u}.c')}{\partial x}} - \overline{\frac{\partial(\bar{c}.u')}{\partial x}} - \overline{\frac{\partial(u'.c')}{\partial x}} - \overline{\frac{\partial(v'.\bar{c})}{\partial y}} - \overline{\frac{\partial(v'.c')}{\partial y}} + \overline{D_m\frac{\partial^2 c'}{\partial x^2}} + \overline{D_m\frac{\partial^2 c'}{\partial y^2}} \quad \text{.........18}$$

After dropping all zeros therefore

$$\frac{\partial\bar{c}}{\partial t} + \frac{\partial(\bar{u}.\bar{c})}{\partial x} = D_m\frac{\partial^2\bar{c}}{\partial x^2} + D_m\frac{\partial^2\bar{c}}{\partial y^2} + \frac{\overline{\partial(-u'.c')}}{\partial x} + \frac{\overline{\partial(-v'.c')}}{\partial y} \quad \text{................19}$$

$\frac{\overline{\partial(-u'.c')}}{\partial x} + \frac{\overline{\partial(-v'.c')}}{\partial y}$ = Advective transport due to $u'v'\ and\ c'$

It is assumed and confirmed experimentally that average advective transport associated with turbulent fluctuations is proportional to the gradient of average concentration [44].

Whereby (Advective transport) $\overline{u'c'} = -\varepsilon_x \frac{\partial \bar{c}}{\partial x}$ $\overline{v'c'} = -\varepsilon_y \frac{\partial \bar{c}}{\partial y}$

hence $\frac{\partial}{\partial x}(\overline{-u'c'}) = \frac{\partial}{\partial x}(\varepsilon_x \frac{\partial \bar{c}}{\partial x})$

$\frac{\partial}{\partial x}(\overline{-v'c'}) = \frac{\partial}{\partial y}(\varepsilon_y \frac{\partial \bar{c}}{\partial y})$

Mean turbulent flux $(\overline{u'c'})$

Taking ε_x *and* ε_y as constants (Eddy Diffusivity), then mass balance equation becomes:

$$\frac{\partial \bar{c}}{\partial t} + \frac{\partial(\bar{u}.\bar{c})}{\partial x} = (D_m + \varepsilon_x)\frac{\partial^2 \bar{c}}{\partial x^2} + (D_m + \varepsilon_y)\frac{\partial^2 \bar{c}}{\partial y^2} \text{............}20$$

But ε_x *and* $\varepsilon_y \gg D_m$ and drop average signal and equation becomes:

$$\frac{\partial c}{\partial t} + \bar{u}\frac{\partial c}{\partial x} = \varepsilon_x \frac{\partial^2 c}{\partial x^2} + \varepsilon_y \frac{\partial^2 c}{\partial y^2} \qquad \text{.............}21$$

For 3-D flow it becomes:

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} + w\frac{\partial c}{\partial z} = \frac{\partial}{\partial x}(\varepsilon_x \frac{\partial c}{\partial x}) + \frac{\partial}{\partial y}(\varepsilon_y \frac{\partial c}{\partial y}) + \frac{\partial}{\partial z}(\varepsilon_z \frac{\partial c}{\partial z}) \text{ ....}22$$

6. Mechanisms of Turbulent Diffusion

6.1. Atmospheric Turbulence: Characteristics and causes of turbulence in the atmosphere

Atmospheric turbulence refers to irregular and chaotic changes in the airflow in the Earth's atmosphere [45]. These changes can vary from small localized disturbances to larger atmospheric phenomena, driven by the irregularities in fluid motion, including eddies and swirls of various sizes. These eddies disintegrate and transfer kinetic energy down the scale, ultimately dissipating as heat, this process is known as an energy cascade [46] [47]. Another key characteristic of atmospheric turbulence is intermittency, which is not uniform throughout the atmosphere because pockets of turbulent air are interspersed with relatively calm areas. Velocity fluctuations enhance the mixing of air masses, leading to more efficient transport of heat, momentum, and moisture in the atmosphere. These fluctuations are from rapid changes in wind speed and direction, which act as hallmarks of turbulence[48][49]. Understanding the causes of atmospheric turbulence is essential for predicting its impacts on weather patterns, aviation, and environmental processes as a whole.

6.1.1. Thermal Turbulence (Convective Turbulence)

This type of turbulence is caused by the uneven heating of the Earth's surface, as a result, the ground heats the air above it, the warm air rises and cooler air descends [50], creating convective currents which are common during the daytime over land, especially in sunny conditions [11] [51].

