UV DISINFECTION OF AIR
SOME REMARKS

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ABSTRACT

This work is a contribution to the understanding of the mechanisms controlling concentration of microorganisms in air by UV treatment. The focus of this article is enclosed systems or in-duct systems. The simple model for calculation of necessary number of UV lamps is presented

CALCULATION AND DESIGN OF UV APPARATUS

Currently UV technology has grown significantly as a competitive method for the disinfection of water. The technology covers a wide range and detailed examinations have been carried out (see for example USEPA 1986; Bolton 2001; Blatchley et al. 1996). As to the disinfection of air, the situation is opposite. The use of Ultraviolet Germicidal Irradiation (UVGI) for air disinfection has a longer history than that of UV for the disinfection of water, and although quite voluminous monographs have been published (see USEPA 1986), today one does not have a detailed understanding as to how and where it is necessary to apply UV for air disinfection. It is not clear what UV doses the equipment should provide and what low levels of microbiological contamination of air should be reached. Such levels may depend on whether one speaks about epidemiological criteria or about terrorist bio-attack danger. How should one calculate the UV required for installations handling air? As example of the fact that water disinfection occupies the major attention of experts, one can see that at the recent UV Congress in Vienna in 2003 and the UV Conference in Karlsruhe in 2004, papers devoted to air treatment were less than 10% of all papers presented. However, it is necessary to note that Nardell (2004) and Fletcher (2004) have introduced serious steps concerning the development of UV technology for disinfection of air.

This article does not contain answers to all the problems and questions concerning the application of UV for air treatment. Instead, the purpose is to discuss a series of concerns that have not previously been considered in detail and are important not only to the development of UV installations, but also to their operation. The focus of this article is enclosed systems or in-duct systems, although some of the comments may be applicable to open field systems.

CALCULATION METHODS FOR UVGI SYSTEMS

Calculation of the Irradiance[1] Distribution

Concerning the formulas used for calculation of the irradiance distribution about a UV lamp, Kowalski (2002) recommended the use of a design procedure for the UV irradiance distribution with the reference to Modest (1993), augmented with the use of the so-called view factor. The expression obtained in Modest (1993) for the irradiance E(x) is the result of integration of the expression

[1]

$$E(x) = \frac{P_{0\lambda}}{2\pi^2 L} \int_{\ell_1}^{\ell_2} \int_{-\phi_0}^{\phi_0} \frac{\left(x - r\cos(\phi)\right)\left(x\cos(\phi) - r\right)}{\left(x^2 + r^2 + z^2 - 2xr\cos(\phi)\right)^2} \, dz \, d\phi$$

where r is the radius of the lamp

L is the length of a lamp

x is the radial distance from the axis of the lamp

ℓ_1 and ℓ_2 are coordinates of the ends of the lamp (see Fig. 1)

$\phi_0 = \arccos\left(\frac{r}{x}\right)$

$P_{o\lambda}$ is the UV radiant power

z is coordinate along axis of the lamp distribution around a UV lamp.

Modern mathematical programs easily allow one to calculate directly the irradiance at a point without requiring the use of the view factor.

If one requires the development of a UVGI system application using medium pressure lamps (MPL) or Xe flash lamps, it is necessary to remember that equation 1, and

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[1] This should be called the "fluence rate", since it incorporates UV coming from all directions; however, since the term "irradiance" is in wide use, this term will be retained.

hence the analytical expression obtained in Modest (1993), is obtained for optically dense lines, that is, for radiation described by major re-absorption. Thus, this formula may be applied only for evaluation of the irradiance distribution for the 185 and 254 nm lines of a MPL. For other lines of the bactericidal emission spectrum of a MPL and for a Xe flash lamp, the formula for optically thin plasma should be used. In this case, the irradiance E(x) is given by [2]

$$E(x)=\frac{P_{0\lambda}}{2\pi^2 L}\int_{l_1}^{l_2}\int_{-\phi_0}^{\phi_0}\frac{\left(x\cos(\phi)-r\right)^2\left(x-r\cos(\phi)\right)}{\left(x^2+r^2-2xr\cos(\phi)\right)\left(x^2+r^2+z^2-2xr\cos(\phi)\right)^{3/2}}\,dz\,d\phi$$

The neglect of this expression gives an error by a factor of $4/\pi$.

