Coronaviruses disinfection of a mobile object by a germicidal UVC lamp

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Abstract The aim of the present work is to study the disinfection of a mobile object by UVGI lamps. Two different disinfection processes are examined: the stationary and dynamic disinfection. In the stationary process, the infected object moves and takes its place under the lamp during a stationary exposure time, \( t_{es} \). However, in the dynamic process the object is in motion with a velocity, \( v \), during a dynamic exposure time \( t_{ed} \). For the stationary disinfection process, the expressions of irradiance lamp and the received dose are established by taking into account the non-uniformity of the light emission into the object surface. In the dynamic disinfection process, novel expressions of the lamp irradiance and the received dose are established by considering the velocity of the object, the non-uniformity of the light emission and so explicit expressions equations depending on dynamic exposure time are reported. The last developments are used to study the disinfection of a mobile object by an airline check-in luggage according to the two disinfection processes. The number of the required lamps to kill different varieties of Coronaviruses is calculated. For the same exposure time, 10 s, the dynamic disinfection process is found to be more efficient than the stationary disinfection process and the number of the required lamps is reduced from 20 to 50%.

List of symbols

| Symbol                  | Description                                                                 |
|------------------------|-----------------------------------------------------------------------------|
| \( d \) (m)            | Mobile object length                                                        |
| \( D \) (m)            | Length of the airline check-in luggage                                      |
| \( D_d \)              | Dose received by surface unity from a lamp                                  |
| \( D_{d, \text{min}} \) (J/m\(^2\)) | Minimum value of the received dose by surface unity                        |
| \( D_{d, \text{max}} \) (J/m\(^2\)) | Maximum dose received by surface unity                                     |
| \( dI_{dL}(\theta(t_{ed})) \) | Dose received by surface unity from a lamp at \( t_{ed} \)                  |
| \( dI_{dL}(t_{ed}) \)  | Elementary lamp irradiance at \( t_{ed} \)                                 |
| \( dD_{dL}(t_{ed}) \)  | Elementary dose received by a surface unity at \( t_{ed} \)                 |
| \( d_n(10 \text{ s}) \) | Number of required lamps per m\(^2\) in 10 s                              |
| \( d_n(10 \text{ s})_{\text{min}} \) | Minimum number of required lamps per m\(^2\) in 10 s                      |
| \( d_n(10 \text{ s})_{\text{max}} \) | Maximum number of required lamps per m\(^2\) in 10 s                      |
| \( d_n(\text{ex}) \)   | Number of required lamps per m\(^2\) in \( t_{ex} \)                        |
| \( D_90 \) (J/m\(^2\)) | Dose received by surface unity in the stationary process                    |
| \( D_{TdL}(t_{ed}) \)  | Total dose received by surface unity during the dynamic exposure time, \( t_{ed} \) |
| \( D_{90} \) (J/m\(^2\)) | Required dose to inactivate 90% of Coronavirus                              |
| \( h \) (m)            | Height of the airline check-in luggage                                      |
| \( I \) (W/m\(^2\))   | Irradiance                                                                  |
| \( I_{dL}(\theta(t_{ed})) \) | Lamp irradiance at \( t_{ed} \)                                           |
| \( I_{TdL}(t_{ed}) \)  | Total irradiance lamp during the dynamic exposure time, \( t_{ed} \)         |
| \( I(10 \text{ s}) \)  | UVGI lamp required to reduce 90% of viruses in 10 s during the stationary disinfection process |
| \( I_{L_{\text{max}}} \) (W/m\(^2\)) | Maximum lamp irradiance                                                   |
| \( I_{L_{\text{min}}} \) (W/m\(^2\)) | Minimum lamp irradiance                                                   |
| \( k \) (m\(^2\)/J)   | Microorganism susceptibility factor                                         |
| \( l \) (m)            | Width of the airline check-in luggage                                       |

This paper is dedicated to the memory of Dr. Ridha Touihri who died from Covid-19.

