METHODS FOR INDOOR AIR DISINFECTION AND PURIFICATION FROM AIRBORNE PATHOGENS FOR APPLICATION IN HVAC SYSTEMS

Z. D. Bolashikov[†], and A. K. Melikov

International Centre for Indoor Environment and Energy, Department of Mechanical Engineering, Technical University of Denmark, 2800 Lyngby, Denmark, www.ie.dtu.dk

ABSTRACT

The present paper is a review on methods and technologies for air cleaning from micro organisms and viruses, which are applicable with the present HVAC practices. The advantages and the drawbacks of air dilution, filtration (HEPA, ULPA), ultraviolet germicidal irradiation (UVGI), photocatalytic oxidation (PCO), plasmacluster ions and other technologies for air disinfection and purification is critically analyzed with respect to the used today air distribution principles. The importance of indoor air characteristics, such as temperature, relative humidity and velocity on the efficiency of the methods is analyzed with consideration of nature of the pathogens themselves. Recent encouraging studies show the benefit of using essential oils as antimicrobial and anti-fungal agents (thyme, bay, cinnamon, clove, etc.). Though their application is confined to the food industry and pharmaceutics, some promising results show possible applicability in the field of ventilation and air conditioning to deactivate the airborne micro-organisms. The applicability of the methods with different types of ventilation used at present indoors, i.e. total volume ventilation (mixing and displacement), as well as advanced air distribution techniques (such as personalized ventilation) is discussed.

KEYWORDS

Pathogen, disease, droplet, respiratory, HVAC, dilution, PV, PCO, PCI, essential oils

INTRODUCTION

Majority of people live, work and recreate in densely populated environments, which facilitate to a greater extend their susceptibility to different pathogens. The threat of getting sick has health related and psychological issues. It reduces the well-being of the population as well as has a strong economical impact due to absenteeism and reduced productivity. Human history remembers a lot of outbreaks of pandemics during its existence, e.g. the Spanish flue of 1918-1919 (H1N1), which was by far the most lethal flue pandemic of the 20th century, infecting about a quarter of the global population and killing more than 40 million people (WHO 2002).

The increased mobility allow the fast spread of new diseases and a greater risk of pandemics, e.g. the Severe Acute Respiratory Syndrome (SARS), emerging of old well known diseases but resistant to the existing drug treatment (Sarita Shah et al.. 2007), etc.. Another thread imposes the fast mutation of some pathogens and their adaptation as a causative of human diseases, e.g. H5N1 strain of avian flu (WHO 2006).

All these factors predetermine the importance of making the indoor environment an “oasis”; a place free from any dangers from pathogens, with high air quality and able to satisfy the thermal preferences of its habitants. Unfortunately, most of our indoor work places are not designed to prevent the spread of airborne pathogens. Even more, the air distribution system could enhance this transmission. Therefore in order to solve this multi-disciplinary problem successfully, knowledge in different fields is necessary: the nature of the pathogen (virulence factors), its generation and survival mechanism before and after affecting the host, possible disinfection methods to eradicate it and the transmission mechanisms among people.

[†] Corresponding Author: *Tel: + 45 4525 4038, Fax: + 45 4593 2166*
E-mail address: zdb@mek.dtu.dk

Taking into account the knowledge required, engineering solutions could be proposed in order to reduce effectively the pathogen loads transmitted in air, disable their virulence, and make them harmless for the healthy inhabitants. The methods applied, should be neither life nor health threatening, nor deteriorating in any way the air quality of occupants nor their thermal comfort, user friendly (if people are to operate them), with low noise emission, high ergonomics and aesthetics.

Airborne Pathogens, Generation

Airborne pathogens are those pathogens that are generated in the respiratory system and transferred in the air as a way of propagation. In her review article Morawska 2005 describes the generation mechanism and sites of pathogens' droplet formation, the factors influencing the process, as well as the fate of the expelled droplets via occupants' respiratory activities. She concludes that though lots of understanding exists, still, more knowledge is needed on the mechanism of pathogen transfer in occupied places.

