

Journal Pre-proof

The mechanical effect of moisturization on airborne COVID-19 transmission and its potential use as control technique

Francisco J. Arias, Salvador De Las Heras



PII: S0013-9351(21)00234-6

DOI: <https://doi.org/10.1016/j.envres.2021.110940>

Reference: YENRS 110940

To appear in: *Environmental Research*

Received Date: 20 October 2020

Revised Date: 19 February 2021

Accepted Date: 22 February 2021

Please cite this article as: Arias, F.J., De Las Heras, S., The mechanical effect of moisturization on airborne COVID-19 transmission and its potential use as control technique, *Environmental Research*, <https://doi.org/10.1016/j.envres.2021.110940>.

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2021 Elsevier Inc. All rights reserved.

The mechanical effect of moisturization on airborne COVID-19 transmission and its potential use as control technique.

Francisco J. Arias^a and Salvador De Las Heras^{a*}

^a Department of Fluid Mechanics, Polytechnic University of Catalonia, ESEIAAT C/ Colom 11, 08222 Barcelona, Spain

* Corresponding author: Tel.: +93 73 98 666 francisco.javier.arias@upc.edu

Mounting evidence from scientific community seems to suggest that COVID-19 virus can potentially spread by airborne transmission. As a result, methods and techniques for preventing environmental contagious, such as ventilation or air filtration have been proposed. Here, it is investigated the effect of moisturization on airborne COVID-19 transmission from a mechanical point of view in which comparatively large water droplets promote the growth -by collision and coalescence, of suspended airborne COVID-19 and then accelerating its gravitational settling. Utilizing a classical raindrop collisional model from cloud science and the available experimental data an expression for the removal time of suspended airborne COVID-19 as function of the relative humidity was derived. The mechanical model is in good agreement with the recent reported experimental research in which high temperature and high relative humidity reduce COVID-19 contagious and then is a point in favor of the mechanic model of the effect of moisture in the COVID-19 airborne transmission. The results encourage further research on the deliberate moisturization of room air (by using ceiling mounted humidifiers) as a potential technique for control of airborne COVID-19 transmission.

Keywords. Airborne COVID-19; Airborne transmission; Moisturization.

1. INTRODUCTION

Until not long ago it was believed that COVID-19 -henceforth covid, spread from person-to-person mostly through respiratory droplets with diameters larger than $5\mu\text{m}$ produced when an infected person coughs or sneezes, (Li et al; 2019). However, mounting evidence seems to suggest that covid can potentially spread by airborne transmission, i.e., via microscopic particles ($\leq 5\mu\text{m}$) which are small enough to stay suspended in the air for hours, (Domingo et al., 2020; Morawska et al., 2020; Wilson et al., 2020; Tropea et al., 2007; WHO 2020; Bontempi, 2020; Jayaweera et al., 2020.), and as a result, methods and techniques for preventing airborne transmission, such as ventilation, (Bhagat, 2020) or air filtration, (Zhao et al., 2020) have been explored.

The object of this work was to analyze a new approach, namely the deliberate moisturization of air (by using humidifiers) in order to promote the growth of suspended airborne covid -by collision and coalescence with water drops, and then accelerating its gravitational settling. In the next sections and utilizing a raindrop collisional model used in meteorology science together with available experimental data the efficiency of this approach is investigated. At this point, it interesting to see that actually it has been demonstrated that the relative humidity of environment reduces the spread of the virus but the reasons either biological or mechanical behind are still unclear. The proposed model confirm that, at least from a mechanical point of view, relative humidity reduces the spread of the virus.

FIG. I. Air flow around a falling particle. Only the air in innermost streamline collides with the particle, the rest goes around it. Credit. Lamb and Verlind, 2011.

FIG. II. Field of the collisional efficiency ϵ for drops of radius R with droplets of radius r from Rogers, 1976, and derived from data from Mason 1971 .