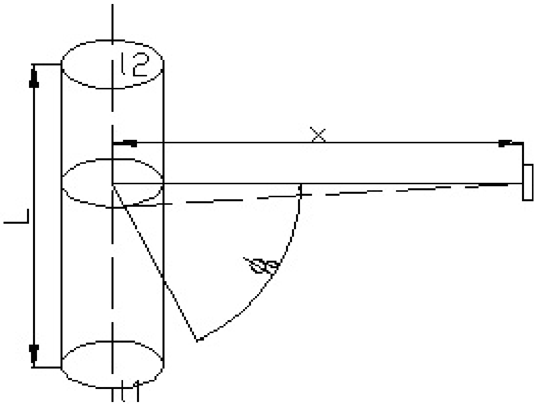

Figure 1. The scheme used for calculation of the irradiance distribution around a UV lamp.

Accounting for Reflected UV

In the calculation of UV dose for UV air recirculators, the UV light reflected from walls of the plant is often taken into account. The walls of the plant are specially made of polished metals for magnification of reflection, in most cases from aluminum and sometimes from stainless steel. Such approaches are grounded on laboratory measurements of the reflection coefficient of the reflector. The reflected UV light can lead to a magnification of the delivered UV dose; nevertheless, we would like to note that for the number of applied problems the account of reflected UV light is redundant. So, for example in the food industry where manufacture leads to formation of dust and aerosols (confectionery factories, milk factories etc.), the interior surface promptly (in some days) is coated with a thin coating from the organic materials, which reflects the UV light poorly. Such situations are sometimes observed even if the recirculators are equipped with dust filters.

It is known that a thin layer of an oxide, dust, or fat molecules gives a dramatic decrease of reflectivity. Suppose that the reflectivity of the polluted surface is 20% and the radius of a lamp is 1 cm. If the wall is 8 cm away from the axis of a lamp, the irradiance at the wall is approximately $0.15P_{o\lambda}$. Hence, from a stainless steel wall, approximately $0.03P_{o\lambda}$ will be reflected. It is hardly necessary to take into account a 3% factor. Certainly if the lamp is closer to the wall, or if the stainless steel is substituted with polished aluminum, the reflection will increase.

Probably, in the electronic industry where the demands to cleanliness of air are very high, one should take reflection into account. In any case, the question of the influence of reflected light and the contamination of walls of the UV apparatus, and the contamination of lamps needs experimental investigations. And in the case of recirculators in conditions where the pollution of interior surfaces is possible, it is recommended to carry out a bioassay of the pilot plant.

Operation of Lamps in a Stream

In the design and calculation of UV systems, it is necessary to consider the environmental conditions accurately, especially for low pressure lamps (LPL) as the normal type, and also for amalgam lamps.

It is well known, that LPLs have rather narrow range of operating temperatures and reach a maximum efficacy at 42ºC. At a temperature of 25ºC, there is a considerable decrease of the UV power and efficacy.

In normal lighting installations, the temperature conditions are ensured by the construction of the fixture. In UV equipment for water disinfection, the necessary temperature environment can be assured using a quartz sleeve.

While working with LPLs in an air stream in the case where the axis of a lamp is perpendicular to stream, and also in the case when the axis of lamp is parallel to stream, there is an infringement of temperature conditions. The temperature of lamp decreases leading to a decrease of the UV irradiance.

Thus, in the design of UV systems it is impossible to use $P_{o\lambda}$ – the power of a lamp measured under normal conditions. It is necessary to measure UV efficiency under the same conditions in which it is planned to use these lamps. This is especially important for systems built into ventilating shafts, where the flow rates are high. In the design of UV systems for high velocities, the axis of the lamps should be arranged parallel to the flow direction. For very high velocities, to provide the required temperature of the lamp's operation, it is necessary to put the lamps into quartz sleeves. For amalgam lamps, it is enough to provide required temperature at the spot where the amalgam is located.

Hence, in the design and calculation of UV systems for air treatment, it is necessary to take into account the type of the lamp, the change of modes of its operation in an air stream, the cleanliness of the air to be treated and the rate of fouling of the lamp's surface. Only after carrying out of field tests is it possible to decide if one should take into account the effect of reflected UV light.