In her article Fiegel 2006 shows that pulmonary activities generating bio-aerosols are the main source for deep lung and environmental transport of airborne pathogens. She marks that applying "saline therapy" (aerosol approach to immobilize bio-aerosols in the lungs) would reduce the airborne pathogen generation, allowing natural clearing mechanisms.

Another form of airborne contamination with infectious bio-aerosols could occur at vomiting or flushing of toilets in public premises. Barker et al. 2001 investigations showed that a sick person can produce 10^7 viruses per 1 ml of vomit and 10^{12} viruses per 1 g of stool material. So with some pathogens promoting vomiting of the host or diarrhea like conditions (SARS, Escherichia coli, Neisseria meningitidis etc.), there is a high risk of spreading the disease. Rusin et al. 1998 found that droplets produced by flushing the toilet could either be inhaled or deposited on surfaces.

The virulence, pathogen generation and the infective dose are other important factors determining the infectivity of a pathogen. Different microorganisms have different methods of breaking the defense of their host and successfully hiding. Also the generation of pathogens is different depending on the stage of the disease (early, advanced or latent). Another point of importance is the infective dose: sometimes a single organism can cause a disease, and is also related to the immune system and/or age of the patient: immuno-compromised people as well as old and very young are more susceptible (Greenwood et al. 2002).

Survival of Pathogens in Air

In order to be able to reach their host and infect him, airborne pathogens need to survive in the surrounding environment, which makes factors like relative humidity and temperature important. Nowadays the knowledge on the influence of relative humidity on pathogenic bacteria is scarce and the little data available is on opportunistic representatives. In general mid-range humidity conditions (40-60%) are shown as more lethal to non-pathogenic bacteria (Hatch et al. 1969). Viruses with more lipids tend to be more persistent at lower relative humidity, while viruses with lesser or no lipid content are more stable at higher relative humidity (Assar 2000). Loosli 1943 showed that humidity levels of 80-90% for 30 minutes could render the influenza virus noninfectious to mice, while exposure to lower humidity levels (17-24%) provided the greatest infectivity. In other studies the survival of some viruses has been shown to be independent of relative humidity (Elazhary 1979). Harper 1961 and Miller et al. 1967 showed that picornaviruses and adenoviruses, respiratory disease causatives and members of non-enveloped virus groups, survive better at high relative humidity. Measles and influenza, both enveloped viruses, survive best in aerosols at low relative humidity (de Jong et al. 1964, Hemmes et al. 1960). Other enveloped viruses have been demonstrated to be least persistent at intermediate relative humidity (de Jong et al. 1976).

Studies also report that the effects of relative humidity on virus survival can be influenced either positively or negatively by temperature. At 20ºC human coronavirus (upper respiratory tract diseases) was reported to be most stable at intermediate humidity, but was also relatively stable at low humidity (Ijaz et al. 1985). Same study also points out that virus survival at 6º C and 80% humidity was very similar to the best survival at intermediate humidity. Lower temperatures have also been shown to enhance rhinovirus survival at high relative humidities (Karim et al. 1985). Enveloped viruses and their patterns of survival at different temperatures (Mayhew et al. 1968 and Ehrlich et al. 1971) may not be

the same like for non-enveloped viruses, especially when the viruses are on surfaces (McGeady et al. 1979).
Still more research is needed in this field, since from safety point of view scientists work with non-pathogenic organisms, which have different structure from their pathogenic relatives (Greenwood et al. 2002).

DISINFECTION METHODS

A great effort has been made to find engineering techniques to keep the airborne pathogens away from occupants in buildings, or at levels low enough to be unable to cause a disease: dilution, filtration, Ultra Violet Germicidal Irradiation (UVGI), etc. The airborne pathogens could be generated from a sick person, from the building itself (HVAC system, building materials etc.) or by an intended release: terrorist attack (LaForce 1984, Kowalski et al. 2003).