2. MATERIALS AND METHODS

2.1 Raindrop Collisional Model

Let us consider the mechanistic model used in cloud physics in which raindrops falling from the sky are growing during their path by a collisional process with other tiny drops encountered during the downward travel, (Rogers, 1976). The raindrop collisional model is based in the calculation of an effective collisional cross section as sketched in Fig. 1, in which a falling drop (the collector drop) will only collide with a second stationary drop (the collected drop) if this drop is inside of a certain area which is less than the geometric area because the air streamlines bowing out around the collector drop carry the smaller drops with them around the drop, and then the effective cross-section becomes less than the actual cross-section. For small travel distances it is allowable to neglect evaporation and growth of the collector drop owing to the environment humidity as well, the validity of this assumption is demonstrated in the appendix. The raindrop collision efficiency, ϵ , is defined as, (Rogers, 1976)

$$\epsilon = \frac{x_o^2}{(R + r_d)^2} \quad (1)$$

where R and r_d are the radius of the collector and collected drop, respectively, and x_o is the critical value of the impact parameter within which a collision is certain to occur and outside of which the droplet will be deflected out of the path of the drop (see Fig. 1). The *collection* efficiency, would be the product of collision efficiency times coalescence efficiency, however, when the collected drops are smaller than $100 \mu\text{m}$ it is usually assumed that the coalescence efficiency is unity, and then the collection efficiency is identical to the collision efficiency, (Rogers, 1976). Mathematically the collisional cross section σ_c is given by

$$\sigma_c = \pi x_o^2 \quad (2)$$

which considering Eq.(1) becomes

$$\sigma_c = \epsilon \pi R^2 \left[1 + \frac{r_d}{R}\right]^2 \quad (3)$$

FIG. III. Absorption time τ as a function of the relative humidity h for collector drops of $300 \mu\text{m}$ and airborne particles of $5 \mu\text{m}$ and $2 \mu\text{m}$ and a temperature of 20°C .

2.2 Collection rate

Once defined the cross section of collision, Eq.(3), it is possible to infer the rate of collection. Because for contagious what seems relevant is if a given water drop is contaminated and it makes no difference whether if inside the drop there is only one or many viruses then for first estimation we can assume that all the virus inside a drop can be considered as a single virus. Then if the cloud formed by the waters drops coming from an infected person are all contaminated by using the diffusion equation we have

$$\frac{dn_c}{dt} = -n_c \sigma_c \phi_R \quad (4)$$

where $\frac{dn_c}{dt}$ is the absorption rate per unit of volume and time of particles of covid, n_c the concentration per volume of particles of covid suspended in the air; and ϕ_R is the flux of water

(collector) drops per unit of area and time.

The flux ϕ_R can be reckoned considering the expression

$$\phi_R = N_R u_t \quad (5)$$

where N_R is the concentration per unit of volume of the collector water drops; and u_t is the approaching velocity which is equal to the gravitational terminal velocity (see Fig. 1). The concentration of water drops suspended in air can be measured by the relative humidity h of the environment according with the following equation, derived in Appendix.

$$N_R = \frac{3fh}{4\pi R^3 \rho} \quad (6)$$

where f is a function of temperature. Taking into account Eq.(6), Eq.(5) becomes

$$\phi_R = \frac{3fhu_t}{4\pi R^3 \rho} \quad (7)$$

Inserting Eq.(7) and Eq.(3) into Eq.(4) one obtains

$$\frac{dn_c}{dt} = -\frac{n_c}{\tau} \quad (8)$$

where an absorption time, τ , was defined as

$$\begin{aligned} \tau &= \frac{1}{\sigma_c \phi_R} ; \\ &= \frac{4\rho R}{3\epsilon fhu_t} \left[1 + \frac{r_d}{R}\right]^{-2} \end{aligned} \quad (9)$$

Solving Eq.(8) yields

$$n_c = n_{co} e^{-\frac{t}{\tau}} \quad (10)$$

where n_{co} is the initial concentration of suspended particles of covid at time $t = 0$.