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1 Introduction

Disinfection is an important action to reduce the propagation of Coronaviruses and especially Sars-Cov 2. The disinfection methods are of two types: physical and chemical [1]. The physical disinfection methods are classified in three categories: irradiation, mechanical action and thermal treatment [2]. UVGI, emitted at 254 nm, is a powerful irradiation method to inactivate surface from microorganisms among them Coronaviruses. It is well known that scattering and absorption occur when the radiation is transmitted. However, in absence of dust, the light scattered and the absorbance by air molecules can be neglected. According to Inagari et al. [3] the inactivation air from Sars-Cov-2 is conducted with a deep ultraviolet light-emitting diode, emitted at 280 ± 5 nm. In this study, we are interested in inactivation surfaces from Coronaviruses, so UVGI lamps are used. In this context, several devices have been described in bibliography [4]. In airports, bus and train station the passenger luggage and packages are disinfected by using an automatic disinfection system as reported by Murthy [5]. The proposed device is similar to the X-ray machines, where the author has used standard Philips light and has estimated the number of lamps to use in order to disinfect surfaces from luggage passenger from Sars-Cov-2. The author has limited the study to a unique disinfection process and it doesn’t take into account the non-uniformity of the light emission to the mobile surface. Recently, Bouri and Shatalov [6] have proposed an UVGI scientific calculator to determine the number of required lamps to disinfect closed area. The number of lamps is determined taking into account the airflow, the distance, the exposure time, the radiant power, and the chamber reflectivity. In fact, we distinct two types of disinfection processes qualified as stationary and dynamic depending on the velocity of the infected object. The present paper is divided in two principal sections. In the first part of this paper, the stationary and the dynamic disinfection processes are described in detail and several novel expressions of the irradiance lamp and the received dose per surface unity are established and reported. In the second part of this paper, the disinfection of passenger luggage according to the two different processes is examined and compared.

2 Different scenario to disinfect objects

2.1 The stationary disinfection process

In this process, an object enters the tunnel thanks to a conveyor belt with uniform velocity. After reaching the central position of the tunnel, the lamp goes on during a stationary exposure time, \( t_{es} \), then the lamp goes out and the object leaves the tunnel with
the same velocity. According to Kamilo and Ohgaki [7] the number of microorganisms at times $t_\text{es}$, $N$, and zero, $N_0$, are connected according the following equation:

$$\ln \left( \frac{N}{N_0} \right) = -k I t_\text{es}$$  \hspace{1cm} (1)

where $k$ (m$^2$/J) and $I$ (W/m$^2$) are, respectively, the microorganism susceptibility factor and the irradiance. The dose received by surface unity in the stationary process, $D_{s}(t_\text{es})$ (J/m$^2$), is given by Eq. (2):

$$D_{s}(t_\text{es}) = I t_\text{es}$$  \hspace{1cm} (2)

Three models are reported in bibliography to calculate the irradiance of a lam. These models are classified in two types, where the lamps are treated as a line source as reported by Keitz and Beggs models [8, 9]. However, the modest model treats the lamp as cylindrical shape [10]. On the bases of last model and according to Bouri and Shatalov [6], the irradiance of a cylindrical lamp of length, $L$, and radius, $r_1$, is given (in the case $r_1 \ll L$) by the flowing expression:

$$I_{sL} = \frac{\varepsilon \rho P}{2\pi L r_1}$$  \hspace{1cm} (3)

where $\varepsilon$ is the distance from the irradiation chamber axis, $L$ and $\varepsilon \approx 0.3$ are, respectively, the length of the lamp and the efficiency of the UVGI source. $\rho = 1/(1 - R)$ is a coefficient depending on the irradiation chamber inner wall reflectivity. $R$ is the reflectance of the wall. The dose received by surface unity from a lamp, $D_{sL}$, at given distance, $r$ (m), depends on the electric power $P$ (W), of the emitted UVGI lamp according the following:

$$D_{sL} = \frac{\varepsilon \rho P t_\text{es}}{2\pi L r_1}$$  \hspace{1cm} (4)

The last expression is in agreement with the equation reported by Bentacor and Vidal [11] after taking into account the factor, $\varepsilon \rho$. The irradiance in the normal direction corresponds to $r = r_0$. So, the lamp irradiance received by a surface element spotted by the angle $\theta$ is given by Eq. (5).