6.1.2. Mechanical Turbulence (Shear Turbulence)

This is caused by the interaction of air with surface features like mountains (Orographic Turbulence), buildings, and trees, or due to wind shear [52] (variations in wind speed and direction with height) which is common near jet streams, fronts, and in the boundary layer [53].

6.1.3. Frontal Turbulence

Is a result where turbulence occurs along weather fronts because of the sharp temperature gradient and wind speed between two air masses [54] [55].

6.1.4. Clear Air Turbulence (CAT)

High-speed winds in the upper atmosphere can interact with slower-moving air, causing turbulence that is not associated with visible clouds or weather systems [56]. Mountain waves are caused by airflow over mountain ranges creating waves in the atmosphere that extend into the upper troposphere and lower stratosphere, leading to CAT [57] [58].

6.1.5. Atmospheric Waves (Rosby Waves)

these are called gravity waves for they are oscillations in the atmosphere that occur when air is displaced vertically and gravity attempts to restore equilibrium and they can break and produce turbulence [59] [60].

7. Introduction to Turbulent Diffusion

Turbulent diffusion is a key process in the mixing and transporting of pollutant masses [61] [62]. Both large and small eddies in the atmosphere play significant roles in mass displacement and disintegration [53], for example when dust is released into the air (mining or construction sites), large eddies transport the dust over a large distances from where it was released but small eddies break the dust into smaller mass concentrations until even mixing is achieved. This mechanism is much more efficient than molecular diffusion, which is a much slower process driven by the random motion of molecules. In the context of turbulent eddies and energy cascades, the enhanced mixing due to diffusion can have both positive and negative impacts, depending on the medium and the type of pollutant involved and convection is among shear dispersion and eddy diffusion which act as influencing mechanisms towards turbulent diffusion. Convection involves the vertical and horizontal transport of pollutants due to convective currents [53], as a result of thermal gradients, then there is advection in turbulent conditions as the process that transports pollutants via bulk motion of the air [63].

8. Mathematical Modeling of Turbulent Diffusion

Turbulent flows are the most common nature of flows in the environment and efforts have been made to develop models to better grasp the concept for analysis and application [64]. One of the most widely used models for predicting pollutant dispersion is the Gaussian Plume Model. This model assumes that pollutant concentration follows a Gaussian distribution, spreading outward from the source[65]. The model incorporates parameters such as wind speed, atmospheric stability, and eddy diffusion coefficients. Secondly, the Turbulent Kinetic Energy (TKE) Model, uses the concept of turbulent kinetic energy to describe the intensity of turbulence by predicting how pollutants will be dispersed by quantifying the energy available for turbulent mixing [64]. Lastly, the Lagrangian Particle Dispersion Models (LPDMs) simulate the paths of individual pollutant particles as they move through a turbulent flow. These models account for the random nature of turbulence by using statistical methods to model the dispersion process[66].

9. Practical Implications

- *Air Quality Management:* Understanding turbulent diffusion is crucial for predicting air pollution levels and implementing effective air quality management strategies. Accurate models enable authorities to issue warnings and implement measures to reduce exposure to harmful pollutants.
- *Environmental Impact Assessments:* Turbulent diffusion models are essential tools in environmental impact assessments, aiding in the prediction of pollutant dispersion from industrial sources, traffic emissions, and accidental releases.
- *Aviation and Urban Planning:* Knowledge of turbulent diffusion is crucial in designing urban layouts to minimize pollution hotspots and in planning flight paths that avoid areas of high turbulence and pollutant concentration.

By understanding the processes and factors that influence turbulent diffusion, scientists and engineers can better predict and mitigate the impacts of air pollution on health and the environment.

Scales of Turbulence

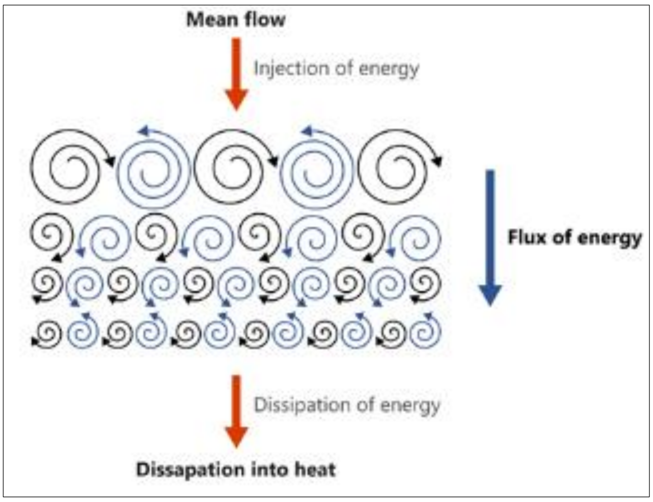

Figure 1 Energy Scale (Altair Engineering)