FIG. IV. Absorption time τ as a function of the relative humidity h for collector drops of $300\mu\text{ m}$ and airborne particles of $5\mu\text{ m}$ and $2\mu\text{ m}$ and a temperature of 5°C .

Figure 2 shows the field of the collisional efficiency ϵ for drops of radius R with droplets of radius r from Rogers, 1976 and derived from data from Mason, 1971. In this figure it is easy to see that the efficiency for collection of airborne covid (particles with radius around $5\mu\text{ m}$ or less) may be a 70% at most for very coarse atomization with droplets with radius around $1000\mu\text{ m}$. However, such a coarse atomization (with radius of the droplet similar than that observed in rain droplets) would be unpractical, and a value between semi-fine to semi-coarse atomization around $300\mu\text{ m}$ seems tolerable, and then a maximum upper limit of the efficiency of collection would be around a 40% . Finally, we can asses the efficiency in the control of covid by the deliberate moisturization of the air as follows.

3. RESULTS

3.1 Control of a suspended cloud

We assume that a cloud of covid is already suspended in the air, and then the water drops generated by the humidifiers located at the top of the building are approaching the cloud with a velocity u_t which is equal than the terminal velocity of the water drop. For spherical drops with radius R a density ρ much more larger than the air density ρ_a , i.e., $\rho \gg \rho_a$ -and then neglecting buoyancy, the terminal velocity is given by

$$u_t = \sqrt{\frac{8\rho g R}{3\rho_a c_d}} \quad (11)$$

where g is gravity and c_d is the drag coefficient (approximately close to 0.4 for spheres). Thus, inserting Eq.(11) into Eq.(9) we have

$$\tau = \frac{2}{3\epsilon f h} \sqrt{\frac{3\rho_a \rho c_d R}{2g}} \left[1 + \frac{r_d}{R}\right]^{-2} \quad (12)$$

To obtain some idea of the effectiveness of collection which is given by the absorption time τ predicted by Eq.(12), we assume some values of the parameters: a Drop radius of $R = 300\mu\text{ m}$; covid airborne particles of $r_d = 5\mu\text{ m}$; $r_d = 2\mu\text{ m}$ and with collection efficiencies $\epsilon = 55\%$ and $\epsilon = 10\%$, respectively, derived from Fig. 2; $g = 9.8\text{ m/s}^2$; $\rho = 10^3\text{ kg/m}^3$; $\rho_a = 1.22\text{ kg/m}^3$; $c_d = 0.4$. The resulting curves are shown in Fig. 3 and Fig. 4 for temperatures of 20°C and 5°C , respectively. It is seen that for relative humidities between 30-70% -where humans can be comfortable, the absorption time can be reduced to a few seconds. Contrariwise, for dry air the time in which the covid can be stay suspended in air is in the order of hours. In the same figures, by comparison, it is seen that an increase in the temperature translates into a decrease of the absorption time, i.e., into an increase of the accelerated settling. This results is in good agreement with recent investigation which conclude that high temperature and high relative humidity reduce covid cases, deaths and improve recovery, (Sarkodie and Owusu, 2020; Azuma et al., 2020).

Finally, because the simultaneous dependence of the airborne transmission in temperature and relative humidity, its seems more suitable the use of absolute humidity H rather than relative humidity h . Fig. 5 shows the absorption time τ as a function of the absolute humidity H for collector drops of $300\mu\text{ m}$ and airborne collected particles of $5\mu\text{ m}$ and $2\mu\text{ m}$; and Fig. 6 shows the absolute humidity H as function of temperature for several values of relative humidity h .

FIG. V. Absorption time τ as a function of the absolute humidity H for collector drops of $300\mu\text{ m}$ and airborne particles of $5\mu\text{ m}$ and $2\mu\text{ m}$ and a temperature of 20°C .

