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Respiratory pandemic and indoor aeraulics of classrooms

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**Abstract**

Respiratory pandemics, such as COVID19, may be transmitted by several modes. The present work focuses on the transmission through small droplets released by people from their mouth by breathing, speaking, coughing, sneezing, and possibly aspirated by other people around through their respiration. An analysis of droplet evolution in simplified situations shows that the droplets reach very quickly a quasi-equilibrium temperature before encompassing an isothermal evaporation process. The removal of droplets from suspension is thus piloted by balance between evaporation and sedimentation. It is shown that ambient relative humidity is a major factor influencing the lifetime of droplets and the distance they may travel. As a consequence, and independently of any other health consideration linked to ambient humidity, it is seen that a dry air is a favourable factor for limiting risk of contamination from COVID19.

Further investigation is made using computational fluid dynamics (CFD) in a classroom geometry. Several ventilation strategies are investigated: classical regulatory mechanical ventilation, open window natural ventilation and displacement natural ventilation. Ventilation has several effects which influence contamination risk: by introducing fresh air, it reduces droplet concentration; humidity released by human occupants is also limited. However, these effects are not uniform in space, and depend on ventilation strategy. Application of a dose–effect model calibrated for COVID19 to CFD results allows to estimate contamination risk. It is shown that contamination risk is higher for regulatory mechanical ventilation, and may be reduced, using natural ventilation in the absence of wind, by a factor 2.3 to nearly 3 when the teacher is sick, and by a factor 6 to 500 when a student is sick. In the presence of wind, the reduction factor is as high as 13 when the teacher is sick and 17 when a student is sick.

**1. Introduction**

Since the apparition of COVID19 at the end of year 2019, massive efforts have been made to understand better transmission modes causing the contamination. After collection of field evidence (e.g. [1–4]), it became apparent that airborne transmission cannot be neglected, and may even be a major vector of contamination (see for example [5–8]). This leads to very practical implications on the minimal distancing rule for people outdoor and indoor (see [9]).

The airborne contamination process consists of first the expulsion of contaminated droplets by a sick person, through breathing, speaking, coughing or sneezing; then the transport of these droplets in the ambient air; and finally the absorption of these droplet by other, possibly non-sick, people. When this occurs indoors, ventilation of the room where the people are present is obviously a key parameter of contamination. The transport of droplets in ambient air is determined by the initial momentum of the droplets, advection by ambient air, and settling under the influence of gravity. Each of these terms has a weight which depends on the mass of the particle. While being transported, droplets also evaporate, leading to a further complication in the process. The seminal work on this subject was done by [10], see the review work of [11], and also [12]. The main finding of these studies is the so-called Wells evaporation–falling curve, showing the competition between two effects, the evaporation and the arrival on the ground (see figure 1 of [12]). The extension of the model done by [12] takes into account the so-called mouth-jet, in which the air velocity and relative humidity are different from ambient.

The main limitation of the Wells-style approach is obviously its inability to take into account the actual airflow in the room and the ventilation and air removal system. Indeed, rooms may be ventilated according to different modes. Natural ventilation corresponds to situations where the air removal is performed through opening, without the help of mechanical devices. These openings may be open windows or doors, or specific devices. Through a window or a door, air may either enter and exit from a single opening (leading to an exchange flow).
When openings are specifically made at both the lower and upper part of the room, it promotes the natural stratification of heated air inside the building, called displacement ventilation (see for example [13–18]). Alternatively, mechanical ventilation may be used. Until recently, in most countries, mechanical ventilation has been based on entrance of air through openings (usually located around the windows), and mechanical withdrawal (usually located near the ceiling, for practical reasons), in a system called “simple-flux”. Volume conservation forces the extracted air to drive the arrival of fresh air. These systems are now superseded by double-flux systems, which allow for heat recovery at the cost of mechanising both air removal and intake through specially designed heat exchangers [19]. For practical reasons, heat exchangers are usually located above a false-ceiling, and thus ventilation openings are located underneath this ceiling. Depending on countries and types of buildings, the volume flux of air to extract is given by standards or regulations. For example, for school buildings (high schools and universities) in France, specific regulations demand a total fresh air inflow of 18 m³ per student and per hour (see [20] and references therein). For a typical class of 30 students, this leads to 0.55 m³/s.

To take into account the effect of ventilation systems on droplet motion in our context, the main tool is computational fluid mechanics (CFD). There has been a lot of work on CFD in the context of indoor air quality, see for example [21,22]. However, very few software include the ability to model evaporating droplets, and even less have been thoroughly validated. The Fire Dynamics Simulator (FDS) from the National Institute of Standards and Technology is one of these (see [23,24]) and we decided to use it for our study. A similar choice has been made by [25,26].

