A Review about Relative Humidity and Sterilization Efficiency with UV-C Radiation in the Air-Conditioned Workplace Areas

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Abstract: In the present article, the effect of relative humidity and thermal comfort conditions of the air of internal conditioned workplace areas to the change of sterilization efficiency with ultraviolet radiation UV-C will be studied. The conditions for thermal comfort in conditioned workplace areas and the effect of these conditions in the sterilization efficiency of the air will be reported. Experimental measurements of scientists is the main information resource of this research. The general conclusion that results, is that as the relative humidity increase, the sterilization efficiency decrease. In addition, the change of sterilization efficiency in regard to the relative humidity of the air, is different depending on the type of microorganism.

Keywords: Sterilization Efficiency, Ultraviolet Sterilization, Air Humidity, Thermal Comfort Conditions

I. INTRODUCTION

The ultraviolet air sterilization take place through the germicidal lamps, which produce ultraviolet germicidal irradiance (UVGI). This radiation is directed towards pathogenic microorganisms. The particular disinfection technology is excessively applied to the incoming air-conditioned air of the hospital areas as well as the items sterilization. Generally, it can be used for sterilization in the conditioned air of workplaces. Germicidal lamps with UVGI are installed inside the pipelines for transfer of conditioned air in the workplaces. The ultraviolet C irradiance or UV-C belongs in the electromagnetic spectrum with wave length between 100 – 280 μm [1], is the most damaging type of ultraviolet irradiance because can causes mutations and carcinogenesis [2].

Once UV irradiance absorbed by DNA of microorganism, then growth is inactivated and multiplication of microorganism is slowed down [3]. So, this technology help us to decrease the population of active pathogenic microorganisms which are contained in the internal air and may be reproduced. The ability of radiation of UVGI lamp to inactivate pathogenic microorganisms is affected by relative humidity of the air. The relative humidity that define the standards for thermal comfort conditions in the conditioned spaces, play an important role in the effect of sterilization process. Low sterilization efficiency in the air increases the airborne infection risk with some pathogenic microorganism for the worker.

II. MICROBIAL LOAD IN THE AIR-CONDITIONED SPACES

During the operation of heating ventilation and air-conditioning systems with central unit, fresh air incoming from external atmosphere to the indoor space through the air pipelines. The internal air of space recirculates on the heat exchangers of the HVAC system to reach the desired temperature. So it is concluded that the microorganism concentrations in the conditioned air are depended by microbial load both internal and external air. Also, the microbial concentrations are different depending on the type of work that is carried out inside the workplace, on the hygiene conditions and quality of atmosphere that prevail in the country as well as the weather conditions. The concentration measurements for the airborne pathogenic microorganisms that are contained in the internal air for various workplace areas are presented in Table 1. The divergence of measurements for the same workplace vary between 5% for office buildings and 4170% for surgery rooms.

Table 1. Microbial load measurements in the various workplaces.

Workplace	*Concentrations (CFU/m²)*	*Ref.*
Hospital rooms	0 – 266	[4]
	0 – 111	[5]
Hospitals (lobby)	833	[6]
Maternity hospitals	0.44 – 44.67	[4]
Operation rooms	0 – 7.33	[4]
	0 – 313	[5]
Schools	830 – 3.1×10^6	[7]
Office buildings	14 – 494	[8]
	10 – 530	

The above measurements become in the different place of world [4, 6], also different sampling method is applied. The CFU is colony forming unit. A microbial colony is equivalent to the population from 0 to 1000 microorganism cells.

III. MATHEMATICAL MODELS OF AIR STERILIZATION WITH UVGI LAMP

The inactivation ratio S or sterilization/deactivation ability or survival fraction S^{-1} of a population with microorganisms that is exposed to ultraviolet radiation, is dimensional size and equal with:

$$S = \frac{N_0}{N} = \frac{1}{\exp(-kD)} \qquad (1)$$

Where:

N_0: Initial microbial population in CFU or CFU/*m²*.

N: Microbial population after exposure to UV-C radiation in CFU or CFU/*m²*.

k: Inactivation rate constant in *cm²/mJ*.

D: Dose of ultraviolet irradiance in *mJ/cm²*.

The inactivation rate constant k is chosen from tables depending on the type of microorganism that intend to neutralize. The dose D is chosen by experimental inactivation curves of each pathogenic microorganism. There is a second model that analyzes the sterilization ability and microorganism inactivation as a function of time S(t). According to this model [9, 10], inactivation ratio is equal with:

$$S(t) = \frac{N_0}{N} = \frac{1}{\exp(-kIt)} \quad (2)$$

Where:

k: Inactivation rate constant in $cm^2 \times sec/mJ$.

