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Review

Review of research on air-conditioning systems and indoor air quality control for human health

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ABSTRACT

With the improvement of standard of living, air-conditioning has widely been applied. However, health problems associated with air-conditioning systems and indoor air quality appear more frequently. In this paper, recent research is reviewed on air-conditioning systems and indoor air quality control for human health. The problems in the existing research are summarized. A further study is suggested on air-conditioning systems and indoor air quality control for healthy indoor air environment.

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Abbreviations: *AC, air-conditioning; ACF, activated carbon fiber; ATD, air terminal devices; CC, cooling ceiling; COP, coefficient of performance; DOAS, dedicated outdoor air system; DV, displacement ventilation; FCU, fan coil unit; GAC, granular activated carbon; HVAC, heating, ventilating and air-conditioning; IAQ, indoor air quality; ICTHS, independent control of temperature and humidity system; MV, mixing ventilation; NAIs, negative air ions; NTP, non-thermal plasma;* NTU_m*, number of mass transfer units; PCO, photocatalytic oxidation;* $PM_{2.5}$*, particulate matter (aerodynamic diameter* $<2.5\ \mu m$*); PV, personalized ventilation; RH, relative humidity; SARS, severe acute respiratory syndrome; SBS, sick building syndrome; SHRTD, sensible heat removing terminal devices;* St_m*, Stanton number of mass transfer; UFAD, under-floor air distribution; UV, ultraviolet; VAV, variable air volume; VOCs, volatile organic compounds.*

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Recherches sur les systèmes de conditionnement d'air et la qualité de l'air intérieur dans le cadre de la santé humaine : tour d'horizon

Mots clés : Conditionnement d'air ; Enquête ; Technologie ; Système frigorifique ; Ventilation ; Qualité de l'air ; Santé ; Confort ; Homme

1. Introduction

Air-conditioning systems have been used in many parts of the world. The purpose of most systems is to provide thermal comfort and an acceptable indoor air quality (IAQ) for occupants. With the improvement of standard of living, occupants require more and more comfortable and healthful indoor environment. People spend 80–90% of their time indoors, and indoor environment has important effects on human health and work efficiency. The factors affecting indoor environment mainly include temperature, humidity, air exchange rate, air movement, ventilation, particle pollutants, biological pollutants, and gaseous pollutants (Graudenz et al., 2005). By analyzing recent studies, Seppanen and Fisk (2002) found that there was an increase in prevalence of sick building syndrome (SBS) between 30% and 200% in the buildings with air-conditioning systems when compared with natural ventilation systems. Death caused by Legionnaires' disease even occurred in air-conditioned buildings. In addition, SARS occurred in 2003. All of these events are a warning for indoor environment problems related to AC systems. It is fair to say that indoor environment problems still exist in many air-conditioned and mechanically ventilated buildings, even though existing standards may be met.

One of the consequences of the worldwide energy crisis in 1970s is the public recognition of the importance of energy saving. The buildings built since then are more airtight and use a great deal of insulation materials to minimize the loss of energy through the building envelope. Fresh air is reduced in air-conditioning systems in order to reduce the energy consumption. Meanwhile, synthetic materials and chemical products (e.g., building materials and decorating materials) have widely been used indoors. The combination of low ventilation rates and the presence of numerous synthetic chemicals results in elevated concentrations of indoor particle pollutants and volatile organic compounds (VOCs) (e.g., benzene, toluene, and formaldehyde). This is deemed to be a major contributing factor to compound hypersensitiveness (Wang et al., 2004a).

However, it is exciting that some comfortable and healthy air-conditioning systems were proposed in the past few years. In order to control the concentration level of indoor pollutants and to improve IAQ, many researchers have investigated the control methods of IAQ. In this paper, recent research will be reviewed on air-conditioning systems and indoor air quality control for human health.

2. Indoor air environment

Indoor air environments must meet the requirement of thermal comfort and IAQ. Thermal comfort is affected by many factors, which mainly include air temperature, air humidity, air velocity, mean radiant temperature, human clothing, and activity levels. The wide use of air conditioning helps to improve thermal comfort, but health problems associated with poor IAQ appear more frequently (e.g., SBS) (Niu, 2004). Many experts believe that IAQ may be the most important and relatively overlooked environmental issue of our time (Gao, 2002). It is indoor pollutants that lead to poor IAQ. Indoor pollutants include particle pollutants and gaseous pollutants.

2.1. *Particle pollutants*

The sources of indoor particle pollutants can be divided into indoor pollution sources and outdoor pollution sources, and the concentrations and composition of indoor particle pollutants are different with different pollution sources. In residential buildings, particles released by indoor pollution sources (e.g., cooking, smoking) were mostly fine particles and ultra-fine particles which were about 80% of the particles in terms of particle counts (See and Balasubramanian, 2006). And $PM_{2.5}$ concentrations could be up to 3 and 30 times higher than the ordinary levels during smoking and cooking, respectively (He et al., 2004). The sources such as sweeping and vacuum cleaner tended to elevate concentrations in the coarse fraction (Howard-Reed et al., 2003). Outdoor particles penetrate into indoor environment through the aperture of doors and windows, and the fresh air of air-conditioning systems. In an urban environment the most abundant particulate matter in terms of number was in the ultra-fine size, smaller than 0.1 μm. There was only a very small share of particles (less than 10%) with diameters larger than 0.1 μm (Thomas and Morawska, 2002; Gramotnev and Ristovski, 2004; Morawska et al., 2004).

