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EMPLOYING ATMOSPHERIC SENSORS AND TURBULENT ENERGY CASCADE THEORY TO QUANTIFY HAZARDOUS AIRBORNE TRANSMISSIBILITY

BY

ANA CAZACU[1], ILIE BODALE[1] and ALIN IULIAN ROŞU[2,3,*]

[1]“Ion Ionescu de la Brad” University of Agricultural Sciences and Veterinary Medicine,
Department of Exact Sciences, Faculty of Horticulture, Iaşi, Romania
[2]“Alexandru Ioan Cuza” University of Iaşi,
Faculty of Physics, Iaşi, Romania
[3]“Gheorghe Asachi” Technical University of Iaşi,
Department of Physics, Iaşi, Romania

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Abstract. Airborne viruses, bacteria, or toxins are dangerous because of the nature of the human transmission pathway through breathing. However, every airborne component must conform to the laws of physics governing atmospheric propagation. Given the fact that most atmospheric flows, at both ground level and throughout the atmosphere, are highly turbulent, the mechanisms of turbulence can be employed to understand the propagation of such components. In this paper, the problem of harmful airborne pathogen transmission is considered in the context of atmospheric turbulence and wall-bounded flow theory. Two approaches are considered: one of them relies on singular measurements of building boundary distances and morphology, and the other relies on constant temperature measurement. The theoretical and practical potential of these approaches is then discussed and explained in a larger urban context.

Keywords: turbulence; SARS-CoV-2; velocity; temperature.

[*]Corresponding author; *e-mail*: alin.iulian.rosu@gmail.com

1. Introduction

The nature of our urban lives means that most it is spent between at least two walls; thus, the study of bounded atmospheric transport phenomena is of great importance to society, especially in the context of our current pandemic. Airborne viruses, bacteria, or toxins are dangerous because of the nature of the human transmission pathway through breathing – however, every airborne component must conform to the laws of physics governing atmospheric propagation (Drossinos and Stilianakis, 2020). Given the fact that most atmospheric flows, at both-ground level and throughout the atmosphere, are highly turbulent, the mechanisms of turbulence can be employed to understand the propagation of such components (Roșu *et al*., 2020; Roșu *et al*., 2021).

This application can be reduced to two risk-quantifying methods: passive (measuring certain relevant spatial and material characteristics of the environment) and active (monitoring relevant variable atmospheric parameters). Using notions regarding the multifractality of turbulent flow and correlations between turbulent energy dissipation and the initial and minimal turbulent length scales, it is possible to employ a modified version of the standard turbulent β model to calculate various atmospheric parameters (Roșu *et al*., 2021a; Benzi *et al*., 1984). The model is initialized by calculating the inner and outer turbulent length scales using local spatial conditions in the context of wall-bounded turbulence (Roșu *et al*., 2020; Pope, 2001). Finally, ways of integrating these methods in the framework of larger urban settings are discussed.

2. Passive Risk-Quantifying Method

Some past works have been devoted to perfecting a scale progression model of atmospheric turbulence; the fundamental equation derived by this model is:

$$l_n(n) = \frac{{l_1}^n}{{l_0}^{n-1}} = l_0 \left(\frac{l_d}{l_0}\right)^{\left(\frac{n}{n_{l_0}}\right)} \tag{1}$$

where $l_n(n)$ is the turbulent vortex scale at a stage *n* in the turbulent energy cascade, l_0 is the initial scale, l_1 is the immediately preceding scale from the initial one, l_d is the diffusion scale which is also the final scale, and n_{l_0} is the final stage for which $l_n(n_{l_0}) = l_d$ (Roșu *et al*., 2021b). Through many other theoretical considerations, an equation of the average dissipation of turbulent kinetic energy is reached (Roșu *et al*., 2021b):

$$\langle\varepsilon\rangle = \left(\frac{V_d}{l_d}\right) \cdot 2^{-2\left[\frac{\ln(l_d)}{\ln(2)-\ln(l_0)+\ln(l_1)}\right]} \cdot \left(\frac{l_1}{l_0}\right)^{3\left[\frac{\ln(l_0)-\ln(l_d)}{\ln(l_0)-\ln(l_1)}\right]} \tag{2}$$

The dependence of $\langle\varepsilon\rangle$ to the first and final scales is shown in Fig. 1.