Once a contaminated droplet concentration has been estimated at the level of the mouth of non-previously contaminated people (so-called “target” people), the final step is to estimate the actual contamination risk. There are several models in the literature, see for example [27–29]. Various research groups have done a huge work to adapt these models to COVID19 pandemic, as [30]. This work is used for our study. However, as there are still many unknowns on COVID19 contamination risk, a relative approach was chosen: a contamination risk is computed for a reference configuration, and the results for other configurations are presented relative to this reference. As this will be discussed, this allows comparison of ventilation strategy even when the contamination model is not very accurate due to the emergence of variants of the virus.

The layout of the present paper follows the evolution of droplets, from their emission by a sick person, to the possible contamination of “target” persons. In Section 2 we discuss droplet characteristics at emission. Then, in Section 3, we work on evaporation–advection of droplet in simplified ambient, leading to an adapted version of the Wells [10] model. This allows to identify relevant physical mechanisms in action through time-scale analysis, and to point the large influence of background relative humidity. This section is concluded by discussions on relevant levels of approximation, including the influence of breathing jet. Section 4 concentrates on modelling droplet transport in realistic classrooms using very large eddy simulation (VLES). First, possible ventilation strategies are exposed and the associated parameters are set; then the VLES tool is presented, together with verification and validation process. The hypotheses made to mimic breathing are exposed. Once droplet are transported, they may reach “target” people, and participate to their contamination. Section 5 introduces a statistical model for contamination risk. Fig. 1 sketches the articulation of Sections 2 to 5. Section 6 presents and discusses the main findings of the study, and Section 7 is the conclusion.

2. Droplet emission characteristics

Determining the size distribution of emitted droplet is not an easy task. Several studies have been made, sometimes contradictory between each other (see [31–33]). The paper [33] makes a review of available data, taking into account 15 detailed experimental studies (see references therein). This shows a large dispersion of data. Part of this dispersion comes from the mode of expulsion (speaking, sneezing, coughing), gender, age, general health of the individuals, dots. Their own experimental work is concentrated on sneezing, with two possible distribution patterns. For some subjects, the distribution is unimodal and is well modelled with a lognormal distribution, with droplet diameter peak at about 500 μm (see their figure 2). In the second case, a bimodal distribution is observed, with a first peak centred on a diameter of 100 μm and a second peak centred on a diameter of around 500 μm (see their figure 3). For both case, they provide a best fit analytical formulation of these distributions (their equations 3.1 and 3.2). From their literature review, one can estimate that normal breathing releases very small droplets (less than 1 μm), cough and speech release medium range particles (1 to 100 μm), and in general around 50 μm), and sneeze the largest droplets with the 500 μm peak mentioned above. A complementary question is to quantify the presence of pathogens in the droplets, see [34]. This reference shows that it is not true to assume that large droplets are more susceptible to contain a load of pathogens able to contaminate. As a consequence, it does make sense, when working on infection by droplets, to consider the distribution of the number of particles and not with the mass. The conversion can be done using equations 3.1 and 3.2 of [33], and it appears that for both mass-distributions, the number-distribution becomes unimodal, with peak respectively at 400 and 80 μm. With such a range of possible droplet sizes, it is not realistic to perform brute force computational fluid dynamics for all values of parameter. It is necessary first to gain understanding of typical time of flight of particles depending to their size, to reduce the scope of investigation. The Wells model presented now offers this possibility.

3. Transport of droplets, evaporation and sedimentation

3.1. Evaporation–advection equations

The Wells model, introduced by [10], considers an isolated droplet of water in still ambient air. The location of the droplet is denoted \( \xi \) and its velocity \( v_e \), so that, with time \( t \), the kinematic equation for this droplet is

\[
\frac{d\xi}{dt} = v_e. \tag{1}
\]

The velocity field of air is \( u(\xi) \), air temperature is \( T_a \) and water partial vapour pressure in air \( s \rho_v \), both are supposed to be uniform out of a thin boundary layer around the droplet. The droplet is supposed to exchange heat, water and momentum with air. The radius of the droplet \( r \) is supposed to be less than 1 mm, so that, for velocities differences
smaller than 1 m/s, the droplet Reynolds number is less than 100 and the flow around the droplet is laminar.