$$I_{sL}(\theta) = \frac{\varepsilon \rho P \cos \theta}{2\pi L r_0}$$  \hspace{1cm} (5)

The dose received by surface unity, $D_{sL}(\theta)$, spotted by the angle $\theta$ is given by the following equation:

$$D_{sL}(\theta) = \frac{\varepsilon \rho P t_\text{es} \cos \theta}{2\pi L r_0}$$  \hspace{1cm} (6)

The maximum values of the irradiance and the received dose by surface unity, $I_{sL\text{max}}$ and $D_{sL\text{max}}$, are obtained by taking $\cos \theta_{\text{min}} = 1$, corresponding to $\theta_{\text{min}} = 0$ rd. The minimum values of the irradiance and the received dose by surface unity, $I_{sL\text{min}}$ and $D_{sL\text{min}}$, are obtained by taking $\cos \theta_{\text{max}} = \frac{m}{\sqrt{1 + (\frac{m}{h})^2}}$ (Fig. 1). So, the lamp irradiance and the received dose by surface unity during a static disinfection process are not uniform and depend on surface position. The stationary disinfection process is qualified as heterogeneous disinfection.

Fig. 1 Disinfection of a mobile object by an UVGI lamp
2.2 The dynamic disinfection process

In this process, the object is in uniform motion with a velocity, $v$. The lamp still goes on during the disinfection process. So, the distance from the midpoint at the normal direction depends on the exposure dynamic time, $t_{ed}$. For the lamp irradiance, $I_{dl}(\theta(t_{ed}))$, and the received dose by surface unity, $D_{dl}(\theta(t_{ed}))$, expressions are given by the following equations:

$$I_{dl}(\theta(t_{ed})) = \frac{\varepsilon P \cos \theta(t_{ed})}{2\pi L r_0}$$

(7)

$$D_{dl}(\theta(t_{ed})) = I_{dl}(\theta(t_{ed}))t_{ed}$$

(8)

Considering the geometry reported in Fig. 1, $\cos(\theta(t_{ed})) = \frac{\text{chosen}}{\sqrt{r_0^2 + (\frac{2}{2} - v_{ted})^2}}$, so $I_{dl}(t_{ed})$ takes the following expression:

$$I_{dl}(t_{ed}) = \frac{I_{dl,\max}}{\sqrt{1 + \left(\frac{2 - v_{ted}}{r_0}\right)^2}}$$

and $I_{dl,\max} = \frac{\varepsilon P}{2\pi L r_0}$

(9)

The elementary values of the irradiance, $dI_{dl}(t_{ed})$, and the dose received by a surface unity, $dD_{dl}(t_{ed})$, from the lamp during an elementary time, $dt$, in a dynamic disinfection process are given by the following equations:

$$dI_{dl}(t_{ed}) = \frac{vI_{dl,\max}(\frac{2}{2} - v_{ted})dt}{r_0^2}$$

$$I_{dl}(t_{ed}) = \left[1 + \left(\frac{2 - v_{ted}}{r_0}\right)^2\right]^{3/2}$$

(10)

$$dD_{dl}(t_{ed}) = dI(t_{ed})t_{ed} + I(t_{ed})dt$$

(11)

The dynamic disinfection process can be seen as a successive of $M$ stationary disinfection process separated by a time unity $\Delta t$. The last parameters are connected to the velocity, $v$, and its length, $d$, according the following equations:

$$d = vM \Delta t = M \Delta x$$

(12)

where $\Delta x$ is the absolute displacement variation. The absolute variation of the irradiance lamp, $\Delta I_{dl}(t_i)$, and the absolute variation of the received dose by surface unity, $\Delta D_{dl}(t_i)$, during dynamic disinfection infection process at the instant $t_i = i \Delta t$, $0 \leq i \leq M$, corresponding to the object position instant $x_i = i \Delta x$, $0 \leq i \leq M$

$$\Delta I_{dl}(t_i) = \frac{vI_{dl,\max}}{r_0^2} \left|\left(\frac{2}{2} - iv \Delta t\right)\right| \left[1 + \left(\frac{2 - iv \Delta t}{r_0}\right)^2\right]^{3/2} \Delta t$$