I: Intensity of UVGI lamp ultraviolet irradiance in mJ/cm^2.

t: Time exposure of microorganisms to ultraviolet irradiance in seconds.

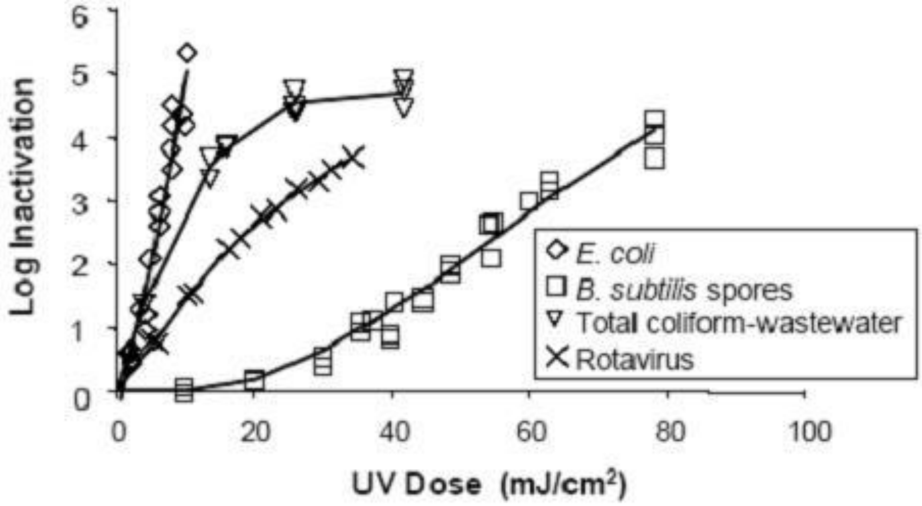

Figure 1: The change of dose D of UV-C in relation to inactivation ability for different pathogenic microorganisms (Chang et al., 1985) [11].

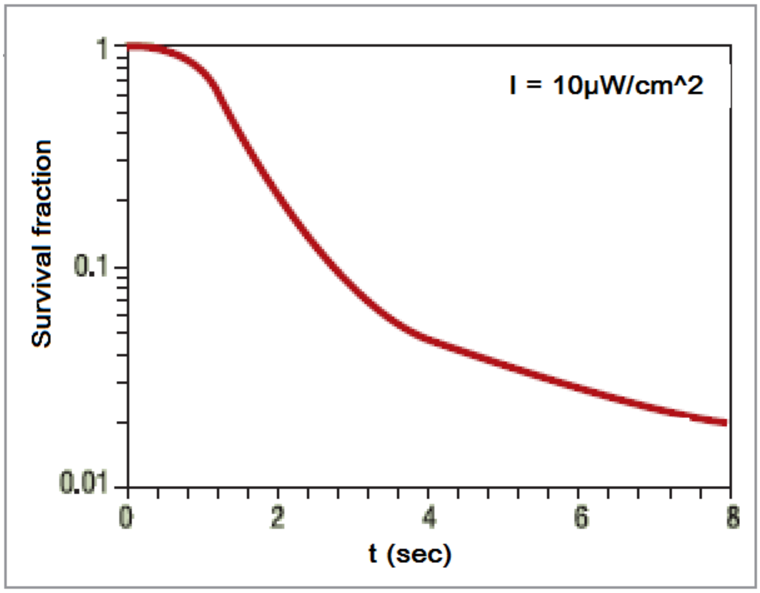

Figure 2: The change of survival fraction of pathogenic microorganisms as a function of time for particular UV-C intensity [9, 12].

IV. THE EFFECT OF RELATIVE HUMIDITY IN THE AIR STERILIZATION PROCESS

There are three different physical quantities and definitions about humidity in the air. The absolute humidity, which is equal with the ratio of water vapor mass within the air to the total volume of air. The specific humidity, which is equal with the ratio of water vapor mass within the air to the total mass of the air. The relative humidity Φ(%) or RH which is equal with the ratio of partial pressure e_w of water vapors in the air-water mixture to the equilibrium vapor pressure e_w^* at a given temperature value.