Following [35], exchange of water vapour and of heat in the vicinity of the drop are supposed to be purely diffusive, leading to Maxwell model, with the evolution of the mass $m$ for droplet of temperature $T$ given by

$$\frac{dm}{dt} = -4\pi DM \rho_u T^3 \left( r_p(T) - r_i \right)$$  \hspace{1cm} (2)

where $D$ is the coefficient of diffusion of vapour in air, $M$ is the molar mass of water, $R$ is ideal gas constant and $p_i(T)$ is the saturation vapour pressure at droplet temperature. Similarly, evolution of droplet temperature is given by

$$\frac{dT}{dt} = -\frac{3\lambda}{C_{pm}\rho_u r^2} \left( T - T_a \right) + \frac{L_v}{mc_{pm}} \frac{dm}{dt}$$  \hspace{1cm} (3)

Here, $\lambda$ is air thermal conductivity, $C_{pm}$ liquid water specific heat, $\rho_u$ density of liquid water, $L_v$ water evaporation latent heat, and radiative exchange of heat are neglected owing to the smallness of Stefan–Boltzmann constant. Momentum equation is simply Newton law with gravity and drag:

$$\frac{d\vec{v}}{dt} = -\frac{g + 1}{m} \vec{F}_D$$  \hspace{1cm} (4)

with the drag force $\vec{F}_D$ is given by Stokes law for small Reynolds number, see [36]:

$$\vec{F}_D = -6\pi \rho_u v_u K r (\vec{u} - \vec{v})$$  \hspace{1cm} (5)

Here, $\rho_u$ is air density, $v_u$ is air kinematic viscosity, and $K$ is a corrective coefficient taking into account the fact that the dynamic viscosity of water is not infinitely large compared with the dynamic viscosity of air, the possible presence of surfactants in the droplet, and interaction between droplets if the droplet density is too high, see [36]. In our context of highly dilute suspension and water dynamic viscosity of order one hundred times air dynamic viscosity, we take $K = 1$ as a first approximation. In the momentum equation thermophoresis and Saffman forces are neglected due to the assumption of still ambient air. More generally, it is legitimate to neglect these forces in the absence of large temperature and velocity gradients, as those which could occur in boundary layers, but are not relevant in room ventilation due to the small temperature and velocity differences (see [37–39]). Note that the same argument applies to Brownian motion for its component linked to variations in background temperature and velocity, while the average effect of uniform background Brownian effect is zero (see [36]).

It is convenient to introduce the characteristic time scales associated with droplet radius, temperature, phase change and velocity evolution (we note $p_{sa} = p_s(T_a)$):

$$\tau_r = \frac{p_{sa}RT_{sa}^2}{\rho_w} \ , \ \tau_\theta = \frac{p_{sa}C_{pu}T_{sa}}{\lambda} \ , \ \tau_L = \frac{\rho_w C_{pu}T_{sa}}{3DP_{sa}} \ , \ \tau_T = \frac{RT_{sa}}{L_vM}$$  \hspace{1cm} (6)

Eqs. (2) to (5) may now be reformulated in non dimensional form, with $\tau = r/\tau_r$, $r_0$ being the initial radius of the droplet, $\theta = T/T_a$ and $\vec{u} = u/\tau_u$, $v_0 = 2gr_T^2/(\rho_u g)$ being the free fall velocity of a droplet of radius $r_0$, leading to

$$\frac{dr}{d\tau} = \frac{1}{\tau_r} \left( \frac{p_s(\theta) - p_i}{p_{sa}} \right)$$  \hspace{1cm} (7)

$$\frac{d\theta}{d\tau} = -\frac{1}{\tau_r} (\theta - 1) - \frac{1}{\tau_L} \frac{p_s(\theta) - p_i}{p_{sa}}$$  \hspace{1cm} (8)

$$\frac{dv}{d\tau} = \frac{p_{sa} \vec{v}}{\rho_w} - \frac{1}{\tau_T} (\vec{u} - \vec{v})$$  \hspace{1cm} (9)

To close the equations, we need the evolution of saturation vapour pressure with temperature, which is given by Clausius–Clapeyron formula with reference temperature $T_s$ (see thermodynamics reference textbooks, e.g. [40]):

$$p_s(\theta) = p_{sa} \exp \left( \frac{L_v M}{RT_s} \left( 1 - \frac{1}{\theta} \right) \right)$$  \hspace{1cm} (10)

Depending on ambient conditions, Eqs. (7) to (10) may lead to droplet to grow, to reach a steady state or to evaporate in finite time. This last possibility is the most generic for ambient partial vapour pressure smaller than its saturation value, in which case a steady state will not exist.