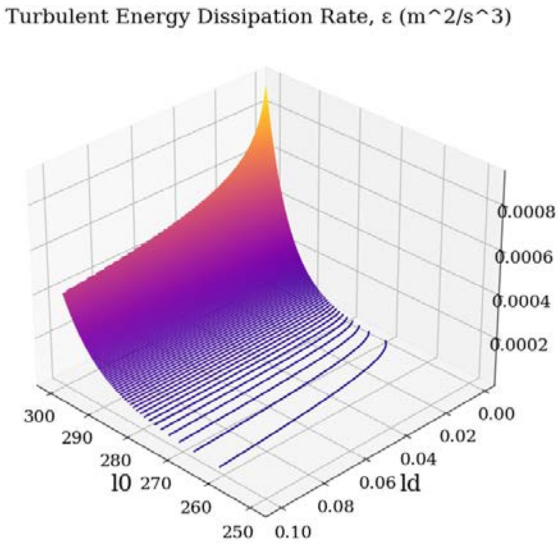

Fig. 1 – Atmospheric turbulent energy dissipation rate ε as a function of a typical set of initial values for the turbulent length scale l_0 and minimal turbulent length scale l_d.

As can be seen, in order to calculate this dissipation, the first, second, and final dissipation scales are needed (Fig. 1) (Roșu *et al.*, 2021a,b). The term V_d is the average velocity of the vortex associated with the dissipation scale and can be theoretically approximated through multifractal considerations (Roșu *et al.*, 2021a,b). Analysis of this equation shows it to be sensitive to variations of the parameter, l_0, but also to l_d (Fig. 1). Indeed, it is only logical for the equation governing mean turbulent diffusion to be sensitive to the diffusion scale. In our last work, a function intersection method was developed so that the need for three initial scales is eliminated; what is instead needed now is l_0 and l_d. Thus, only the initial and final scales are necessary in order to approximate the dissipation of turbulent energy according to a modified β model theory – our past works show promising results in this direction using lidar data (Roșu *et al.*, 2021a,b).

A discussion on the importance of this theory is necessary in the given context. It is crucial to note that the propagation of any harmful airborne corpuscles, from pathogens to terrorist chemical warfare agents, logically and invariably depends on atmospheric mixing determined by dissipation and convection. This is true both in instances of long-distance transport and short-distance homogenization. Thus, it is more than fair to assume that a higher dissipation will result in a greater distribution of potentially harmful airborne agents. Attempting to employ these theories in a practical manner, two approaches can be defined: a passive approach, and an active approach.

The passive approach relies on considering two characteristic spatial dimensions of a wall-bounded region of turbulent flow, wherein l_0 can be approximated as the width of the turbulent corridor and l_d as a characteristic roughness dimension of the walls. This reasoning is performed from a practical perspective; it is impossible for the formed vortices to have a larger characteristic length scale than the distance between the given walls, and solid boundary roughness has been previously used in many similar atmospheric studies (Schlichting and Gersten, 2016). Attempting to more precisely establish l_0 and l_d, the structure of wall-bounded turbulence must be considered. Close to the boundary, there is a viscous layer, followed by a mixed layer which precedes the general turbulent region (Schlichting and Gersten, 2016). The following wall parameter is important in establishing these domains:

$$y^+ = \frac{y u_\tau}{v} \tag{3}$$

where y^+ is the nondimensional wall parameter, y is the distance from the wall, u_τ is the shear velocity, and v is the kinematic viscosity (Schlichting and Gersten, 2016). The wall parameter can also be considered as a "local Reynolds number" (Schlichting and Gersten, 2016). It results that the turbulent layer boundary is found at a critical $y^+ = 11.63$, thus the distance from the wall to this boundary is $y \equiv y_P$ (Molland and Turnock, 2007):