$$\Phi = \frac{e_w}{e_w^*} 100\% \quad (3)$$

The relative humidity in the air can be determined easily from the psychrometric chart if the dry bulb air temperature and wet bulb air temperature are known. Furthermore, the equilibrium vapor pressure e_w^* can be calculated using approximate equations. August-Roche-Magnus equation [13]:

$$e_w^* = 6.1094 \exp\left(\frac{17.625 T_d}{T_d + 243.04}\right) \quad (4)$$

A.L. Buck equation [14]:

$$e_w^* = 6.1121 \exp\left[\left(18.678 - \frac{T_d}{234.5}\right)\left(\frac{T_d}{T_d + 257.14}\right)\right] \quad (5)$$

Where, T_d the dry bulb temperature of air in degrees Celsius, and e_w^* the equilibrium water vapor in hPa. Another equation of Goff-Gratch [15], is more complex than previous models. The relative humidity can be easily expressed as a function of air pressure and vapor pressure, also can be expressed as a function of air temperature, that is, a function Φ=f(T,P) [13, 14, 15]. If the inactivation ratio S could be expressed as a function of air pressure and temperature, S=f(T) or S=f(P), it would be possible to study the change of quantity S with regard to relative humidity.

The inactivation ability S, can be affected directly by dose of ultraviolet irradiance, the inactivation rate constant k and the intensity of ultraviolet irradiance l. Also, it is proved that the inactivation ability during sterilization process with UV-C is not directly affected by temperature [16]. However, inactivation ability can be affected indirectly, that is, the change of quantities k, D, l with regard to the temperature, consequently causes change to the quantity S because S = f(k, D, I).

L.A. Fletcher report that an increase of relative humidity from 58% to 73% during air sterilization with UV irradiance in bacteria B. Cepacia, causes an increase of survival percentage S^{-1} from 9% to 50% for D = 5 J/m². An increase of dose D from 5 to 20 J/m² and the same relative humidity levels, the survival percentage is increased from 2% to 12% [17]. This means that an increase of relative humidity over than 58% causes decrease to the germicidal activity of UV-C irradiance for the specific bacteria. There are other scientists which report that the effect of UV-C irradiance decreases the inactivation ability S of pathogen microorganisms once Φ>50%. In addition, the degree of influence is different depending on the type of bacteria [18].

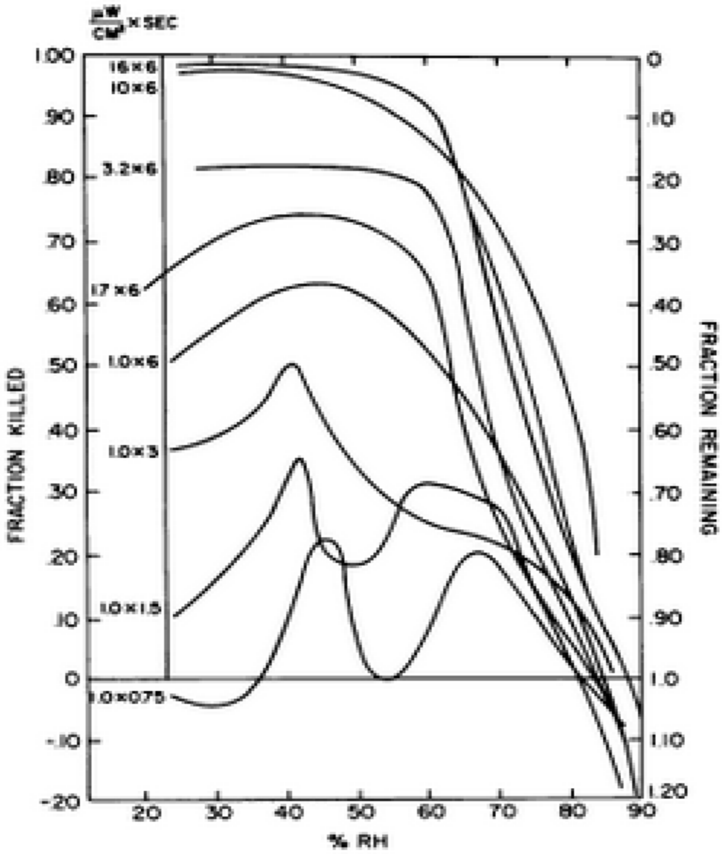

Figure 3: The change of survival fraction of bacteria Serratia m. As a function of the relative humidity in the air for various UV dose values and exposure time values in μW/cm²×sec (Riley and Kaufman, 1972) [19].

Riley and Kaufman were studied the behavior of bacterium Serratia marcescens and extracted analytical curves about change of relative humidity the survival ratio and the dose of irradiance [19]. These curves allow us to export mathematical equations using regression analysis for calculation of inactivation ability with regard to the relative humidity.