(13)

$$\Delta D_{dl}(t_i) = (\Delta I(t_i) i + I(t_i)) \Delta t$$

(14)

The total irradiance lamp and the total received dose per surface unity during the dynamic exposure time, $t_{ed} = M \Delta t$, for a dynamic disinfection process denotes, respectively, by $I_{Tdl}(t_{ed})$ and $D_{Tdl}(t_{ed})$ are given by Eqs. (14) and (15).

$$I_{Tdl}(t_{ed}) = \sum_{i=0}^{i=M} \Delta I_{dl}(t_i)$$

(15)

$$D_{Tdl}(t_{ed}) = \sum_{i=0}^{i=M} \Delta D_{dl}(t_i)$$

(16)

3 A case study

Considering an airline check-in luggage of dimensions ($D = 0.9$ m, $l = 0.75$ m and $h = 0.43$ m), the total surface to disinfect is $2.8$ m$^2$ [5]. The used germicidal UVC lamp is of length $L = 0.9$ m and electric power $P = 30$ W placed on the top of the tunnel. In absence of reflector, $\varepsilon P = 0.3$[6].
Table 1 The minimum/maximum number of lamps per surface unity, \( \frac{d_{nL}}{dS} \text{min} \)/\( \frac{d_{nL}}{dS} \text{max} \), and the minimum/maximum of lamps, \( n_{L\text{min}}/n_{L\text{max}} \), in the static disinfection process for different microorganisms

| Coronavirus                      | \( D_0 \) (J/m²) | \( k \) (m²/l) | \( I(t_{es} = 10 \text{ s}) \) (W/m²) | \( \frac{d_{nL}}{dS} \text{min} \) | \( n_{L\text{min}} \) | \( \frac{d_{nL}}{dS} \text{max} \) | \( n_{L\text{max}} \) |
|----------------------------------|------------------|----------------|----------------------------------------|---------------------------|----------------|---------------------------|----------------|
| Sars-Cov-2 [13]                 | 7                | 0.351250       | 0.66                                   | 0.18                      | 0.50           | 0.32                      | 0.89           |
| Berne virus (Coronaviridae) [14] | 7                | 0.32100        | 0.72                                   | 0.19                      | 0.54           | 0.35                      | 0.98           |
| Murine Coronavirus (MHV) [15]   | 15               | 0.15351        | 1.50                                   | 1.5                       | 1.13           | 0.73                      | 2.04           |
| Canine Coronavirus (CCV) [16]   | 29               | 0.08079        | 2.85                                   | 0.77                      | 2.15           | 1.37                      | 3.88           |
| Murine Coronavirus (MHV) [16]   | 29               | 0.08079        | 2.85                                   | 0.77                      | 2.15           | 1.37                      | 3.88           |
| SARS Coronavirus CoV- P9 [17]   | 40               | 0.05750        | 4                                       | 1.08                      | 3.03           | 1.95                      | 5.46           |
| Murine Coronavirus (MHV) [18]   | 103              | 0.02240        | 10.28                                  | 2.78                      | 7.77           | 5                         | 14             |
| SARS Coronavirus (Hanoi) [19]   | 134              | 0.01720        | 13.38                                  | 3.61                      | 10.12          | 6.51                      | 18             |
| SARS Coronavirus (Urban) [1]    | 241              | 0.00955        | 24.11                                  | 6.51                      | 18.23          | 11.73                     | 32.85          |
| Average [12]                    | 67               | 0.03433        | 6.71                                   | 1.81                      | 5.07           | 3.26                      | 9.14           |