3.2 Biological effects

Although the scope of the present work is strictly restricted to the mechanical effect of moisturization on airborne covid and its possible use as technique for control in which microscopic water drops are deliberately used to sweep up suspended covid, nonetheless, it is worthy to mention, at least, some recent studies on the virus stability under different environmental conditions including relatively or absolute humidity. The interested reader is referred to Carducci et al., 2020, who recently reviewed survival experiments on corona viruses (and their surrogates), air monitoring and epidemiological-air flow model studies. In those experiments interesting results were obtained by Prussin et al., 2018, who demonstrated that the relation between survival and relative humidity shows a typical U-shaped curve: the coronavirus surrogate survived better at high ($> 85\%$) and low ($< 60\%$) humidity, with a significant decrease in infectivity at middle range of relative humidity (60% to 85%). Then, the effect of humidity is not the same for all viruses, for example H1N1 survival was higher at 70% relative

humidity compared with lower relative humidity values (Doremalen et al., 2013; Peng and Jimenez, 2020).

3.3 Floor water puddle

Continuous moisturization, i.e., continuous injection of water into the environment may not be the most efficient strategy and a better approach could be by using intermittent discharges of moisturization. Such discharges could be performed in a similar fashion than commercial electric air fresheners and controlled either by continuous monitoring and surveillance of the air or by fixed intervals of time.

For continuous monitoring and surveillance the discharges can be performed when a certain critical threshold signal is attained in the environment. The trigger signal can be, for example, a given critical level of CO_2 in the room, where it has been recently investigated that the amount of CO_2 could be a suitable indicator for quantification of the amount of air exhaled by other persons and then is also a measure of the risk for contagious of covid, [1]. For example, the normal amount of CO_2 in a open space is around 400 ppm, however, inside of rooms if the CO_2 level recorded by a monitor is around 800 ppm that means that approximately the 1% of the air we are breathing is for a second time. So, discharges of moisturization could be programmed when the level of CO_2 are so high that the no fresh air overcome, say, 1000 ppm. The duration of the discharge should be in the order of the absorption time τ given by Eq.(9).

However, environmental moisturization also can be performed by fixed intervals of time exactly as electric air fresheners are used in homes and buildings. For this last case, it is interesting to estimate the minimum time permissible between discharges which is mainly determined by the evaporation rate of the micro puddle of water formed in the floor if any removal system is used to prevent its formation. Indeed, because we are working with collector droplets with sizes between semi-fine to semi-coarse atomization, i.e., radius between 100 to 300 μm , they will settle down on the floor and then a water puddle will be formed as pictorially depicted in Fig. 7. Therefore, the time between discharges must be large enough in order to allow that such a water puddle be able to evaporate, of course, if any removal system is used. This natural evaporation occurs as fog and mist droplets with varying diameter of between 10-15 micron and then may be removed with ease by the weak currents of air near to surface. The time of evaporation of the water puddle is controlled by surface tension of the water and the contact angle with the floor surface and can be calculated as follows.

FIG. VI. Absolute humidity H as function of temperature for several values of relative humidity h .

FIG. VII. Physical model of horizontal puddle formation and evaporation.

First, inasmuch that water drops are settling on the floor a puddle is formed and spread only to the point where a maximum thickness is attained which is determined by the surface tension of water γ and the contact angle θ of the drop with the soil. The thickness of the puddle is given by, (Pierre-Gilles et al.,2002),

$$\delta_p = \sqrt{\frac{2\gamma(1 - \cos\theta)}{\rho g}} \quad (13)$$

The above formula predicts that the evaporative time of the puddle could be reduced by controlling the contact angle θ , which is a parameter which can be controlled by suitable selection of the material covering the soil. For the sake of illustration, most of the floors are composed by ceramics which usually varies from $\theta = 10^\circ$ to 60° , (Watanabe, 2009), and then with a surface tension around $\gamma = 70$ mN/m, we obtain thickness between 0.4 mm to 2 mm. However, the floor could be deliberately covered with a super-hydrophilic material which can reduce the contact angle around