According to Figure 3, the highest killed fraction irrespective of UV dose is noted in the relative humidity range between 40%<Φ<45%, the change of relative humidity is almost periodic for small exposure time from 0.75 to 1.5 sec and relative humidity range between 25%<Φ<75%. Apart from above, the effectiveness of germicidal UV irradiance is affected by temperature of internal space. A relative humidity about 50-52% notes the minimum effectiveness [20]. J. Peccia and M. Hernandez report that an increase of relative humidity from 50% to 95% causes decrease of responsibility factor Z (μW/cm²×sec) of UV-C irradiance for mycobacterium bovis BCG. Also, mycobacterium Parafortuitum notes the maximum responsibility factor for relative humidity range between 40%<Φ<50% [21]. About Bacillus subtilis, the increase of relative humidity from 50% to 95% causes a minimum decrease of responsibility factor Z [22]. Two other studies from Rentschler and Nagy report that the inactivation ability in microorganism Escherichia coli is not affected by related humidity [23].

V. THERMAL COMFORT CONDITIONS

During the precise design of HVAC systems, relative humidity is a most important parameter among other with regard to the thermal comfort conditions for internal conditioned air in the buildings.

There are standards that define the limits of relative humidity in the air during cooling and heating so that the climate inside the workplace to be satisfactory. The combination of that limits with information of previous unit about the change of sterilization efficiency as a function of relative humidity, can give a response if the optimal air sterilization with UV irradiance take place in the limits of relative humidity for thermal comfort conditions. ASHRAE considers that the maximum relative humidity value that should be taken into consideration for incoming air during design study of air-conditioning systems should not exceed 65% in workplace areas [24]. The Greek standards of Technical Chamber of Greece about the thermal comfort conditions, report the limits of relative humidity for cooling and heating below [25].

Table 2. Thermal comfort conditions depending on relative humidity in Greece.

Workplace	*Heating (Winter)*	*Cooling (Summer)*
Office buildings	30 – 35%	40 – 50%
Restaurants	30 – 40%	50 – 60%
School, educational spaces	35 – 40%	40 – 50%
Libraries – Museums	40 – 50%	40 – 55%
Hospital rooms	30%	50 – 60%
Operation rooms	30%	50 – 60%
Hospital rooms (lobby)	30%	45 – 50%

VI. CONCLUSIONS

During the air sterilization process with UV-C radiation, the inactivation ability decreases as the relative humidity increases for the majority of pathogenic microorganisms. The effect of ultraviolet radiation is different for each microorganism. The inactivation ability or sterilization degree with regard to the relative humidity is not changed linearly. The change curve of inactivation ability as a function of relative humidity is depended by dose of ultraviolet radiation and exposure time of microorganism in the radiation (Fig. 3).

The inactivation ability is not seriously affected of relative humidity in the range that must be observed so that prevail thermal comfort conditions in the air-conditioned air. According to standards for thermal comfort, the relative humidity in the summer must be higher than winter, consequently the inactivation ability is decreased and is necessary to increase the dose of UVGI lamp so that the reduction of ability to be counterbalanced. Also, it is proven that certain aforementioned bacteria exhibit maximum sterilization efficiency in the range between $40\% < \Phi < 60\%$.

Especially for hospitals, before installation of a sterilization system with UVGI lamps in the pipelines of conditioned air, it’s necessary to know thermodynamic characteristics of incoming air, in the next step should become a research in order to study how the relative humidity affects microorganisms that we intent to neutralize.

Ethical statement: The author declare that they have followed ethical responsibilities

Conflict of Interest: The author declares no competing interests in relation to the work

REFERENCES

[1] ISO 21348, Definitions of solar irradiance spectral categories.
[2] Pfeifer G.P. (1996). Technologies for Detection of DNA Damage and Mutations, pp.440, Springer, New York.
[3] Kowalski W.J. (2009). Ultraviolet Germicidal Irradiation Handbook, Springer-Verlag, Berlin.

[4] Ortiz G., Yaguue G., Segovia M. and Catalan V. (2009). A study of air microbe levels in different areas of a hospital, Current Microbiology, Vol. 59, pp. 53-58.

[5] Azimi F., Naddafi K., Nabizadeh R., Hassanvand M.S., Alimohammadi M., Afhami F. and Musavi S.N. (2013). Fungal air quality in hospital rooms: A case study in Tehran Iran, Journal of Environmental Health Science & Engineering, Vol. 11(30), pp. 1-4.