3.1 Stationary disinfection process

According to Kowalski et al. [12], the dose required to inactivate 90% Coronavirus (Sars-Cov-2) is 7–241 J/m² the mean of which is \( D_{90} = 67 \text{ J/m²} \) and its susceptibility to UVC radiation is ranged from 0.00955 to 0.351250 m/J², the mean of which is \( k = 0.03433 \text{ m/J²} \) [1, 13–19]. The UVGI lamp required to reduce 90% of viruses in 10 s, \( I(t_{es} = 10 \text{ s}) \), is calculated and reported in Table 1. The obtained values are ranged from 0.66 to 24.11 W/m², the mean of which is \( I(t_{es} = 10 \text{ s}) = 6.71 \text{ W/m²} \). The maximum/minimum irradiance of the used lamp is calculated according to Eq. (5) and is, respectively, \( I_{S\text{max}} = 3.7 \text{ W/m²} \) and \( I_{S\text{min}} = 2.06 \text{ W/m²} \). According to Murthy [5], the number of required lamps per m², \( \frac{d_{nL}}{dS} \text{(10 s)} \), can be determined according the following:

\[
I(t_{es}) = -\ln\left(\frac{N}{N_0}\right) / k t_{es}
\]  \( (17) \)

The required irradiance to reduce 90%, \( I(t_{es} = 10 \text{ s}) \), of viruses in 10 s is calculated and reported in Table 1. The obtained values are ranged from 0.66 to 24.11 W/m² with an average value of 6.71 W/m². The maximum/minimum irradiance of the used lamp in a stationary disinfection process is calculated according to Eq. (5) and is, respectively, \( I_{S\text{max}} = 3.7 \text{ W/m²} \) and \( I_{S\text{min}} = 2.06 \text{ W/m²} \). According to Murthy [5], the number of required lamps per m², \( \frac{d_{nL}}{dS} \text{(10 s)} \), for an exposure time of 10 s can be determined according the following:

\[
\frac{dnL}{dS}(10 \text{ s}) = \frac{I(t_{es} = 10 \text{ s})}{I_{SL}}
\]  \( (18) \)

The last equation permits us to deduce the total number of lamps, \( n_L(10 \text{ s}) \), to disinfect a surface \( S \) (m²):

\[
n_L(10 \text{ s}) = \frac{I(t_{es} = 10 \text{ s})}{I_{SL}} S
\]  \( (19) \)

So, the minimum/maximum number of lamps by surface unity, \( \frac{d_{nL}}{dS} \text{min}(10 \text{ s})/\frac{d_{nL}}{dS} \text{max}(10 \text{ s}) \), is evaluated by replacing \( I_{SL} \) in Eq. (18) by \( I_{SL\text{min}} \) and \( I_{SL\text{max}} \), respectively. The minimum/maximum number of required lamps \( n_{L\text{min}}(10 \text{ s})/n_{L\text{max}}(10 \text{ s}) \) to disinfect surfaces in the airline check-in luggage is evaluated also by replacing \( I_{SL} \) in Eq. (19) by \( I_{SL\text{min}} \) and \( I_{SL\text{max}} \). We report in Table 2 the last parameters for different viruses. We note that the average values of \( \frac{d_{nL}}{dS} \text{min}(10 \text{ s}) \) and \( \frac{d_{nL}}{dS} \text{max}(10 \text{ s}) \) are, respectively, 1.81 and 3.26. The average values of lamps \( n_{L\text{min}}(10 \text{ s}) \) and lamps \( n_{L\text{max}}(10 \text{ s}) \) are, respectively, 5.07 and 9.14. The number of required lamps per m², \( \frac{d_{nL}}{dS} \text{(es)} \), for an exposure time \( t_{es} \) is connected to \( \frac{d_{nL}}{dS} \text{(10 s)} \) by the following equation:

\[
\frac{dnL}{dS}(t_{es}) = \frac{dnL}{dS}(10 \text{ s}) \times \frac{10}{t_{es}}
\]  \( (20) \)

Likewise, the number of lamps for an exposure time \( t_{es} \) is connected to \( \frac{dnL}{dS} \text{(10 s)} \) according to Eq. (21).

\[
n_L(t_{es}) = n_L(10 \text{ s}) \times \frac{10}{t_{es}}
\]  \( (21) \)