Dilution

Dilution of room air with clean disinfected air is one of the easiest methods to remove pathogens and to decrease the risk of infections in rooms. Natural, mechanical and hybrid ventilation are often used to supply clean air in rooms. However this method has its limitations, which will be discussed in the following.

Filtration

A method widely used today is the filtration of air in HVAC systems. Classification and guidelines exist for applying filtration as part of the ventilation system and are widely used by designers (ANSI/ASHRAE Standard 52.2-1999, ISO 14644-1 1999). Studies show that filtration is a good method to stop outside pathogens into penetrating the building envelope through the mechanical ventilation. Kowalski et al. 1998, Kowalski et al. 2002 showed that "80- and 90-per-cent filters can produce air-quality improvements that approach those with HEPA filters, but the most at much lower cost". Another finding is that microorganisms of penetrating size range of HEPA filters are predominantly nosocomial infections (HEPA filters remove 99.97% of all particles 0.3 μm or larger in diameter).

UVGI irradiation

UVGI light is emitted by mercury vapour arc lamps at a wavelength of 253.7 nm usually. UVGI damages the pathogen DNA/RNA and makes them harmless: they cannot reproduce once they have entered their host. Laboratory research has shown that the germicidal effect of UVGI is a function of two factors mainly: the intensity of the UVGI energy and the time span of exposure (Luckiesh 1946, Riley et al. 1976, Chang et al. 1985, Ko et al. 2002). These studies found dependence on pathogen susceptibility on the presence or absence of cell wall and its thickness. Since smallpox, influenza and adenovirus lack cell wall they are more easily inactivated (Jensen 1964), while spores (e.g. Bacillus anthracis) are the most difficult to inactivate due to their protective cover (Knudson 1986). There are two ways to use UVGI application in practice: ceiling/wall mounted or in-duct application.
Disinfection of air by upper room mounted UVGI started in the 30s in USA (W. F. Wells 1935, W. F. Wells 1955). The inactivation process occurs when the pathogens enter the UVGI zone (1.8m above the floor). The inactivation rate of UVGI in rooms could be enhanced by either increasing the intensity of light, or promoting higher velocities in rooms (better mixing), or creating a temperature gradient to facilitate transport of pathogens (Riley and Permutt 1955, Riley et al. 1971a, 1971b). Another important factor for the UVGI efficiency is the level of relative humidity. Studies (Peccia et al. 2001, Xu et al. 2005) show that with increased humidity in the environment the pathogens are more likely to survive the germicidal effect of the UVGI lamp. An adverse health effect of UVGI on humans is the mild form of erythema of skin or painful photokeratitis of eyes. Therefore UVGI lights are kept in deep louver enclosures to prevent overexposure at eye level or excessive reflection from ceilings, but those casings absorb a big amount of the useful UV energy, making it less efficient. So far, there are some guidelines for upper-room UVGI application published (First et al. 1999a, 1999b).
In buildings with lower than 2.4m ceilings duct UVGI irradiation must be applied. The problems of direct eye contact or skin contact are not relevant here, so the systems could be operated at even higher intensities. Several studies concentrated their effort in understanding the location of the UVGI system as part of the HVAC, the intensity at which to operate, considering the multiple reflections

within the metal ducts (Kowalski et al. 2000, Kowalski et al. 2001).

Photocatalytic oxidation

Photocatalytic oxidation (PCO) is a process where a chemical compound is oxidized to simpler radicals using a strong reduction agent (TiO_2, WO_3, ZnS etc) in the presence of a light source (Fluorescent or UV light). This technology is innovative and still in research phase, especially in purging airborne bacteria. The results are somewhat encouraging, since some pathogens are readily destroyed after treatment with a TiO_2 coated PCO unit (Krishna et al. 2005, Pal et al. 2007). An enhancement of the germicidal effect could be achieved by doping TiO_2 photocatalyst with Ag^+ ions (Vohra et al. 2006). The process of pathogen inactivation is still under explanation and further research is required (Pal et al. 2007).