[6] Park D.U, Yeom J.K., Lee W.J. and Lee K.M. (2013. Assessment of the levels of airborne bacteria gram-negative bacteria and fungi in hospital lobbies, International Journal of Environmental Research and Public Health, Vol. 10, pp. 541-545.

[7] Flannigan B., Samson R.A and Miller J.D. (2011). Microorganisms in Home and Indoor Work Environments: Diversity Health Impacts Investigation and Control, 2nd edition, CRC Press, Florida.

[8] Szymczak M.J. and Gorny R.L. (2010). Bacterial and Fungal Aerosols in Air-Conditioned Office Buildings in Warsaw Poland - The Winter Season, Journal of Occupational Safety and Ergonomics, Vol. 16(4), pp. 465-476.

[9] Kowalski W.J. and Bahnfleth W.P. (2000). UVGI Design Basics for Air and Surface Disinfection, Heating Piping Air-conditioning Engineering, pp.100-110.

[10] Severin B.F., Suidan M.T. and Engelbrecht R.S. (1983). Effects of temperature on ultraviolet light disinfection, Environmental Science & Technology, Vol. 17(12), pp. 717-721.

[11] Chang J.C.H., Osoff S.F., Lobe D.C., Dorfman M.H., Dumais C.M., Qualls R.G. and Johnson J.D. (1985). Inactivation of pathogenic and indicator microorganisms, Applied and Environmental Microbiology, Vol. 49(6), pp. 1361-1365.

[12] Sharp G. (1939). The lethal action of short ultraviolet rays on several common pathogenic bacteria, Journal of Bacteriology, Vol. 37, pp. 447-459.

[13] Lawrence M.G. (2005). The relationship between relative humidity and the dew point temperature in moist air: A simple conversion and applications, Bulletin of the American Meteorological Society, Vol. 86, pp. 225-233.

[14] Buck A.L. (1987). New equations for computing vapor pressure and enhancement factor, Journal of Applied Meteorology, Vol. 20, pp. 1527-1532.

[15] Goff J.A. (1957). Saturation pressure of water on the new Kelvin temperature scale, Transactions of the American Society of Heating and Ventilating Engineers, pp. 347-354.

[16] Severin B.F., Suidan M.T., Rittmann B.E. and Engelbrecht R.S. (1984). Inactivation kinetics in a flowthrough UV reactor, Journal of the Water Pollution Control Federation, Vol. 56(2), pp. 164-169.

[17] Fletcher A. (2004). The Influence of Relative Humidity on the UV Susceptibility of Airborne Gram Negative Bacteria Louise, Aerobiology Research Group, University of Leeds, Vol. 6(1), pp. 12-19.

[18] Peccia J.L., Werth H.M., Miller, S.M. and Hernandez, M.T. (2001). Effects of Relative Humidity on the Ultraviolet Induced Inactivation of Airborne Bacteria, Aerosol Science and Technology, Vol. 35, pp. 728-740.

[19] Riley, R.L. and Kaufman E.J. (1972). Effect of Relative Humidity on the Inactivation of Airborne Serratia marcescens by Ultraviolet Radiation, Applied Microbiology, Vol. 23(6), pp. 1113-1120.

[20] Gwangpyo K., First M.W. and Burge H.A. (2015). The Characterization of Upper-Room Ultraviolet Germicidal Irradiation in Inactivating Airborne Microorganisms, Environmental Health Perspectives, Vol. 110(1), pp. 95-101.

[21] Peccia J.L. and Hernandez, M.T. (2004). UV-Induced Inactivation Rates for Airborne Mycobacterium bovis BCG, Journal of Occupational and Environmental Hygiene, Vol. 1(7), pp. 430-435.

[22] Peccia J.L. and Hernandez, M.T. (2001). Photo reactivation in Airborne Mycobacterium parafortuitum, Applied and Environmental Microbiology, Vol. 67(9), pp. 4225-4232.

[23] Environmental Control for Tuberculosis. Basic Upper-Room Ultraviolet Germicidal Irradiation Guidelines for Healthcare Settings. Department of Health and Human Services. NIOSH. 2009. . Available at *http://www.cdc.gov/niosh/docs/2009-105/pdfs/2009-105.pdf*

[24] Availabe at: ASHRAE Standard 62.1-2013.

[25] Availabe at: Technical Guidance 2425/86 of Technical Chamber of Greece (TGTCG).