$$y_P = 11.63\left(\frac{v}{u_\tau}\right) \tag{4}$$

Thus, presupposing a region which is bounded by two flat structures or walls found at a distance L from one another, and considering the fact that both walls will present their own viscous layers:

$$l_0 = L - y_{P_1} - y_{P_2} \tag{5}$$

However, in many urban contexts, it is found that many wall-bounded or structure-bounded areas are limited by walls that possess similar or even almost identical morphology:

$$l_0 \cong L - 2y_P = L - 23.26\left(\frac{v}{u_\tau}\right) \tag{6}$$

Now, $\frac{v}{u_\tau}$ must be defined in more comprehensible terms for our theoretical application. With dimensions, the typical law-of-the-wall can be written as:

$$u = \frac{u_\tau}{\varkappa} \ln\left(\frac{y}{y_k}\right) \tag{7}$$

where $\varkappa = 0.14$ is the von Kármán constant, and y_k is a "roughness length" which shows the distance from the turbulent boundary at which $u = 0$ (Schlichting and Gersten, 2016). Logically, it is inferred that if $y = y_k$, the logarithmic term shall yield 0 and the velocity becomes null. It is possible to also define a "roughness height" k_s which is a measure of the surface roughness of the wall itself:

$$y_k = \left(\frac{v}{u_\tau}\right) e^{[-\varkappa C^+({k_s}^+)]} \tag{8}$$

where ${k_s}^+$ is the dimensionless roughness height and $C^+\left({k_s}^+\right)$ is the constant usually found in the non-dimensional version of the law-of-the-wall (Schlichting and Gersten, 2016). This constant is found to be 5 for smooth surfaces and 8 for "fully rough" surfaces (Schlichting and Gersten, 2016). However, it is also found that $C^+\left({k_s}^+\right)$ is not a monotonic function – even in the transition areas between smooth and rough, its value fluctuates between 8 and 9, decreasing semi-linearly towards 5 as smoothness increases (Tani, 1987; Schlichting and Gersten, 2016). Considering the surface imperfections of walls in an urban context, it is then reasonable to state that $C^+\left({k_s}^+\right) = 8$. Thus:

$$y_k = 0.03762 \left(\frac{v}{u_\tau}\right) \tag{9}$$

In "non-hydraulic flow smoothness" conditions, which are almost always the case for atmospheric flows, it is known that $y_k \cong \frac{k_s}{30}$ (Whipple and Kelin, 2004).

Hence, it is possible to approximately define the previously unknown term for our particular case:

$$\frac{v}{u_\tau} \cong \frac{k_s}{1.12885} \tag{10}$$

This can then be replaced to yield:

$$y_P \cong 10.3025 k_s \tag{11}$$

thus:

$$l_0 \cong L - 20.605 k_s \tag{12}$$

Given that k_s is a measure of surface roughness, and the surface imperfections of many urban buildings and walls is of the order of millimeters or centimeters, it is found that $20.605k_s$ is, at most, of the order $\sim 10^{-1}m$ (Schlichting and Gersten, 2016). It is of note that, according to scale inequalities found in previous works, numerical experimentation shows that the model becomes usable for l_0 of the order of tens or hundreds of meters (Roșu *et al.*, 2021a,b). Then, it is reasonable to assume that the model is impractical in the context of building corridors or other small, enclosed spaces. However, because of these theoretical limitations, the quantity $20.605k_s$ is much smaller than acceptable values for L.

Furthermore, in the context of large, both open and closed spaces, the formation of substantial air currents can severely decrease the viscous layer. Finally, it has been argued that the mixed and viscous layers may not exist at all in some of the more extreme rough urban areas – even though y_k is found to increase with roughness, it is possible that extreme roughness produces stresses large enough to completely disrupt the pre-turbulent region (Cheng and Castro, 2002). In fact, this explicitly happens if the roughness elements are large enough that they project out of the viscous layer (Schlichting and Gersten, 2016). Given all these issues, it is plausible to offer the following interpretation:

$$l_0 \cong L, l_d \cong y_k \cong \frac{k_s}{30} \tag{13}$$

Thus, in order to implement the turbulent staging model for wall-bounded turbulence for large distances between wall boundaries, only two spatial measurements are required: the distance between the wall boundaries, and the roughness of the wall boundaries. Given the fact that these measures need to be collected only once, this is the passive application of the theorem, and the atmospheric turbulent dissipation between two walls in the given circumstances is:

$$\langle\varepsilon\rangle(L, k_s) = \left(\frac{30V_d}{k_s}\right) \cdot 2^{-2\left[\frac{\ln(k_s)-3.4011}{\ln(2)-\ln(L)+\ln(l_1)}\right]} \cdot \left(\frac{l_1}{L}\right)^{3\left[\frac{\ln(L)-\ln(k_s)+3.4011}{\ln(L)-\ln(l_1)}\right]} \tag{14}$$

with V_d and l_1 inferred through equations found in our previous works (Roșu *et al.*, 2021a,b).

3. Active Risk-Quantifying Method

From an active perspective, many works have been written on the study of the effect of fluctuating atmospheric parameters on the propagation and transmission of SARS-CoV-2. However, even choosing two rather obvious parameters, temperature and relative humidity, can present many challenges. Various reports have arrived at contradictory conclusions regarding these parameters even when using similar meteorological and epidemic data (Yuan *et al*., 2020). Beyond strictly scientific papers, both a popular University Hospitals article and a ScienceDaily article agree, for example, that low humidity leads to higher risk of infection (UH Hospital Article, 2020; ScienceDaily Article, 2020). However, a well-cited recent paper has shown that the infection spreading distance increases significantly in cool and humid climates (Zhao *et al*., 2020); confusingly, a different study finds significant correlation between higher temperatures and higher humidity and an increase in infectivity (Wang *et al*., 2021). Meanwhile, one of the most influential recent studies on the subject arrives to the conclusion that temperature and humidity are negatively correlated to the virus transmission – and, interestingly, that PM2.5 air pollution is positively correlated (Lolli *et al*., 2020).

At this point, it is important to reiterate what is certainly known about SARS-CoV-2 transmission: it is mainly transmitted via respiration through inhalation of infected droplets and particles (Greenhalgh *et al*., 2021). Also, infection can occur over small, but also large distances (Greenhalgh *et al*., 2021); it also appears to be the case that particles with a larger mass travel less (Greenhalgh *et al*., 2021; Zhao *et al*., 2020). Then, it is possible to formulate the following statement: there is no simple relation between temperature, relative humidity, and transmissivity; however, there are "critical values" for which transmission can occur most efficiently. It seems that these values fluctuate around what is found in relatively dry and temperate climates – it is possible that in very dry air the droplets dissipate and evaporate rapidly, and in very humid air droplets are blocked, reaching a "critical humid mass" wherein it is impossible for the virus to propagate itself efficiently. It is unclear whether or not very humid atmospheric flows, or even flows that manifest fog or mist, are restrictive to SARS-CoV-2 transmission – some limited research has been done, instead, on the risk of misting disinfecting systems. Also, it has been found that artificial fog of the type commonly used in many social activities does not appear to increase transmission risk – this might be because the fog is usually formed through dry ice compounds, or through glycol or glycerin compounds.

In any case, the following proposal is given: a different physical quantity can be calculated and employed in order to approximately and qualitatively predict transmission risk in an atmospheric turbulent flow; furthermore, this quantity can also be used to explain the complicated relations between transmissibility, temperature and relative humidity. This quantity is the Nusselt number, which is defined as the ratio between convective heat transfer and conductive heat transfer. In our application, which is the evaporation of spherical liquid droplets in air, the following equation is commonly used:

$$Nu = 2 + 0.4Re^{\frac{1}{2}}Pr^{\frac{1}{3}} \tag{15}$$

wherein Re is the Reynolds number, and Pr is the Prandtl number (McAllister *et al*., 2011). While Re can be obtained with the following common approximation:

$$Re \cong \left(\frac{l_0}{l_d}\right)^{\frac{4}{3}} \tag{16}$$

there are many ways to describe the Prandtl number strictly as a function of temperature – many of these ways are based upon approximating functions from real data sets. For standard atmospheric pressure and temperatures (Travis and Piccioni Koch, 2015; Kays and Crawford, 1993):

$$Pr \cong 0.84725 - 6.65 \cdot 10^{-4}T + 7 \cdot 10^{-7}T^2 \tag{17}$$

Given this equation, it is then possible to estimate the droplet Nusselt number in a given wall-bounded atmospheric turbulent flow region:

$$Nu \cong 0.00355 \left(\frac{l_0}{l_d}\right)^{\frac{2}{3}} [(T - 950)T + 1.21036 \cdot 10^6]^{\frac{1}{3}} \tag{18}$$

Since this term of the equation usually is of the order of hundreds with normal temperatures and our given scale conditions, the number 2 has been dropped from the original equation. A larger Nusselt number corresponds to more active convection, with turbulent flow typically in the hundreds to thousands range, thus we must assume that the approximation holds very well (White, 1984).

The Nusselt number is correlated with the occurrence of mist, and also with the diameter of the droplets – it is specifically found that there exist, in the context of heat transfer, optimal mist droplet diameters that yield high Nusselt numbers (Alhajeri *et al*., 2019; Ye *et al*., 2019). It is possible that this non-monotonic relation between droplet diameter and heat transfer is what has produced confusion and incertitude regarding the relation between temperature, humidity and transmissivity. It is also found that there might be an inverse relationship between mist temperature and the Nusselt number – this would appear to confirm the fact that higher transmissivity arises from lower temperatures (Ye *et al*., 2019).

4. Conclusion

In conclusion, it is possible to mitigate potential episodes of SARS-CoV-2 high transmissibility simply by passively measuring certain distances and roughness parameters and actively measuring air temperature. These principles and measurements can then be extended to a larger urban setting. From a passive perspective, a green city with increased vegetation and buildings composed of smooth boundaries and materials with high radiative reflectivity is ideal. Vegetation represents soft boundaries that attenuate turbulent flows, that normalize temperature and humidity, and that improve urban air quality; then, while it has been presented in this work why smooth building boundaries might be beneficial, materials with high radiative reflectivity would result in lower heat flux from the surface, which would then produce less convection. From an active perspective, the addition of city-wide temperature sensors might be beneficial. This would help predict high transmissibility events by approximately calculating the Nusselt number using the previously-mentioned passive method and temperature measurements.

It must be highlighted that, in order for Nusselt number calculations to be performed, it might be unfeasible to employ anything other than a full network of temperature sensors for a given wall-bounded region. The thermal law-of-the-wall cannot be used properly in this context, since some of its considerations require that both boundaries have the same temperature, which might be unrealistic. Furthermore, the law is much more applicable for flows with low Prandtl numbers, which is also disputable given the fact that the model may only function with flow boundaries separated by large distances.

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UTILIZAREA SENZORILOR ATMOSFERICI ȘI A TEORIEI TURBULENȚEI PENTRU A CUANTIFICA TRANSMISIVITATEA PATOGENILOR ATMOSFERICI

(Rezumat)

Virușii, bacteriile sau toxinele transmise pe cale aeriană sunt periculoase din cauza naturii căii de transmitere umane prin respirație. Cu toate acestea, fiecare componentă aeriană trebuie să fie conformă cu legile fizicii care guvernează propagarea atmosferică. Având în vedere faptul că majoritatea fluxurilor atmosferice, atât la nivelul solului, cât și în întreaga atmosferă, sunt extrem de turbulente, mecanismele turbulenței pot fi utilizate pentru a înțelege propagarea unor astfel de componente. În acest articol, este analizată problema transmisiei patogenilor în contextul turbulenței atmosferice și a curgerilor atmosferice mărginite de domenii solide. Două abordări sunt luate în considerare: prima se bazează pe măsurători singulare ale distanțelor și morfologia pereților urbani, iar a doua se bazează pe măsurarea temperaturii. Potențialul practic și teoretic al acestor abordări este ulterior analizat și explicat într-un context urban major.