Plasmacluster Ions

New and interesting technology that emerged commercially on the market and claims to neutralize 26 kinds of harmful airborne substances is the Plasmacluster Ions technology (PCI). It uses negative (O_2^-) and positive (H^+) ions that inactivate the pathogen by binding on their surfaces, changing the structure of the proteins/polysaccharides by stealing an OH^-radical and thus changing the properties of the pathogen rendering it "impotent" to infect (Sharp Corporation 2005).Possible elevated levels of ozone (O_3) could also be the case.

Essential oils

Latest studies show that essential oils used in pharmaceutics, cosmetics and food and beverage industries have a strong germicidal effect and could be applied in ventilation industry. Furthermore, essential oils' antimicrobial effect is enhanced in air environment rather than when in solution media (Hammer et al. 1999, Pibiri et al. 2003, Inouye et al. 2003). But their application is still going through an intensive research. Another factor limiting their application is the hypersensitivity reaction of some occupants to certain essential oils (mint, thyme, oregano etc), and the fact that some of those oils also exhibit cytotoxic activity (Inouye et al. 2003).

DISINFECTION METHODS AND AIR DISTRIBUTION TECHNIQUES

The following discussion is limited to mechanical ventilation only. Essentially, two principles of room air distribution are commonly used in practice: mixing and displacement ventilation. Mixing ventilation aims to create a homogeneous environment in the occupied zone: the clean air is supplied at high velocity which promotes mixing with the room air and thus with the pathogens generated by a sick occupant. The mixing will enhance the risk of disease transmission for the other habitants. On the other hand, displacement ventilation introduces the conditioned air at a slightly lower temperature (3-6^{0}C) than room temperature through floor or wall mounted diffusers. The cold air spreads along the floor and moves upwards, entrained by flows generated from heat sources (people, equipment etc.), and then it is exhausted close to the ceiling. Due to high risks of draught, supply velocities are kept low, which promotes easy destruction of the displacement pattern at certain human activities like walking, coughing, sneezing etc. Though more efficient in removing contaminants, particulate matter and droplets from the occupied zone compared to mixing ventilation, already at a speed of 1.0 m/s of a moving person in a closed environment with displacement ventilation, close to complete mixing situation is reported (Mattsson 1999, Bjørn et al. 1997). Mundt (2001) and Mattsson (2002) showed that displacement effect starts to decline for particles already in the range 5-10 μm, suggesting influence of gravity forces. Therefore bigger droplets with more pathogens would deposit on surfaces and contribute contaminating hands or fomites. Dilution could solve to some extend the problem of controlling the level of pathogens, but the limiting factor here would be the induced local thermal discomfort of the occupants: both with mixing and displacement this would be associated with draught problems. Another issue could be the cost effectiveness of this scenario: bigger ducts, more powerful fans, over-sizing of the HVAC unit. To overcome the associated problems with diluting the air, UVGI technology could be used instead. Mounted at the ceiling level, louvers with a UVGI encased, would work quite well with the mixing principles. The generated mixing would bring faster the pathogens to the upper part of the