### 3.2. Analysis of time scales

The four time constant defined in Eq. (6) are all proportional to $r_0^2$, and using the numerical values of Table 1, we can compute the ratios of time scales relative to the time scale of radius evolution $\tau_r$, leading to $\tau_\theta = 0.026$, $\tau_L = 0.18$ and $\tau_T = 0.0055$. Thus the slowest process is radius evolution, meaning that droplets reach a quasi-equilibrium in terms of temperature and fall velocity fast relative to the evaporation. As a consequence, at first approximation, the left-hand side of Eqs. (8) and (9) may be set to zero, leading, for order of time between $\tau_\theta/40$ and $\tau_L$, to a fixed value $\theta_0$ for temperature and simple dependence of velocity with of $\theta(\tau)$:

$$\left( \theta_0 - 1 \right) + \frac{r_0}{\tau_L} \left( \frac{p_s(\theta_0) - p_i}{p_{sa}} \right) = 0$$  \hspace{1cm} (11)

$$\vec{u} = \vec{u}_0 + \frac{mC_{pmL_v}(\theta)^2}{\rho_u} \tau_T$$  \hspace{1cm} (12)

It is now possible to be more precise than this simple order of magnitude estimation by computing the actual value of $\theta_0$ as function of ambient relative humidity $\phi_a = p_a/p_{sa}$ from Eqs. (10) and (11), in the form of an inverse function:

$$\phi_a = \frac{\tau_L}{r_0} \left( \theta_0 - 1 \right) + \exp \left[ \frac{L_v M}{RT_s} \left( 1 - \frac{1}{\theta_0} \right) \right]$$  \hspace{1cm} (13)

Fig. 2 gives the evolution of $\theta_0$ as function of relative humidity. As expected, $\theta_0$ is always less than one, since evaporation takes energy out of the droplet, and its value is one for a relative humidity $\phi_a = 1$ which prevents evaporation. The maximal temperature reduction is for zero relative humidity, with $\theta_0 \approx 0.945$. Then, injecting $\theta \approx \theta_0$ into Eq. (7), we get:

$$\vec{v} = \sqrt{\frac{1 - 2 \left( \frac{p_s(\theta)}{p_{sa}} \right) - p_i}{2 \frac{p_s(\theta)}{p_{sa}}}}$$  \hspace{1cm} (14)

showing that the droplet disappears by evaporation in a finite time given by

$$t = \frac{1}{2} \frac{p_{sa}}{p_i} \tau_r$$  \hspace{1cm} (15)

Note that is similar to the so-called $r$-square law in the constant temperature analysis (e.g. [35]). Using eq (13), this gives the value of evaporation time as function of ambient relative humidity $\phi_a$.

This analysis puts an order of magnitude on the upper limit for the existence of droplets in suspension in air. However, it does not give the actual lifetime of droplets, since evaporation process competes with sedimentation, in which droplets leave the suspension state by impacting on the ground. Typical time-scale for impacting on the ground, assuming the droplets emitted horizontally from height $h$ (typically the
Here, we used, from Eq. (11),
\[ \frac{\rho_a(\theta_j) - \rho_v}{\rho_{sa}} = \frac{r_L}{r_0} (1 - \theta_j). \]

Fig. 3 gives the lifetime of droplets as function of background relative humidity for initial radius 25 and 250 μm.

Furthermore, the longest lived droplets correspond to initial radius \( r_{0\text{max}} \) given by equating both terms in Eq. (17):

\[ \frac{1}{2} \frac{\rho_{sa}}{\rho_a(\theta_j) - \rho_v} r_j = r_s \]

leading to

\[ r_{0\text{max}} = r_{00} \cdot (1 - \theta_j)^{1/4} \quad \text{with} \quad r_{00} = \left( \frac{9 g v_w h}{8 \rho_{w} L_c} \right)^{1/4} \]

and the associated maximal residence time is given both by Eqs. (15) and (16)

\[ t_m = \frac{1}{2} \frac{\rho_{sa}}{\rho_a(\theta_j) - \rho_v} r_j = \frac{9 g v_w h}{2 g r_{00}^2} \]