$\theta = 10^\circ$ resulting into a puddle thickness around 0.2 mm. On the other hand, the characteristic time for evaporation of this puddle can be estimated by a balance of mass in the puddle. Let us consider a large puddle with a height δ_p and surface area A_p as depicted in the model, Fig. 7. If the puddle is large enough the mass of water m_p of the puddle is approximated as

$$m_p \approx \delta_p A_p \rho \quad (14)$$

On the other hand, if E_m is the evaporation i.e., the loss of water per unit of time and unit of surface (in units of $\text{kg}/(\text{m}^2 \text{ s})$), then the rate of change of mass of the puddle is given by

$$\frac{dm_p}{dt} = -E_m A_p \quad (15)$$

inserting Eq.(14) into Eq.(15) and after integration one obtains

$$m_p = m_{p0} e^{-\frac{t}{\tau_e}} \quad (16)$$

where an evaporative characteristic time τ_e , was defined as

$$\tau_e = \frac{\rho \delta_p}{E_m} \quad (17)$$

which after inserting Eq.(13) becomes

$$\tau_e = \frac{1}{E_m} \sqrt{\frac{2\rho\gamma(1-\cos\theta)}{g}} \quad (18)$$

Many semiempirical formulations for the evaporation from an open water surface are available in the literature, one of them is the well-known Penman equation, (Penman, 1948), or the simplest adaptation due to Shuttleworth, 1993, but just for the sake of illustration, from experimental data from undisturbed water pools for an air temperature around 20°C , and relative humidity around 37% could be around $8 \times 10^{-5} \text{ kg}/\text{m}^2 \text{ s}$, (Shah, 2012), and then with a $\delta_p \approx 0.2 \text{ mm}$ we obtain a characteristic time of evaporation around $\tau_e \approx 40 \text{ mins}$.

Therefore, if the time for discharges must be reduced below it would necessary strategies or systems to prevent the growth of the water puddle. Those strategies already exist and are well known, e.g., the use of chemical absorbent such as charcoal, road salt, etc... Finally, an alternative approach is the use of humidifier-desiccant dehumidifier closed cycle in which the humidity is collected at the bottom of the building then filtered through a desiccant unit and after that being re-humidified, pumped and re-injected in the ceiling of the building (e.g., using classical rotating drum dehumidifier). This last option not only will prevent the formation of the water puddle but also will allow the continuous moisturization of the environment for covid control.

4. SUMMARY OF RESULTS AND CONCLUSIONS

In this work a study on the effect of moisturization of room air on airborne COVID-19 transmission from a mechanical point of view was performed. Some interesting conclusions are resulting by this study as follows:

(a) An analytical expression, Eq.(12), is derived which predicts the absorption time of airborne covid-19 as function of temperature, relative humidity and the size of water drops.

- (b) For the range of relative humidities comfortable for human standards the absorption time of airborne covid could be reduced to a few seconds.
- (c) The predictions of the mechanical model agree with reported data in which it was found that high temperature and high relative humidity reduce covid cases, deaths and improve recovery.
- (d) It seems that a better parameter for assessment is the absolute humidity rather than relative humidity.
- (e) The results seem to indicate that the deliberate moisturization of room air (by using ceiling mounted humidifiers) could be a potential technique for control of airborne covid transmission.