room, where they would be inactivated, but for sure this principle would not yield feasible, when applied to displacement. Once taken by the hot convection flow around humans, the pathogens would be exhausted close to ceiling. Therefore the UVGI technology here is the in-duct installation, useful for large halls with displacement ventilation, where people spent most of the time seated: theaters, concert halls, offices etc. (Buttolph 1948, Menzies et al. 2003). Filtration or PCO could also be the case of controlling the pathogen levels in buildings. However filters are not efficient in protecting occupants once pathogens are generated inside the occupied space: they are effective at removing the microorganisms or toxins present in the outside air: in-duct installation. Sometimes filters themselves can become source of bacterial growth and thus contribute to high pathogens' levels of the respirable range: less than 1.1 μm, especially at elevated humidity, higher than 80% RH (Möritz et al. 2001). On the other hand, the existing problem of PCO could be the by-products formation: a result from oxidation. Some radicals produced can deteriorate the Indoor Air Quality (aldehydes etc.) or even prove hazardous (formaldehyde), and thus make their application useless in occupied places. Other feature is the economical point: filters need to be regularly changed as well as the coating of the PCO unit, also both exert additional load on the HVAC system, resulting in more powerful fans. An alternative solution, in rooms with mixing ventilation could be the usage of chill-beams or convectors, recirculating part of the room air through a heat exchanger and a small local HEPA filter and an incorporated UVGI unit as well. All these findings suggest new, more suitable for the purpose systems of air ventilation: systems that would reduce to a minimum the airborne route of pathogens within the occupied places. A possible solution is the personalized ventilation (PV), that aims to provide clean air within the breathing zone of each occupant, and thus to improve the inhaled air quality. An improved thermal comfort, by providing individual control to each occupant, is another benefit from the personalized ventilation. Thus personalized ventilation has potential to increase occupants satisfaction, to decrease reports on SBS symptoms, and to increase work performance (Melikov 2004). When properly applied PV has greater potential to prevent occupants from airborne pathogens compared to total volume. Research in the field is just starting but there are evidences suggesting that: "in rooms with mixing ventilation the PV would always protect the occupants from airborne pathogens and is superior to mixing alone" (Cermak and Melikov 2007). However in rooms with displacement ventilation, PV promotes mixing of the exhaled air with the room air (Melikov et al. 2003, Cermak et al. 2004). Similar observations are true for rooms with underfloor ventilation as well (Cermak and Melikov 2003, 2004; Cermak et al. 2004, Cermak and Melikov 2007). So there is a risk of transmission of airborne infections to occupants, who are not protected by high efficiency PV i.e. occupants who are not at their work stations. The positive feature of a PV system is its feasibility and the small flow rates used, as well as the close proximity to the occupant. A small filter or UVGI unit could be included in the PV system, which uses room air assuring that each occupant gets clean disinfected from pathogens air. This would further enhance the effect of the PV system, however field studies to prove this are necessary.