3.2 Dynamic disinfection process

In this process, we consider an object in motion with a velocity ranged from 0.05 to 1 m/s. The absolute displacement variation is \( \Delta x = 0.01 \text{ m} \). So, the number of object position is \( M = 90 \). We report in Fig. 2 the variation of the absolute variation of the irradiance lamp, \( \Delta I_{SL}(t_i) \), versus the exposure time, \( t_i \) (s), for two different velocity, \( v = 0.05 \text{ m/s} \) and \( v = 0.2 \text{ m/s} \). The plotted curves are
Table 2 The lamp irradiance and the received dose by surface unity during a dynamic disinfection process for different velocity of the object

| v (m/s) | t_{ed} (s) | I_{TdL} (W/m²) | D_{TdL} (J/m²) |
|---------|------------|-----------------|-----------------|
| 0.05    | 18         | 8.58            | 154.36          |
| 0.1     | 9          | 4.23            | 38.59           |
| 0.2     | 4.5        | 2.14            | 9.75            |
| 0.3     | 3          | 1.42            | 4.34            |
| 0.4     | 2.25       | 1.07            | 2.44            |
| 0.5     | 1.8        | 0.86            | 0.86            |
| 0.6     | 1.5        | 0.71            | 1.08            |
| 0.7     | 1.29       | 0.61            | 0.80            |
| 0.8     | 1.125      | 0.54            | 0.61            |
| 0.9     | 1          | 0.48            | 0.48            |
| 1       | 0.9        | 0.43            | 0.39            |

Fig. 2 Variation of the absolute variation of the irradiance lamp, $\Delta I_{dl}(t_i)$, versus the exposure time, $t_i$ (s), for a mobile object with two different velocity $v = 0.05$ m/s and $v = 0.2$ m/s.

symmetric around a particular time, $t_{45} = 45 \Delta t$, corresponding to the passage of the object below the central position of the device. The shape of the curves looks like a flying bird. We report in Fig. 3 the variation of the absolute variation of the received dose per surface unity, $\Delta D_{dl}(t_i)$, versus the object position, $x_i$, for two different velocity $v = 0.3$ m/s and $v = 0.6$ m/s. The plotted curves are asymmetric and present two different behaviors separated by the particular position $x_{45} = 0.45$ m. The values of $I_{TdL}$ and $D_{TdL}$ are deduced and reported in Table 2, for different velocity object. According to the reported values, empirical equations connecting the total irradiance, $I_{TdL}$, and the total received doses by a surface unity, $D_{TdL}$, to the dynamic exposure time, $t_{ed}$, are established (Eqs. 22, 23) for the dynamic disinfection process.

$$I_{TdL} \approx 0.476 t_{ed}$$

$$D_{TdL} \approx 0.4817 t_{ed}^2$$

So, we can deduce an empirical equation connecting $I_{TdL}$ and $D_{TdL}$ for a dynamic disinfection process by combining Eqs. (22) and (23):

$$D_{TdL} = 1.012 I_{TdL} t_{ed}$$

As the velocity of the object increases, the irradiance of the lamp and the total received dose per surface unity decreases. For instance considering $v = 0.2$ m/s, the total irradiance of the lamp is close to 2.14 W/m² and total received dose by surface unity is of 9.75 J/m².

We report in Fig. 4 the variations of the total irradiance of the lamp, $I_{TdL}$, in the dynamic process versus the velocity of conveyor belt. According this figure, $I_{TdL}$ decreases rapidly as the conveyor velocity increases for $v < 0.4$ m/s. When $v > 0.4$ m/s, $I_{TdL}$ decreases slowly. In order to compare the efficiency of the different process, we consider an exposure time $t_{ed} = 10$ s, which correspond to a velocity of $v = 0.09$ m/s, so $I_{TdL} = 4.76$ W/m² and $D_{TdL} = 48.17$ J/m². In this process, the total irradiance of the lamp is more
Fig. 3 Variation of received dose per surface unity, $\Delta D_{dL}(t_i)$, versus the mobile position, $x_i$ (s), for a mobile object with two different velocity $v = 0.3$ m/s and $v = 0.6$ m/s.

Fig. 4 The variation of the total irradiance lamp in the dynamic disinfection process, $I_{TdL}$ (W/m²) and the minimum/maximum ($I_{sLmin}$ (W/m²)/$I_{sLmax}$ (W/m²) versus object velocity $V$ (m/s).