5. APPENDIX

5.1 Derivation of the drop concentration as function of relative humidity

The absolute humidity is given by the mass of the water divided by the volume of the air and water vapor mixture

$$H = \frac{m_{H_2O}}{V} \quad (19)$$

considering spherical drops of water with radii R , mass $\frac{4\pi R^3}{3}\rho$ being ρ the density of water, then

Eq.(19) can be rewritten as function of the concentration of particles of water N_R as

$$H = \frac{4}{3}\pi R^3 \rho N_R \quad (20)$$

and then

$$N_R = \frac{3H}{4\pi R^3 \rho} \quad (21)$$

on the other hand, the absolute humidity H can be expressed as function of the relative humidity h , expressed in % as

$$H \text{ (kg / m}^3\text{)} = fh \quad (22)$$

where f is a function of temperature T and is given by

$$f \text{ (kg / m}^3\text{)} = \frac{6.112 \times 18.02 e^{\left(\frac{17.67T}{T+243}\right)}}{(273.15+T) \times 100000 \times 0.08314} \quad (23)$$

where T is expressed in degrees Celsius. Thus, Eq.(21) yields

$$N_R = \frac{3fh}{4\pi R^3 \rho} \quad (24)$$

5.2 Derivation of the effect of local humidity

In previous sections the effect of the local humidity on the collector drop during its gravitational falling was neglected and then a certain justification is required. The local humidity effect is manifested in two ways which are counteracting each other, namely. First there will be a trend for reduction of the size of the collector drop because the losses owing to surface evaporation, and second, there will be an opposite trend for increasing its size owing to the collisions and coalescence

with other drops. Nevertheless, although this effect must be taken into consideration for traveling long distances, however, for distances around 2 meters or 5 meters (the height of the room) the flight time is in the order of a few seconds and then evaporation and growth of the droplet is insignificant. According with the well-known Maxwell's equation for diffusive evaporation of drops, (Fuchs, 1959; Duguid, 1941, the evaporation rate controlled by diffusion is given by

$$\frac{d(R^2)}{dt} = -\frac{2D}{\rho}(H_s - H_\infty) \quad (25)$$

where R is the radius of the drop; t is time; D the diffusion coefficient; H_s the saturation concentration; H_∞ the surrounding concentration. After integration yields

$$R = R_o \sqrt{1 - \frac{2D}{\rho R_o^2}(H_s - H_\infty)t} \quad (26)$$

If it is assumed that the vapor obeys the ideal gas law, $H_s \approx \frac{p_s M}{r_g T}$, where, p_s is the saturation vapor pressure of the evaporating substance, M is the molecular weight, r_g is the gas constant, and T is the absolute temperature, then Eq.(26) may be rewritten as:

$$R = R_o \sqrt{1 - \frac{2D p_s M}{\rho R_o^2 r_g T} \left(1 - \frac{H_\infty}{H_s}\right) t} \quad (27)$$

where R_o is the initial radius of the drop, i.e., at $t = 0$. Therefore, the maximum upper limit of evaporation rate is obtained when $H_\infty = 0$ and thus Eq.(27) becomes

$$\frac{R}{R_o} = \sqrt{1 - \frac{2D p_s M}{\rho R_o^2 r_g T} t} \quad (28)$$

On the other hand the growth rate of a collector drop owing to the collision with the surrounding drops which are much smaller than the collectors drop, -as is our case of study, is approximately given by, (Rogers, 1976)

$$\frac{dR}{dt} \approx \frac{\bar{\epsilon} H_\infty u_t}{4\rho} \quad (29)$$

where $\bar{\epsilon}$ is an effective average value of collection efficiency for the droplet population. Assuming a constant approaching terminal velocity, u_t , after integration of Eq.(29) yields

$$\frac{R}{R_o} = 1 + \frac{\bar{\epsilon} H_\infty u_t}{4\rho R_o} t \quad (30)$$

inserting the terminal, approaching velocity given by Eq.(11) becomes

FIG. VIII. Variation of the collector radius considering evaporation (red) and growth (blue) for a collector drop with initial radius R_o during flight time t .

$$\frac{R}{R_o} = 1 + \frac{\bar{\epsilon} H_\infty}{2} \sqrt{\frac{2g}{3\rho\rho_a R_o c_d}} \cdot t \quad (31)$$