CONCLUSION

Perfect solutions to stop the airborne disease transmission does not yet exist, but the available disinfection techniques can be successfully implemented, provided that air distribution in rooms, as well as the flow interactions from human activities and the pathogen characteristics is understood. One of the most highly efficient methods in neutralizing pathogens and rendering them harmless to the occupants is the UVGI. Yet due to its adverse health effects its application is limited within the occupied place itself, but could be readily used in the HVAC system itself together with filtration, providing even better protection for habitants and reducing the risks of bio-terrorists' attacks.

REFERENCE

1. A. K. Melikov, R. Cermak et al. (2003) "Impact of airflow interaction on inhaled air quality and transport of contaminants in rooms with personalized and total volume ventilation", Proceedings: Healthy Building 2003, Singapore, 2, p. 500-510.
2. A. K. Melikov (2004) "Personalized ventilation", Indoor Air 2004; 14 (Sppl7), p. 157-167.
3. ANSI/ASHRAE Standard 52.2-1999 "Method of Testing General Ventilation Air Cleaning Devices for removal Efficiency by Particle Size".

4. A. Pal, S. O. Pehkonen, L. E. Yu, M. B. Ray (2006), ”Photocatalytic inactivation of Gram-positive and Gram-negative bacteria using fluorescent light”, Journal of Photochemistry and Photobiology A: Chemistry 186 (2007), p. 335-341.
5. A. Vohra, D. Y. Goswami, D. A. Deshpande, S. S. Block (2006), ” Enhanced photocatalytic disinfection of indoor air.” ELSEVIER, Applied Catalysis B: Environmental 65 (2006), p. 57-65.
6. C. G. Loosli et al. (1943), “Experimental Airborne Influenza Infection: I. influence of humidity on survival of virus in air”, Proc Soc Exp Biol Med. 53, 205-6.
7. C. J. Mayhew et al.. (1968), “Assessment of aerosol stability of yellow fever virus by fluorescent-cell counting”, Appl Microbiol. 16: 263-266.
8. D. Greenwood, R. C. B. Slack, J. F. Peutherer (2002) “Medical Microbiology”, Sixth edition, published by Churchill Livingstone.
9. D. Menzies, J. Popa, J. A. Hanley et al. (2003)”Effect of ultraviolet germicidal lights installed in office ventilation systems on workers’ health and wellbeing: double blind multiple crossover trial”, The LANCET, v. 362, p. 1785-1791.
10. E. Bjørn et al. (1997) “Displacement ventilation – effects of movement and exhalation”, Proc. of Healthy Buildings 1997, Washington DC, USA, p. 163-168.
11. E. Mundt (2001) “Non-buoyant pollutant sources and particles in displacement ventilation”, Building and Environment 36, p. 829-836.
12. F. M. LaForce (1984), “Airborne infections and modern building technology”, Proceedings: 3rd International Conference on Indoor Air Quality and Climate, Stockholm, Sweden, 109-127
13. G. B. Knudson (1986),”Photoreactivation of ultraviolet-irradiated, plasmid-bearing, and plasmid-free strains of Bacillus anthracis.”, Appl Environ Microbiol 1986, 52, p. 444-449.
14. G. J. Harper (1961), “Airborne microorganisms: survival tests with four viruses”, Journal of Hygiene, Cambridge, 59: 479-486.
15. G. Ko, M. W. First, H. A. Burge (2002), “The characterization of upper-room ultraviolet germicidal irradiation in inactivating airborne microorganisms.”, Environ Health Perspect 110, p 95-101.
16. ISO 14644-1 (1999) “Clean rooms and associated controlled environment – Part 1: Classification of air cleanliness”, First Edition.
17. J. Barker et al. (2001) “Spread and prevention of some common viral infections in community facilities and domestic homes.”, Journal of Applied Microbiology 91, 7-21.
18. J. C. Chang, S. F. Osoff, D. C. Lobe et al. (1985), “UV inactivation of pathogenic and indicator microorganisms.”, Appl Environ Microbiol 49, p. 1361-1365.
19. J. Fiegel, R. Clarke and D. A. Edwards (2006) “Airborne infectious disease and the suppression of pulmonary bioaerosols”, Elsevier Vol.11 (1/2), 51-57.
20. J. G. de Jong and K. C. Winkler (1964), “Survival of measles virus in air”, Nature 201: 1054-1055.
21. J. G. de Jong et al. (1976), “Aerosol stability functions of Semliki Forest virus”, Appl Environ Microbiol. 32: 315-319.
22. J. H. Hemmes et al. (1960), “Virus survival as a seasonal factor in influenza and poliomyelitis”, Nature. 188: 430-8.
23. J. Peccia, H. M. Werth, S. Miller and M. Hernandez (2001), “Effects of Relative Humidity on the Ultraviolet Induced Inactivation of Airborne Bacteria”, Aerosol Science and Technology 35, p. 728-740.
24. K. A. Hammer, C. F. Carson, T. V. Riley (1999), ”Antimicrobial activity of essential oils and other plant extracts”, Journal of Applied Microbiology, 86, p. 985-990.
25. J. L. Buttolph (1948) “Ultraviolet Air Disinfection in the Theater”, Journal of the SMPE, v. 51, p. 79-91.
26. L. Morawska (2005) “Droplet Fate in Indoor Environments, or Can We Prevent the Spread of

Infection?", Proceedings: Indoor Air 2005, P-9 – P-23.