Table 3 The number of required lamps per surface unity, $\frac{d\eta}{dS}$, and the number of lamps, $n_L$, in the dynamic disinfection process for different Coronaviruses

| Coronavirus                | $\frac{d\eta}{dS}$ | $n_L$ |
|----------------------------|--------------------|-------|
| Sars-Cov-2                 | 0.139              | 0.389 |
| Berne virus (Coronaviridae)| 0.151              | 0.423 |
| Murine Coronavirus (MHV)   | 0.315              | 0.882 |
| Canine Coronavirus (CCV)   | 0.599              | 1.677 |
| Murine Coronavirus (MHV)   | 0.599              | 1.677 |
| SARS Coronavirus CoV- P9   | 0.840              | 2.352 |
| Murine Coronavirus (MHV)   | 2.160              | 6.048 |
| SARS Coronavirus (Hanoi)   | 2.810              | 7.84  |
| SARS Coronavirus (Urbani)  | 5.065              | 14.182|
| Average                    | 1.410              | 3.948 |

important than its maximum value in the static disinfection process, $I_{dLmax} = 3.7$ W/m². This proves that the dynamic disinfection process is more efficient and gives a uniform disinfection.

According to Eqs. (20) and (21), we report in Table 3 the number of required lamps per m² $\frac{d\eta}{dS}$, and the number of lamps, $n_L$, by changing $I_{dL}$ by $I_{TdL}$ for all the viruses studied in this work for an exposure disinfection time $t_{ed} = 10$ s in the dynamic disinfection process. By comparing the number of required lamps in the stationary and dynamic process reported in Table 2 and in Table 3, we conclude that the number of required lamps in the dynamic process disinfection is reduced from 22 to 56%.
Table 4 The total received dose by surface unity, $D_{T_{dL}}$ (J/m²), for different values of the total number of stationary position, $M$, for the same exposure time $t_{ex} = 10$ s and $v = 0.09$ m/s.

| $M$  | 4.5 | 9   | 30  | 45  | 60  | 75  | 90  | 120 | 180 | 225 | 450 | 900 | 1800 | 3600 |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|
| $D_{T_{dL}}$ (J/m²) | 50.25 | 32.61 | 27.71 | 25.21 | 24.76 | 24.52 | 24.34 | 24.14 | 23.93 | 23.85 | 23.69 | 23.6 | 23.56 | 23.54 |

Fig. 5 Variation of the total received dose per surface unity, $D_{T_{dL}}$ (J/m²), versus the logarithm of the number of stationary position, Log $M$. 

In this section, we discuss the effect of the number of the stationary position, $M$, on the total dose received doses by a surface unity, $D_{T_{dL}}$, for the same exposure time $t_{ex} = 10$ s and $v = 0.09$ m/s. We report in Table 4 the values of $D_{T_{dL}}$ (J/m²) for different values of $M$. We report in Fig. 5 the variation of $D_{T_{dL}}$ (J/m²) versus Log $M$. The obtained results show two different behaviors. In fact when Log $M < 4.3$ ($M = 75$), $D_{T_{dL}}$ (J/m²) decreases rapidly. However, when Log $M \geq 4.9$ ($M = 90$), $D_{T_{dL}}$ (J/m²) is almost constant. So, this justify our choice, $M = 90$, to calculate the total dose received by surface unity as it reported earlier.

4 Conclusions

The disinfection of a mobile object can be conducted according to two distinct disinfection processes: stationary and dynamic. In the stationary disinfection process, the object lies motionless during the disinfection process. This kind of disinfection is found to be non-uniform and qualified as heterogeneous disinfection. However in the dynamic process, an object is disinfected in motion; this kind of disinfection is uniform and qualified as homogenous disinfection. The dynamic disinfection process is found in one part to be more efficient than the stationary one. The required lamps in the dynamic disinfection process have been reduced by more than 22%. According to the literature, the disinfection of a mobile object is treated for the first time and presents an opportunity to develop theoretical and experimental researches.

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