SIMPLE MODEL FOR THE CALCULATION OF THE EFFICACY OF A RECIRCULATING AIR UV DISINFECTION UNIT

The range of application of the small UV equipment for air disinfection in buildings has expanded considerably. The principle of the device of such equipment (UV recirculation unts) is very simple – UV lamps, a ventilator pumping the air through radiation zone and sometimes filters (see Figure 2)

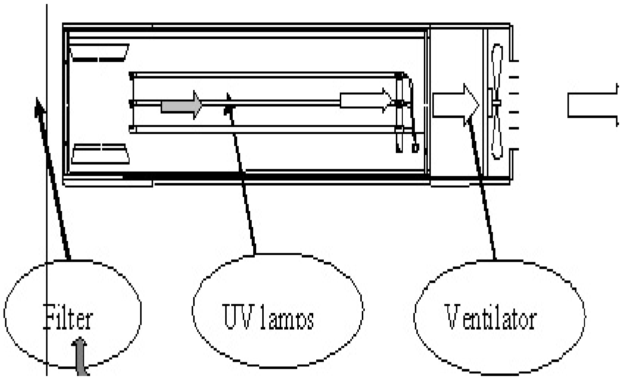

Figure 2. The principal scheme of operation of the UV recirculator.

During operation the air in the space of a building, the air is injected by a ventilator into the radiation zone, and in transiting its air is disinfected and then pushed out back into the building space. Obviously, the efficiency of UV recirculators depends on the allocation of air flows in a room and on the location of the recirculator. To understand, how important is the position of the recirculator in a room, consider an extreme case. Suppose one needs to disinfect air in a room containing a wardrobe. If one places the recirculator inside the wardrobe, one only receives very clean air inside the wardrobe, but it will not influence the air in a room. Of course, this is obviously a farfetched example; nevertheless, it shows that while developing systems for UV disinfection one should accurately take into account in detail the geometry of a room and calculate the motion of air flows created by recirculator.

By virtue of complex calculations of fluid dynamics, it is possible to give engineers a simple model permitting them to estimate promptly and without the complex calculations the necessary size of the UV recirculator system. In this paper such attempt is undertaken.

Assumptions

Consider an apartment of volume V, and the volume of dead air space zones V_d. Assume that the air from dead air space zones does not reach the recirculator, and the air in the remaining space moves evenly and with a uniform velocity. Also assume that for the recirculator itself, the model of complete intermixing is valid; in other words that each part, transiting through radiation zone receives a UV dose which equals $\langle E \rangle \cdot \langle t \rangle$, where $<E>$ is the average irradiance in the irradiation zone and $< t >$ is the average transit time of a particle through the irradiation zone.

Also consider that the microorganisms in the recirculator decay according to the law e^{-kD}, where k is the UV sensitivity[2] of microorganisms to UV radiation and D is the UV dose applied.

The increase of number of microorganisms in the air happens in two ways. The first is in the immediate volume of an apartment, or on a surface with subsequent injection into the volume according to the law $\ln 2/\tau$, where τ is the average division time of microorganisms for the given environment. The second is due to a constant source, for example the carrier of an infection which sneezes out q cells per second and then it is necessary to count this value per unit volume.

Assume that such microorganisms are immediately and instantaneously distributed into the volume of the apartment. For illustration of the offered model we consider four-seated hospital chamber with the volume of 6 × 6 × 3 = 108 m^3. Assume that each patient coughs or sneezes 3 times per hour, and for each sneeze throws out in a room about 500 microorganisms (Kowalski and Bahnfleth 1998). Then q will be 0.015 particles per second per m^3. And for this estimate we use the Influenza A virus, for which $k = 0.00119$ cm^2/μJ (Kowalski 2002.)

Dependence of the Concentration of Microorganisms in the Air on the Operating Time of the UV recirculator

Let the initial concentration of microorganisms be n_o. At a time t the concentration will be n. The change of concentration of microorganisms in volume is given by the equation

$$\frac{dn}{dt} = n \cdot \left(\frac{\ln(2)}{\tau} - \frac{kDQ}{V - V_d} \right) + q \qquad [3]$$

where Q is the flow rate of air through the recirculator.

The solution of this equation is

$$n(t) = \frac{q}{a} + \left(n_0 + \frac{q}{a} \right) \cdot \exp(-at) \qquad [4]$$

where $a = \dfrac{\ln(2)}{\tau} - \dfrac{kDQ}{V - V_d}$

The obtained solution is easy to analyze.