27. M. A. Elazhary and J. B. Derbyshire (1979), "Effect of temperature, relative humidity and medium on the aerosol stability of infectious bovine rhinotracheitis virus", Can J Comp Med. 43 (2): 158-67.
28. M. C. Pibiri, C. Seignez, C. A. Roulet (2003), "Methods to Study the Effect of Essential Oils on Microbes Present in Ventilation Systems.", CISBAT, p. 185-190.
29. M. K. Ijaz et al. (1985), "Survival characteristics of airborne human coronavirus 229E", J Gen Virol. 66 (Pt 12): 2743-8.
30. M. L. McGeady et al. (1979) "Survival of coxsackievirus B3 under diverse environmental conditions", Appl Environ Microbiol. 37 (5): 972-7.
31. M. Luckiesh (1946), " Applications of germicidal, erythemal and infrared energy.", New York: D. Van Nostrand Company.
32. M. Mattsson (1999) "Ventilation distribution of occupant-generated particles in a room with displacement ventilation", Proc. of Indoor Air 2002, Monterey, California, p 509-514.
33. M. Mattsson (2002) "Vertical distribution of occupant-generated particles in a room with displacement ventilation", Proc. of Indoor Air 2002, Monterey, California, p 509-514.
34. M. M. Jensen (1964), " Inactivation of airborne viruses by ultraviolet irradiation", Applied Microbiol 1964, 12, p. 418-420.
35. M. T. Hatch et al. (1969), "Bacterial Survival: consequences of airborne state", An Introduction to Experimental Aerobiology, John Wiley and Sons, New York.
36. M. W. First, E. A. Nardell, W. T. Chaisson, R. L. Riley (1999a),"Guidelines for the application of upper-room ultraviolet germicidal irradiation for preventing transmission of airborne contagion-part I: basic principles." ASHRAE Transactions 1999, 105, p. 869-876.
37. M. W. First, E. A. Nardell, W. T. Chaisson, R. L. Riley (1999b),"Guidelines for the application of upper-room ultraviolet germicidal irradiation for preventing transmission of airborne contagion-part II: design and operational guidance." ASHRAE Transactions 1999, 105, p. 877-887.
38. M. Möritz, H. Peter et al. (2001) "Capability of air filters to retain airborne bacteria and molds in heating, ventilating and air-conditioning (HVAC) systems.", Int. J. Hyg. Environ. Health 203, p 401-409.
39. N. Sarita Shah, Abigail Wright, Gill-Han Bai et al. (2007) "Worldwide Emergence of Extensively Drug-resistant Tuberculosis", Emerging Infectious Diseases, Vol.13, No. 3, 380-387.
40. P. Xu, E. Kujundzic, J. Peccia et al. (2005), "Impact of Environmental Factors on Efficacy of Upper-Room Air Ultraviolet Germicidal Irradiation for Inactivating Airborne Mycobacteria", Environ. Sci. Technol. 2005, 39, p. 9656-9664.
41. R. Cermak and A. K. Melikov (2003) "Performance of Personalised Ventilation in a Room with an Underfloor Air Distribution System", Proceedings: Healthy Building 2003, Singapore, 2, p.486-491.
42. R. Cermak and A. K. Melikov (2004) "Transmission of Exhaled Air between Occupants in Rooms with Personalised and Underfloor Ventilation", Proceedings: Roomvent 2004, Coimbra: DEM-FCT, Univ. Coimbra.
43. R. Cermak and A. K. Melikov (2007) "Protection of Occupants from Exhaled Infectious Agents and Floor Material Emissions in Rooms with Personalized and Underfloor Ventilation", HVAC&R Research, vol. 13,N 1, p. 23-38.
44. R. Cermak , A. K. Melikov et al. (2004) "Distribution of contaminants in the occupied zone of a room with personalized and displacement ventilation", Proceedings: Roomvent 2004, Coimbr: DEM-FCT, Univ. Coimbra.
45. R. Ehrlich and S. Miller (1971), "Effect of relative humidity and temperature on airborne Venezuelan equine encephalitis virus", J Appl Microbiol. 22: 194-200.
46. R. L. Riley, S. Permut, J. E. Kaufman (1971a), "Convection, air mixing, and ultraviolet air

disinfection in rooms.", Arch Environ Health 1977, 22, p. 200-207.