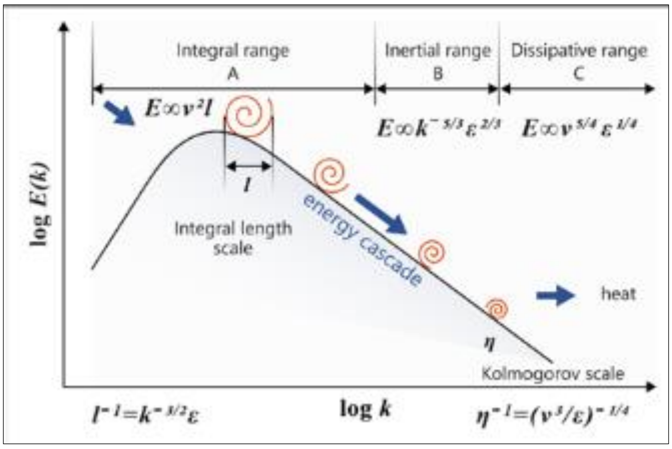

Figure 2 Turbulence Energy Spectrum (Altair Engineering)

To give context in a nutshell, energy cascade is a concept that describes how kinetic energy is transferred from large to small scales in a turbulent flow until it is dissipated as heat and this process is fundamental to understanding turbulent fluid dynamics and is central to many applications in engineering, meteorology, oceanography, and environmental science.

9.1. Large-Scale Energy Input

The process begins with energy being injected into the flow at large scales Fig 1 and Fig 2. These large scales are often associated with external forces or boundary conditions, such as wind blowing over the ocean or air flowing around a building. These large-scale motions are relatively stable and structured.

9.2. Transfer to Smaller Scales (Inertial Range) Fig 2

At the large scales, turbulence causes a breakdown of these structured motions, and the energy begins to cascade down to smaller and smaller scales through a nonlinear process of eddies breaking up into smaller eddies. This range, where energy is transferred without being dissipated, is called the inertial range. In this range, there is no significant loss of energy due to viscosity, instead, energy is transferred between scales[67].

9.3. Kolmogorov's Hypothesis

A fundamental idea in turbulence theory, developed by Andrey Kolmogorov in 1941, is that in the inertial range, the transfer of energy is self-similar and universal, independent of the specific properties of the flow. The energy transfer rate per unit mass (denoted by ε in Fig 2) remains constant across scales within the inertial range. The Kolmogorov scaling laws describe how energy spectrum varies with wave number (k) in this range, following a -5/3 power law[44]:

$$E\ (k) \propto k^{\left(-\frac{5}{3}\right)} \qquad \text{………………..23}$$

9.4. Small-Scale Dissipation

The energy cascade continues until it reaches very small scales where viscous forces become significant. At these small scales, known as the Kolmogorov microscale, the energy is dissipated as heat due to molecular viscosity. This dissipation marks the end of the energy cascade [44], [68].

9.5. Reynolds Number and Turbulence

The energy cascade is directly related to the Reynolds number of the flow, a dimensionless quantity that measures the ratio of inertial forces to viscous forces. High Reynolds numbers correspond to turbulent flows where the energy cascade is most pronounced, and the inertial range is wide[44].

Grand effects of turbulence are recognized on different spatial levels which in turn call for special attention and analysis. These are divided into three categories based on temporal and spatial variances. Characteristically micro-scale turbulence affects areas up to a few hundred meters over a duration that typically lasts for seconds to minutes [69] [70]. It promotes local mixing that enhances the mixing of pollutants close to the ground or their source, making the distribution of pollutants more uniform in a small area. Secondarily it causes rapid and short-term fluctuations in pollutant concentrations, affecting air quality measurements and human exposure at specific locations [71]. Secondly, Meso-Scale Turbulence covers distances from a few kilometers to a few hundred kilometers lasting from minutes to hours e.g. Thunderstorms, sea breezes, and urban heat islands [72]. It is a perpetrator of regional transport where pollutants are transported across cities, regions, or even from rural to urban areas, also comprised of boundary layer mixing responsible for vertical mixing within the atmospheric boundary layer, affecting how pollutants are distributed from the ground up to several kilometers in altitude e.g. pollution plumes. Lastly, Macro-Scale Turbulence affects areas from hundreds to thousands of kilometers over periods of hours to days or even longer [73]. Its impact ranges from long-distance transport, atmospheric mixing, and climate influence.