Using the second expression, this is

\[ t_m = \left( \frac{9 g v_w \rho_v L_c}{4 g} \right)^{1/2} (1 - \theta_j)^{-1/2} \]

with as before \( \theta_j \) given as function of \( \phi_a \) by inversion of Eq. (13). Figs. 3 and 4 give the evolution of \( t_m \) and \( r_{0\text{max}} \) as function of background relative humidity \( \phi_a = \rho_i/\rho_{sa} \), with numerical values of constants given in Table 1 and \( h = 2 \) m. On Fig. 3, the solid line represents the lifetime of droplet of optimal size for maximal lifetime, as given on Fig. 4. Other curves correspond to a fixed value of the initial size (see caption). Due to the competition between evaporation and sedimentation, two regimes are found for the curve with initial radius 200 μm: below a given level of relative humidity, which depends on droplet size, the removal of droplets is due to evaporation and above it, it is due to sedimentation. It can be seen that for radius smaller than about 150 μm, the removal regime is mainly evaporation. Thus, in high relative humidity, the maximal lifetime on droplets can be much more than 15 min.

### 3.3. Levels of approximation

Several approximations were made in the above paragraphs. Strictly speaking, Eqs. (2) to (5) are valid only for small Reynolds number. However, when the Reynolds number is less than 100, the correction factor are not large. Moreover, as we have seen, the terminal droplet velocity of the droplet is reached very quickly and in this situation the Reynolds number is much smaller. An extra simplification is made in Eq. (2) by neglecting the laminar flow induced by evaporation itself, the so-called Stefan flow, see for example [35,41]. The presence of dissolved species in the droplet, which may modify the thermodynamics of water, is also neglected, as well as the variation of physical quantity of air as function of humidity. It was nevertheless decided in this section to accept all these assumptions to keep the model simple and easily understandable. The correction would indeed be small and would not affect orders of magnitudes of time-life and distance reached by the droplet, in particular with regard to the very crude assumptions on the flow carrying the droplets. In Section 4, on the other hand, using a numerical tool, these assumptions are not made.
3.4. Taking into account breathing

So far, we assumed a zero background velocity and uniform background temperature and relative humidity. This is obviously not the case in real situations. The particles are expelled from the mouth of the sick person in the breathing jet. A simplified description of the effect of this jet is possible. The breathing jet may be simulated as a turbulent jet starting at the mouth with expelled air velocity \( u_e \), temperature \( T_e > T_a \) and relative humidity \( \phi_e > \phi_a \). Ambient air is entrained into the jet, leading to a continuous decrease of velocity, temperature difference and water vapour partial pressure proportional to the inverse of the distance to the mouth, possibly corrected with a virtual origin compensation (see [42,43]). In this situation, the droplet first evolves inside the jet, where it may or not evaporate, and then if not evaporated yet, leaves the jet due to sedimentation, and then may evaporate or reach the ground. Fig. 5 gives the lifetime and distances reached by droplets calculated from our model as function of initial diameter and ambient relative humidity. Equations cannot be integrated analytically, and numerical integration with order 4 Runge-Kutta method was performed. The results are not absolutely intuitive compared with the uniform background humidity case, as relative humidity decreases from large values to the background one when following droplet from emission to out of the jet. The work of [12] is a further effort in using a more precise jet model than the one we used, at the cost of complexity, in order to take into account buoyancy effects influence on plume trajectory. Still more refined jet models may be found in [44] to take into the cross flow and in [45] to take into account alternating jet caused by inspiration and expiration. The limitations of this approach nevertheless are twofold: (1) there is a temptation to refine more and more the jet model, thus losing the elegant simplicity of the analysis; but (2) it will never be able to take into account all the flow physics in a room, leading to doubts on the quantitative results no matter how far the model has been refined. It was therefore decided to turn to numerical simulations to get insight of droplet evolution in realistic situations.

4. Evolution of a group of droplets using very large eddy simulation

4.1. Ventilation strategies for a classroom

We concentrate on the case of a classroom with one teacher and 28 students of adult corpulence. The classroom is 7.2 m wide and 8.2 m long, with a ceiling height of 2.5 m. It is equipped with 2 doors of surface 1.4 m\(^2\) each, one leading to the corridor and one to an adjacent classroom, and 2 windows of surface 2.25 m\(^2\) each, see Fig. 6.

Several ventilation strategies are considered: (1) the regulatory mechanical ventilation with injection and withdrawal of 0.15 m\(^3\)/s as explained in the introduction, with two intake and to extraction points located on the ceiling; (2) natural ventilation through open windows; (3) natural ventilation by displacement.