47. R. L. Riley, S. Permut, J. E. Kaufman (1971b), "Room air disinfection by ultraviolet irradiation of upper air. Further analysis of convective air exchange.", Arch Environ Health 1955, 23, p. 35-39.
48. R. Riley, S. Permut (1955), "Room air disinfection by ultraviolet irradiation of upper air. Air mixing and germicidal effectiveness.",. Arch Environ Health 1955, 22, p. 208-219
49. R. Riley, M. Knight, G. Middlebrook (1976), " Ultraviolet susceptibility of BCG and virulent tubercle bacilli,", Am Rev Resp Dis, 113, p.413-418.
50. Sharp Corporation (2005), "Plasmacluster Ions Proven Effective Against Airborne Highly Pathogenic H5N1 Avian Influenza." Sharp News, Press Release No. 05-012.
51. S. Inouye, Abe, H. Yamaguchi and M. Asakura (2003), " Comparative study of antimicrobial and cytotoxic effects of selected essential oils by gaseous and solution contacts.", The International Journal of Aromatherapy, vol. 13, p. 33-41.
52. S. K. Assar and S.S. Block (2000), "Survival of microorganisms in the Environment", In: Block, S.S.,ed. Disinfection, Sterilization, and Preservation, Lippinkott-Williams, 2000.
53. S. W. B. Newsom (1972) "Microbiology of hospital toilets", The Lancet 300 (7779), 700-703.
54. W. F. Wells (1936), "On air-born infection. Study II. Droplet and droplet nuclei.", American Journal of Hygiene 20, 611-618.
55. W. F. Wells (1955), "Airborne contagion and air hygiene.", Cambridge(MA), Harvard University Press.
56. WHO (2002) "Bulletin of the World Health Organization", 80 (3), 261.
57. WHO (2004) "WHO Guidelines for the global surveillance of severe acute respiratory syndrome (SARS)", Department of Communicable Disease Surveillance and Response, World Health Organization.
58. WHO (2006) The 40th Session of the Subcommittee on Planning and Programming of the Executive Committee, World Health Organization
59. W. J. Kowalski, W. P. Bahnfleth (1998), "Airborne Respiratory Diseases and Mechanical Systems for Control of Microbes", HPAC Engineering, July 1998, p. 34-48.
60. W.J. Kowalski, W. P. Bahnfleth (2000),"Effective UVGI system design through improved modeling.", ASHRAE Transactions 2000, 106 (2), p. 4-13.
61. W.J. Kowalski, W. P. Bahnfleth (2001),"UVGI design basici for air and surface disinfection." IUVA News 2001,3 (5), p. 4-7.
62. W. J. Kowalski, W. P. Bahnfleth (2002), "Airborne-microbe Filtration in Indoor Environments. The critical aspects of filter sizing and a methodology for predicting a filter's effectiveness against allergens, bacteria, and viruses.", HPAC Engineering, January 2002, p. 57-69.
63. W. J. Kowalski, W. P. Bahnfleth (2003), "Immune-building technology and bioterrorism defense", HPAC Engineering, January 2003, p 57-62.
64. W. S. Miller, and M. S. Artenstein (1967), "Aerosol stability of three acute respiratory disease viruses", Proc Soc Exp Biol Med. 125, 222-227.
65. Krishna, S. Pumprueg, S. H. Lee et al. (2005), "Photocatalytic disinfection with titanium dioxide coated multi-wall carbon nanotubes", Trans IChem, Part B, Process Safety and Environmental Protection, 83 (B4), p. 393-397.
66. Y. G. Karim et al. (1985), "Effect of relative humidity on the airborne survival of rhinovirus-14", J Appl Microbiol. 31 (11): 1058-61.