To obtain some idea of the comparative growth and evaporation rate of the collector drop predicted by Eq.(28) and Eq.(31), respectively., we assume some typical values of the parameters: a vapor

diffusion coefficient $D = 2.9 \times 10^{-5} \text{ m}^2/\text{s}$, (Chen et al, 2018); $M = 1.8 \times 10^{-2} \text{ kg/mol}$; $r_g = 8.3 \text{ J/(K mol)}$; $g = 9.8 \text{ m/s}^2$; $\rho = 10^3 \text{ kg/m}^3$; $\rho_a = 1.22 \text{ kg/m}^3$ and $c_d = 0.4$ and $p_s = 2.0 \text{ kPa}$ for a room temperature $T = 291 \text{ K}$, with an absolute humidity $H_\infty = 5.5 \times 10^{-3} \text{ kg/m}^3$ corresponding with a relative humidity of $h \approx 35\%$ and a conservative low effective average value of collection efficiency $\bar{\epsilon} \approx 0.1$. The resulting curves are shown in Fig. 8. It is seen, that if one considers typical terminal velocities from Eq.(11) around $\approx 4 \text{ m/s}$ or thereabouts, for drops with $300 \mu\text{m}$ of radius, then with realistic ceiling levels of the room, say, 3 meters as best, the falling time will be less than one second, which according with Fig. 8 the effect of evaporation and growth is definitively negligible.

NOMENCLATURE

A_p = puddle surface area
 c_d = drag coefficient
 D = diffusion constant
 E = evaporation
 f = parameter given by Eq.(23)
 g = gravity
 h = relative humidity expressed in %
 H = absolute humidity
 m_{h_2o} = mass of water in a parcel of air
 M = molecular weight
 n_c = concentration of covid per volume
 n_{co} = concentration initial of covid per volume
 N_R = concentration of water drops
 p = pressure
 r_d = radius of the collected drop containing the covid
 r_g = gas constant
 R = radius of the collector drop
 t = time
 T = temperature
 u_t = approaching, terminal velocity
 V = volume of a parcel of air
 x_o = critical value of the impact parameter

Greek symbols

δ = puddle thickness
 ϵ = collision efficiency
 ϕ = flux of water drops
 γ = surface tension
 λ_c = length path of covid particles
 ρ = density of water
 ρ_a = density of air
 σ_c = collisional cross section

τ = absorption time
 τ = evaporation time
 θ = contact angle

subscripts

d = covid airborne particle
 o = reference value, initial
 p = puddle
 s = saturation
 ∞ = surrounding,

ACKNOWLEDGEMENTS

This research was supported by the Spanish Ministry of Economy and Competitiveness under fellowship grant Ramon y Cajal: RYC-2013-13459.