Generally speaking, one should note that strategies (1) and (2) tend to promote mixing in the room, while strategy (3) is based in thermal stratification of air in the room with a lower layer of fresh air and an upper layer of warmer air. In this case, the sizes of the lower and higher openings determine the height of each layer. The are generally chosen so that the fresh air layer extend up to above the head of people in the room. Opening area for to this purpose are given by [18] (their Eq. (11)). When applying this equation in our case, with 29 occupants, a ceiling height 2.5 m and an fresh layer height 2 m, the effective opening area for has to of order 8 m\(^2\) for each of the lower and higher opening, and thus a geometrical opening area of 10 to 12 m\(^2\). This is not realistic for purely geometrical reason, and we decided to take a surface of the same order as the surface of case (2), i.e. lower and upper opening of areas 2.25 m\(^2\) each. From [18], Eq. (1), this corresponds to a fresh layer height of 1.3 m to 1.5 m depending on pressure drop coefficients through the opening. Furthermore, [46] shows that diffusion tends to blur the interface into an intermediate transition layer. They give estimates of thickness of this transition layer. For the situation of the present paper, this thickness is more than 10%–20% of the room height, showing that in any case, for such low-ceiling rooms, it is likely that people will have their heads in the transition layer.

The reference case is mechanical ventilation with all doors and windows closed (strategy 1 in above classification). We also considered the possibility of opening doors or windows in the mechanical ventilation configuration. We also considered as a sensibility study the possibility of a 2 m/s wind perpendicular to the windows.

4.2. Very large eddy simulation using FDS

The classroom is simulated using the software FDS developed by NIST [23]. FDS is a three-dimensional computational fluid mechanics code, explicit in time and finite-volume on structured mesh in space [23]. The pressure solver is based on fast Fourier transform inversion. Heat exchange and variation of air temperature are taken into account in the model, allowing realistic and well validated stratified and buoyant flow configurations [23]. Turbulence is modelled according to a Large Eddy Simulation strategy using a Smagorinski or a Deardorff subgrid model. The droplets are modelled using a Lagrangian
technique, where a subset of droplets are followed explicitly by the code, see explanations in chapter 8 of [23]. This is well validated for realistic simulation of droplets advected in a flow [24].

Verification and validation of the model can be summarised as a three stage process: the first step is verification and validation according to standards [47–49]. The second step is internal validation on complex experimentally documented reference cases by the team practising the simulation, this is [24,50]. The third stage is to perform a thorough review and sensitivity analysis (including mesh convergence) for the specific case under consideration. Validation process showed that the code is very effective when used in a Very Large Eddy Simulation configuration, i.e. when the filter length of the submodel, which coincide with meshsize, is not well in the inertial range of turbulence, allowing relatively coarse grids.

For the present study, we used uniform hexaedic cells of lateral dimension 10 cm, and grid convergence was checked by making a simulation with 5 cm lateral dimension cells. Heat is released by each human being by convection, at a rate of 100 W, see [51,52]. Breathing is mimicked by alternating expiration and inspiration at the mouth of each human being, with care taken to ensure that there is no synchronisation of the respiration. Temperature and relative humidity of expelled air are 33 °C and 100%, as in [12]. Concerning droplet emission, injection diameter is 38 μm. This was decided as a compromise from Fig. 5 showing that the droplets the more likely to travel far from their ejection are of radius of order 20 μm, and experimental data collected by [33] which advocate an order of size around 50 μm for speech and cough.

The boundary conditions are applied directly on the windows and doors if they are open and there is no wind taken into a account. In case of wind, a dozen of cells are modelled out of the room to allow for the establishment of the flow. The relative humidity initially in the classroom and of incoming fresh air is set at 40%. Ambient temperature of air is 20 °C. Walls, floor and ceiling are assumed to be at ambient temperature, and there is no lighting system. The results are delivered by the model in terms temperature, velocity and humidity fields, and also in terms of number of droplets and mass of droplet inhaled by "target" people.

5. Assessment of contamination risk

As stated in the introduction, [27–29] suggest various models for virus contamination risk, and [30] did work to adapt these models to COVID19 pandemic. The simplest model is the exponential model [28]

\[ P(d) = 1 - \exp \left( -\frac{d}{k} \right) \]  

(22)

where \( P(d) \) is the probability of being infected with a given dose \( d \) and \( k \) a parameter dependent on the disease (both expressed in terms of number of pathogen agents absorbed by the "target" individual). The dose \( d \) is the total amount of pathogen agents inhaled in a reference time. This model has been refined by [27,28] to take into account the effect of droplet size distribution, however, the more refined a model is, the less robust, and the more data it needs for validation. As a general rule of thumb, such an empirical model with \( n \) parameters needs of order \( 10^n \) data based on clinical evidence, and owing to the short time since the appearance of COVID19, it would not be realistic to take a model with too many parameter. In this optics, after early work on SARS by [29] showing that the single parameter exponential model was performing well, specific work on COVID19 by [30] showed its adaptation to the present context and was able to estimate the value of parameter \( k \) for the variants of COVID19 known at the time of its work in the range \( 6.4 \cdot 10^{-3} \cdot 9.8 \cdot 10^3 \) with the most likely value \( 1.6 \cdot 10^5 \). For our work we took the worst case value \( 6.4 \cdot 10^4 \).