10. Experimental Methods and Techniques and Instruments for Measuring Turbulent Diffusion

Measuring turbulent diffusion involves a combination of field and laboratory techniques to understand the behavior of fluid particles during the diffusion process[74]. Some field techniques are employed such as tracer gas release experiments which are a direct and effective method for studying turbulent diffusion in the atmosphere (e.g., sulfur hexafluoride, SF6) or particles (e.g., fluorescent particles) into the atmosphere, and their dispersion is tracked using gas analyzers measuring the concentration of tracer gases at various locations or particle counters to detect and count tracer particles [75]. The experiment follows a manageable mechanism of tracer selection in which the gas has to be non-reactive, non-toxic, and mainly detectable at low concentrations [75], and also controlled release from a point source or over a specified area using ground-based sources, aircraft, or balloons, depending on the study requirements. Gas analyzers and LIDAR are employed during monitoring and taking measurements at regular intervals to capture the temporal and spatial distribution of the tracer [76].

Tracer release experiments offer several significant advantages as they provide direct and empirical data, capturing real-world dispersion patterns and turbulence effects with high accuracy. This precision allows for the accurate assessment of how substances disperse under various atmospheric conditions, additionally, the data obtained from these experiments is crucial for validating and refining atmospheric dispersion models, enhancing their predictive capabilities. The versatility of tracer release experiments also makes them adaptable to a wide range of environments and scenarios, from urban settings to remote areas, ensuring their broad applicability [77]. The shortcomings include the selection of an appropriate tracer that is detectable, safe, and representative of the substance being studied, and the logistical complexity of coordinating the release and monitoring over potentially large areas which can be logistically challenging [78].

LIDAR (Light Detection and Ranging) is a versatile remote sensing technology that can indeed be used to measure aspects of turbulent diffusion in the atmosphere but is traditionally known for mapping the Earth's surface [79], its applications extend to atmospheric sciences, including the study of turbulence and diffusion processes [79]. It employs Doppler, scanning LIDAR, and high-resolution profiling which are responsible for measuring the frequency shift of the backscattered laser light caused by the motion of aerosols and particles in the air, scanning to collect data on aerosol concentration and movement, and taking high-resolution vertical profiles of aerosol and particulate matter concentration in the atmosphere. LIDAR is beneficial for high spatial and temporal resolution providing detailed, real-time data on aerosol concentration and wind profiles, remote sensing capability for measuring atmospheric conditions over large areas and at various altitudes without the need for in-situ sensors and thirdly the capability of three-dimensional mapping and visualizations of pollutant dispersion [80]enhancing the understanding of diffusion patterns. Challenges faced are data interpretation, from LIDAR data log requires advanced algorithms and expertise, weather dependency, and costly equipment [80]. Other field experiments used include SODAR (Sound Detection and Ranging) and Drone-based Sampling.

Laboratory Techniques include quite a few ways to measure turbulent diffusion under controlled conditions. Wind tunnels are controlled environments used to study the effects of air moving over or around objects. They are valuable tools for measuring turbulent diffusion, particularly in environmental studies, aerospace engineering, and industrial applications [81]. By simulating atmospheric conditions, wind tunnels allow researchers to observe and analyze the behavior of gases, particles, and other substances under controlled turbulence. Major advantages of using wind tunnels are a controlled environment, precise control over wind speed, direction, and turbulence intensity allowing for repeatable experiments and scalability for experiments which can be scaled down or up, making it feasible to test large-scale phenomena in a laboratory setting, visualization, and realistic simulations with the ability to mimic real-world conditions for accurate and reliable results [81]. Challenges encountered include the complexity of designing experiments that accurately replicate real-world conditions and instrumentation sensitivity as high-precision instruments are required to measure small-scale turbulence and diffusion accurately.