6. REFERENCES

- Li H; Liu S.M; Yu X.H; Tanga S.L; Tang C.K. 2020. Coronavirus disease 2019 (covid-19): current status and future perspective. *International Journal of Antimicrobial Agents*. in press
- Domingo J.L; Marquès M; Rovira J. 2020. Influence of airborne transmission of SARS-CoV-2 on covid-19 pandemic. A review, *Environmental Research*, Volume 188, 109861
- Morawska L; Milton D.K. 2020. It is time to address airborne transmission of covid-19. *Clin Infect Dis*2020;ciaa939.
- Wilson N.M; Norton A; Young F.P; Collins D.W. 2020. Airborne transmission of severe acute respiratory syndrome coronavirus-2 to healthcare workers: a narrative review. *Anaesthesia*. 75 (8). 1086-1095.
- Tropea C; Yarin A; Foss J. 2007. *Springer Handbook of Experimental Fluid Mechanics*. Springer. ISBN 978-3-540-25141-5.
- World Health Organisation. 2020. Scientific brief. Transmission of SARS-CoV-2: implications for infection prevention precautions.
- Bontempi E; 2020. First data analysis about possible covid-19 virus airborne diffusion due to air particulate matter (PM): The case of Lombardy (Italy), *Environmental Research*, Volume 186, 109639
- Jayaweera M; Perera H; Gunawardana B; Manatunge J. 2020. Transmission of covid-19 virus by droplets and aerosols: A critical review on the unresolved dichotomy, *Environmental Research*, Volume 188, 109819
- Bhagat R.K; Wykes M.S; Dalziel, S.B & Linden, P. 2020. Effects of ventilation on the indoor spread of covid-19. *Journal of Fluid Mechanics*, 903, F1.
- Zhao B, Liu Y, Chen C. 2020. Air purifiers: A supplementary measure to remove airborne SARS-CoV-2. *Build Environ*.177:106918.
- Lamb D; Verlinde J. 2011. *Physics and Chemistry of Clouds*. Cambridge University Press.
- Rogers R.R. *A short course in cloud physics*. Pergamon, Oxford, 1976
- Mason B.J. *The Physics of Clouds*. Clarendon Press, Oxford, 671 pp.
- Sarkodie S.A; Owusu P.A. 2020. Impact of meteorological factors on covid-19 pandemic: Evidence from top 20 countries with confirmed cases, *Environmental Research*, Volume 191, 110101

- Azuma K; Kagi N; Kim H; Hayashi M. 2020. Impact of climate and ambient air pollution on the epidemic growth during covid-19 outbreak in Japan, *Environmental Research*, Volume 190, 110042
- Carducci , A.; Federigi, I.; Verani, M. 2020. Covid-19 Airborne Transmission and Its Prevention: Waiting for Evidence or Applying the Precautionary Principle? *Atmosphere*. 11, 710.
- Prussin II A.J; Schwake D.O; Lin K; Gallagher D.L; Buttlng L; Marr L.C. 2018. Survival of the Enveloped Virus Phi6 in Droplets as a Function of Relative Humidity, Absolute Humidity, and Temperature *Appl. Environ. Microbiol*, 84, 12
- Doremalen V; Bushmaker T; Munster V.J.2013. Stability of Middle East respiratory syndrome coronavirus (MERS-CoV) under different environmental conditions, *Eurosurveillance*, 18, 20590
- Peng Z; Jimenez JL. 2020. Exhaled CO₂ as COVID-19 infection risk proxy for different indoor environments and activities. *medRxiv*. DOI: 10.1101/2020.09.09.20191676.
- Pierre-Gilles de Gennes; Françoise Brochard-Wyart; David Quéré. 2002. *Capillarity and Wetting Phenomena-Drops, Bubbles, Pearls, Waves*. Alex Reisinger. Springer.
- Watanabe T. 2009. Wettability of ceramic surfaces -A wide range control of surface wettability from super hydrophilicity to super hydrophobicity, from static wettability to dynamic wettability. *Journal of Ceramic Society of Japan*. 117(12) 1285-1292.
- Penman H.L. 1948. Natural evaporation from open water, bare soil and grass. *Proc. Roy. Soc. London A*(194), S. 120-145.
- Shuttleworth W.J. 2007. Putting the vap' into evaporation. *Hydrol. Earth Sys. Sci*. 11(1), 210-240.
- Shah M.M. 2012. Improved method for calculating evaporation from indoor water pools. *Energy and Buildings*. 49, pp 306-309
- Fuchs N.A. 1959. *Evaporation and Droplet Growth in Gaseous Media*. Pergamon Press. London. UK.
- Duguid H.A. 1941. A study of the evaporation rates of small freely falling water droplets. Doctoral thesis. University of Missouri-Rolla. T. 2290. p.p. 77.
- Chen X; Wang X; Chen P.G; Liu Q. 2018. Determination of diffusion coefficient in droplet evaporation experiment using response surface method. *Microgravity Science and Technology*, Springer. 30, pp.675-682.