To compute the dose \( d \) we follow [30] who suggest to take a viral load for sick people at \( 10^6 \) to \( 10^8 \) per millilitre of expectorated droplet. There are irreducible uncertainties in this value because the load depends on sick individuals and on the phase of the disease, see [53]. Here we retain the upper value. Since droplets are partially evaporated when they reach the "target" individuals, the concentration of pathogens has increased, and we correct for this effect by computing the actual mass of the droplet, knowing its initial mass.

The application of the dose–effect model together with FDS simulation allows to compute, in a given geometry and ventilation configuration, for a given exposure time, the probability for one "target" individual, to get the disease. This probability is function of the room geometry and configuration, denoted by the letter \( C \), of the location in the room \( x \) (this is cause by the overall flow), of exposure time \( t \), of the viral load of the infected person \( v \), and of parameter \( k \):

\[ P = P(C, x, t, v, k) = 1 - \exp \left( -\frac{d(C, x, t, v)}{k} \right) \]  

(23)

In a steady regime (which is reached quickly after the beginning of the simulation), doubling the exposure time is similar to doubling the viral load of the infected person or dividing by two parameter \( k \):

\[ d(2t, v)/k = d(t, 2v)/k = 2 \cdot d(t, v)/k. \]

It follows that \( P(C, x, 2t, v, k) = 1 - \exp \left( -\frac{2d(C, x, t, v)}{k} \right) \approx 2P(C, x, t, v, k) \) as long as \( d(C, x, t, v)/k \ll 1 \) i.e. the probability is small. This means that, within this small probability assumption, and although the phenomenon is highly non linear, there is partial linearity with respect to viral load \( v \) and parameter \( k \) which are the two most uncertain parameters. This allows to use ratio of probabilities to compare ventilation strategies by taking the ratio of probability in the studied configuration to the probability in the reference configuration, uncertainties on \( v \) and \( k \) are in a way cancelled in this limit of small probabilities.

6. Results and discussion

Results of the models for all studied configurations are given in Table 2. Two situations are considered: the case when the teacher is sick and the case where it is one of the students. In this case, the
result is given as an average of all possible student being sick. In Table 2, the results are given in absolute values $P$ and in terms of relative risk. Relative risk is given by the ratio of the value of $P$ in a given situation to the value of $P$ for a reference simulation. Two reference simulations, indicated in Table 2 by symbols (*) and (**) are respectively for the sick teacher situation and for the sick student situation, both with regulatory mechanical ventilation. These results may also be interpreted in terms of risk reduction coefficients, which are the inverse of relative risk coefficients. Thus, contamination risk is higher for regulatory mechanical ventilation, and may be reduced, using natural ventilation in the absence of wind, by a factor 2.3 to nearly 3 when the teacher is sick, and by a factor 6 to 500 when a student is sick. In the presence of wind, the reduction factor is as high as 13 when the teacher is sick and 17 when a student is sick.

This reduction in risk is due to two factors. The first one is the augmented ventilation rate, leading to a lower droplet concentration. The second one is the reduction of ambient relative humidity. Indeed, as seen in Section 3, decreasing relative humidity sharply reduces the lifetime of droplets in uniform ambient (see the dashed curve on Fig. 3) and also when breathing jet is modelled (see Fig. 5). Indeed, analysis of CFD results shows that natural ventilation leads to a much lower average ambient humidity compared with mechanical ventilation. The simulations were made using an incoming air of relative humidity 40% and temperature 20$^\circ$C. This is representative of European climate in late spring and early summer. These conclusions will still hold in colder temperature, since by heating the incoming air its relative humidity would be decreased. They could be questioned in hot humid climate.