1. If $a > 0$, then the quantity of microorganisms increases in some time, even with a working recirculator.
2. If $a = 0$, then the concentration of microorganisms remains at a stationary value.

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[2] Hereinafter, only UV light of 254 nm is considered; the generalization to other wavelengths does not present any difficulties.

3. If $a < 0$, then there is a decrease in the concentration of bacteria, but is not lower than limiting value which equals
$$n_3 = \frac{q}{\frac{kDQ}{V - V_d} - \frac{\ln(2)}{\tau}}$$

DISCUSSION

For a wide class of applications, it is possible to neglect reproduction of microorganisms in dry air. Then the solution obtained by us is

$$n(t) = \frac{q \cdot (V - V_d)}{kDQ} + \left(n_0 - \frac{q \cdot (V - V_d)}{kDQ}\right) \cdot e^{-\frac{kDQ}{V - V_d}t}, \quad [5]$$

Depending on the relation of quantities included in this equation, three variants of the change of concentration of particles are possible; however in any case the limit of concentration, which quantity of microorganisms will achieve will be

$$\frac{q \cdot (V - V_d)}{kDQ} \quad [6]$$

If the initial concentration of microorganisms, that is, concentration at the moment of switching on the UV system, is more than this value, the concentration will reduce; if it is less, the concentration will grow even at UV system which is on.

Thus if it is required to achieve the concentration of microorganisms n^*, then a UV recirculator must ensure a UV dose

$$D > \frac{q \cdot (V - V_d)}{n^* kQ} \quad [7]$$

So, for the assumptions given above, one wants, for three air changes per hour, that the concentration of microorganisms is less than 1 CFU per m^3. The productivity of the UV system will be 0.09 m^3/sec under the condition that the UV dose provided is not less than ≈ 13 mJ/cm^2. Hereinafter, the aggregate volume of stagnant bands is supposed to be equal 15% of the whole volume of a room. Thus, one obtains the necessary minimal dose for all UV systems. Then on using the data declared by the manufacturers, one can determine the necessary size of the UV system for the given requirements. One should clearly understand that reduction of microbiological contamination of the air in stagnant bands will not occur, since the UV recirculator can only influence the air exposed to UV processing. Apparently, the complexity connected with the organization of airflows so that all air has had the necessary UV processing is the main deficiency of UV recirculators. The UV systems described by Nardell (2004) are unconditionally deprived of such deficiency, but at use of unclosed irradiators, presence of people in handled room is restricted at this time, or it is not supposed at all, that is not always possible to fulfill in practice. One can also use a computational fluid dynamics (CFD) analysis to look at complex flows (Noakes et al. 2004).

For single-tube recirculators in a cylindrical housing, a method can be developed at once tpo allow one to obtain the number of UV lamps necessary to achieve a required level of disinfection. For single-tube recirculators the following expression is valid

$$D_{ap} = \frac{\langle E \rangle \cdot V_{ap}}{Q} = \frac{P_{UV\_lamp} \cdot (R - r_0)}{Q} \quad [8]$$

where D_{ap} = dose of irradiation provided with one apparatus

V_{ap} = the volume of the apparatus

R = the interior radius of the shell (e.g., 10 cm)

r_0 = the exterior radius of the lamp or a quartz sleeve (e.g., 1 cm)

$P_{\text{UV lamp}}$ = germicidal power of the UV lamp. (e.g., 30 W)

Equating expressions [7] and [8] one obtains that the number of UV lamps should be more than

$$\frac{q \cdot (V - V_d)}{n^* k P_{UV\_lamp} \cdot (R - r_0)} \quad [9]$$

For the example given, and a recycling of air and velocity of air pollution by microbes according to eq. 9, one obtains that it is necessary to have five UV lamps of the specified power for concentration Influenza A virus to be less than 1 CFU per m^3.

CONCLUSIONS

In this article, sources of error are considered as they relate to errors in calculation and the choice of UV recirculators for air disinfection. A simple model is derived permitting one to quickly estimate the necessary amount and power of UV recirculators for air disinfection in buildings. It is necessary emphasize that the given model easily allows one to obtain results with quite good precision, but it is only an estimate. Precise calculations should be based on the fluid dynamics of air flows for a specific apartment, taking into account possible barriers in the trajectory of air jets. In any case, for the engineer making calculations the knowledge and understanding of aerodynamics is required.

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