11. Computational Models for Turbulent Air Pollution Diffusion

Computational models are essential tools for predicting and analyzing the dispersion of air pollutants. These models utilize mathematical equations and algorithms to simulate how pollutants move and spread in the atmosphere[82]. There are several types of computational models, each with its approach to handling turbulent diffusion, and here are the three key types: Gaussian plume models, Eulerian models, and Lagrangian models. Gaussian Plume Models are among the simplest and most widely used models for predicting the dispersion of pollutants from point sources, such as smokestacks. They assume a steady-state distribution of pollutants and describe the concentration of pollutants as a Gaussian distribution, which spreads out from the source in a bell-shaped curve. It describes how pollutant concentration decreases with distance from the source, both horizontally and vertically, and Its simplicity sprouts as a result of relatively few input parameters, making it computationally efficient and easy to use, but its Limitations are, less accurate in complex terrains and changing meteorological conditions and assumes pollutants are well-mixed immediately, which may not be true for all sources [83][84]. Secondly, the Eulerian model uses a fixed grid to represent the atmosphere, solving differential equations to describe the concentration of pollutants at each grid point accounting for various atmospheric processes, including advection, diffusion, chemical reactions, and deposition [85]. They are time-dependent and comprehensive, incorporating detailed physical and chemical processes affecting pollutants. However, they are computationally intensive due to the need for high-resolution grids and detailed process descriptions [85]. Lastly, the Lagrangian Models track the paths of individual pollutant particles or air parcels as they move through the atmosphere, using stochastic methods to simulate the random motion of particles due to turbulence[86]. It is ideal for studying short-term, localized pollution events and tracking pollutant dispersion from accidental releases but is computationally demanding, especially for large numbers of particles or long simulation periods, and requires detailed meteorological data and turbulence parameters.

Future Directions

Multiple scholars have highlighted the importance of future research orientation and innovation which is the sole reason for all the scientific progress made thus far. The future directions in studying the turbulent diffusion of air pollutants involve addressing current research gaps, leveraging technological advancements, and fostering interdisciplinary collaboration. One significant area of focus is the integration of machine learning and AI algorithms to analyze large datasets, identify turbulent diffusion patterns, improve model parameterizations, and predict pollutant dispersion under various scenarios [87]. By concentrating on these areas, scientists can enhance their understanding of turbulent diffusion processes, improve predictive models, and develop more effective strategies to mitigate the impacts of air pollution. Another critical need is the detailed characterization of turbulence, particularly in terms of turbulence structure and dynamics[88][89]. Secondly, multi-scale interactions of how small-scale turbulent eddies interact with larger scales can provide insights into the overall diffusion. The future of turbulent pollutant diffusion research and management is poised to benefit from significant technological advancements, computational modeling, policy development, and interdisciplinary collaboration such as holistic studies, conducting comprehensive studies that link pollutant diffusion and dispersion to health outcomes, ecological impacts, and socio-economic factors.

12. Conclusion

Air pollution, exacerbated by industrialization and urbanization, remains a critical global challenge with profound implications for human health, ecosystems, and climate stability. Understanding turbulent diffusion, the complex process through which pollutants disperse in the atmosphere is crucial for accurately predicting and mitigating its impacts. Air pollution consists of various harmful substances emitted from sources like industry and transportation, which can lead to respiratory and cardiovascular diseases in humans and cause significant environmental damage, including ecosystem disruption and climate change. Turbulent diffusion plays a pivotal role in dispersing pollutants over large distances in the atmosphere. This process involves chaotic and irregular air movements that enhance the mixing and dilution of pollutants, thereby influencing their concentration and distribution patterns. Modeling turbulent diffusion poses challenges due to its complex nature governed by intricate mathematical equations and the need for high-quality data on atmospheric conditions and pollutant sources. Accurate modeling of turbulent diffusion is essential for assessing air quality, ensuring regulatory compliance, and developing effective mitigation strategies to reduce adverse health and environmental impacts. Future advancements in sensor technology, remote sensing (like LIDAR), and computational power will enhance the ability to monitor and model turbulent diffusion with greater precision and resolution. The integration of diverse scientific disciplines including atmospheric science, engineering, and health sciences is essential for advancing our understanding of turbulent diffusion and its impacts, thereby facilitating comprehensive and effective solutions. Strengthening air quality regulations based on improved modeling capabilities will help mitigate pollutant dispersion and protect public health and the environment. Advancing our understanding of turbulent pollutant diffusion is not only a scientific endeavor but also a necessity for sustainable development and environmental stewardship. By addressing research gaps, leveraging technological innovations, and fostering interdisciplinary collaborations, we can better predict, manage, and mitigate the impacts of air pollution, safeguarding health and preserving ecosystems for future generations. As we move forward, integrating these efforts will be crucial in creating cleaner, healthier, and more resilient communities worldwide.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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