### Table 2

| Sick person | Configuration | $P$  | Rel. risk coef. |
|-------------|---------------|------|-----------------|
| Teacher     | Mechanical, all doors closed (*) | 14.5 | 1               |
| Teacher     | Mechanical, open door next to the teacher | 14.3 | 0.99            |
| Teacher     | Mechanical, open door at the back of the room | 11.6 | 0.8             |
| Teacher     | Open windows, closed doors, no wind | 4.9  | 0.34            |
| Teacher     | Open windows, open doors, wind | 1.1  | 0.07            |
| Teacher     | Open windows, closed doors, wind | 7.0  | 0.48            |
| Teacher     | Displacement natural ventilation, no wind | 6.4  | 0.44            |
| Student     | Mechanical, all doors closed (**) | 8.7  | 1               |
| Student     | Mechanical, one open door next to the teacher | 2.4  | 0.27            |
| Student     | Open windows, open doors, wind | 0.5  | 0.06            |
| Student     | Open windows, open doors, no wind | 1.4  | 0.16            |
| Student     | Displacement natural ventilation, no wind | 0.015 | 0.002        |

### 7. Conclusion

The present work focused on airborne transmission of COVID19 through droplets in suspension, with the application to classroom aerodynamics in minds. After a review of droplet characteristics at emission, an analysis of droplet evolution in simplified situations showed that the droplets reach very quickly a quasi-equilibrium temperature before encompassing an isothermal evaporation process. The removal of droplets from suspension is piloted by the balance between evaporation and sedimentation. It was shown that ambient relative humidity is a major factor influencing lifetime of droplets and the distance they may travel. As a consequence, and independently of any other health consideration linked to ambient humidity, it is seen that a dry air is a favourable factor for limiting risk of contamination from COVID19.

A further investigation was made using CFD code FDS, chosen because it is able to cope with temperature, humidity and droplet evolution. Several ventilation strategies were investigated: classical regulatory mechanical ventilation, open window natural ventilation and displacement natural ventilation. Ventilation has several effect which influence contamination risk: by introducing fresh air, droplet concentration is reduced; humidity released by human occupants is also limited; when considering mechanical ventilation, air is mixed, whereas when considering displacement ventilation, a cleaner layer is located at the bottom of the room. However, in the present case, this cleaner layer is to low to be realistically in the zone used by occupants to breathe.

Application of a dose–effect model calibrated for COVID19 allowed to estimate relative contamination risk for several configurations. It was shown that natural ventilation solutions performs better than mechanical.

The main conclusion of this study is that regulatory mechanical ventilation is the least effective strategy to reduce the risk of indoor contamination. It also shows that the situation where the teacher is sick brings a higher risk than the case when it is the students. This is mainly because the teacher always faces students in our configurations. However, this must be tempered by the fact that one student out of 28 is sick has a much higher probability than the fact that the teacher is sick. Opening the windows brings a major improvement in all situations, and displacement ventilation appears to be the most effective strategy when there is no wind in the sick student configuration, leading to a risk reduction which reaches a factor 500.

The limitations of this work pave the way for further investigation. Beyond the limitations already discussed in the paper, we would like to stress three points. (1) This work was done assuming no face mask is worn, and this has a positive effect on limiting contamination risk. (2) The hypothesis was made that once all water has disappeared from the droplets, the remaining virus particles are deactivated and may not be reactivated; discussion of this hypothesis is out of the scope of the present paper and demand full research on its own. (3) We considered a 20$^\circ$C external temperature. In this case, natural ventilation (either through open windows or with displacement ventilation) does not generate any difficulty. This would not be the case with colder external temperature, with the possible need to pre-heat incoming air, leading to an excessive energy consumption.

### CRediT authorship contribution statement

P. Carlotti: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualisation. B. Massoulié: Investigation, Formal analysis. A. Morez: Visualisation, Software, Investigation. A. Villaret: Visualisation, Software, Investigation. L. Jing: Investigation. T. Vrignaud: Visualisation, Software, Investigation. A. Pfister: Validation, Supervision, Methodology.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Acknowledgements

The authors would like to thank Prof. Jean-Marc Chomaz from Ecole Polytechnique, and the organisers of IAFSS 2021 special session on COVID19, Profs. Arnaud Trouvé from University of Maryland and Ken Matsuyama from Tokyo University of Science for fruitful discussions during this session.

### References

[1] J. Lu, J. Gu, K. Li, C. Xu, W. Su, Z. Lai, D. Zhou, C. Yu, B. Xu, Z. Yang, COVID-19 outbreak associated with air conditioning in restaurant, Guangzhou, China, 2020, Emerg. Infect. Diseases 26 (7) (2020) 1628–1631, http://dx.doi.org/10.3201/eid2607.200764.