Chemical characteristic of indoor particles is another research topic. Sawant et al. (2004) and Cao et al. (2005) investigated the chemical characteristics of $PM_{2.5}$. The main composition of $PM_{2.5}$ and mass percentage inside the residences are organic carbon (40–60%), nitrate (13–14%), trace elements (11–12%), ammonium (8%), elemental carbon (6%), and sulfate (4%). The main composition of $PM_{2.5}$ and mass percentage at the schoolroom sites are organic carbon (26–50%), nitrate (20%), trace elements (22%), elemental carbon (6–7%), and sulfate (6–7%). From the results above, it can be found that organic carbon is the largest contributor to $PM_{2.5}$, and has largest impact on the characteristics of $PM_{2.5}$. $PM_{2.5}$ containing much organic carbon not only contribute to the propagation of bacteria, but help bacterial spread. $PM_{2.5}$ endanger occupants' health directly or indirectly. Furthermore, the dust accumulating on hot surfaces (e.g., heaters and light fixtures) is likely to emit chemicals when heated. Pedersen et al. (2001, 2003) compared the emission characteristics of VOCs during heating of different dust samples relevant to the indoor environment. Emissions of VOCs from heated dust from different sources were surprisingly similar. For most of the samples studied, the emissions were considerable already at 150 °C. Inorganic gases such as CO, CO_2, NO_X and NH_3 have been identified among the emissions from indoor dust heated at 150–600 °C.

Particle pollutants endanger human body through three approaches, namely respiration canal, skin, and alimentary canal. It is the most dangerous approach that particle pollutants enter human body through respiration canal (Kavouras and Stephanou, 2002). The harm degree of particle pollutants to human body is related to the chemical characteristic, diameter magnitude, and quantity. The chemical characteristic of particle pollutants is the main factor because the chemical characteristic determines the degree and speed of biochemistry processes which particle pollutants participate in and disturb in human body. Most of the particle pollutants in air are quite small. They have difficulty in settling and being captured. Conversely, it is easy for them to enter respiration canal deeply together with inhaled air. Moreover, the surface of particle pollutants can adsorb harmful gases, liquid and microbe, which increases the harm to human body (Tham and Zuraimi, 2005; Morawska, 2006).

Most of indoor particle pollutants are ultra-fine particles (smaller than 100 nm, nanoscale particles called by toxicologist) in terms of particle counts. Ultra-fine particles possess new physical, chemical and biologic characteristics (Kagon et al., 2005). Therefore future research could explore the behavior of indoor ultra-fine particles, distribution and effects on indoor environment, and the aggradation of ultra-fine particles in human body, movement and effects on health.

2.2. *Gaseous pollutants*

2.2.1. *Primary gaseous pollutants*

Primary gaseous pollutants mainly include CO, CO_2, SO_2, NO_X, O_3, radon and VOCs. Chemical materials have widely been used indoors recently. The chemical materials can release many kinds of chemical pollutants at room temperature, and VOCs are the main composition of these chemical pollutants. VOCs can cause many symptoms, such as headache; eye, nose, and throat irritations; dry cough; dizziness and nausea; tiredness. VOCs also have bad effects on respiration systems, blood vessel systems, and nerve systems. Moreover, VOCs may be carcinogenic (Huang and Haghighat, 2002). The physical and chemical characteristics of VOCs attract many researchers, and become a research topic.

Indoor pollution sources of VOCs mainly include building materials, decorating materials, and articles used indoors. Among them building materials and decorating materials are the main pollution sources of VOCs (Cox et al., 2002). They mainly include carpet, man-made board, fine board, agglutination board, composite floor, cork, paint, adiabatic layer, and heat pipeline. Many numerical models have been developed for simulating the surface emission of VOCs from building materials and decorating materials, and VOCs sorption (Won et al., 2001; Yang et al., 2001; Hodgson et al., 2002; Haghighat and Huang, 2003; Huang and Haghighat, 2003; Murakami et al., 2003; Zhang and Xu, 2003; Wilke et al., 2004; Xu and Zhang, 2004; Zhang and Niu, 2004; Kim and Kim, 2005; Lee et al., 2005; Li and Niu, 2005). Some experiments have also been performed to investigate VOCs diffusion inside the materials (Meininghaus and Uhde, 2002; Onwandee et al., 2005; Huang et al., 2006; Zhang et al., 2007). The main conclusions are as follows:

- The dimensionless emission rate of VOCs is only a function of the ratio of mass transfer Biot number to the partition coefficient and of mass transfer Fourier number.
- For the multi-layer materials, the top layer materials strongly delay VOCs emission from the bottom layer materials. The multi-layer materials have a much longer VOCs emission time and a slower VOCs decay rate than the single-layer materials.
- Polar VOCs are more easily adsorbed and quickly desorbed from building materials and decorating materials, which can reduce VOCs concentrations in the room air initially and elevate them as the time progresses.

Plenty of paint is usually used to protect or beautify decorating materials and furniture, but VOCs emitted by paint affect IAQ more seriously. Many experimental and numerical investigations on the emission of VOCs from paint have been conducted (Chang et al., 2002; Fjällström et al., 2003; Zhang and Niu, 2003a,b; Li et al., 2006). The main conclusions are as follows:

- 23 individual VOCs were detected, and the 7 major VOCs were 1-ethyl-3-methylbenzene, 1,2,4-trimethylbenzene, *n*-hexane, 1,3,5-trimethylbenzene, propylbenzene, *o*-xylene, and toluene. The sum of the amount of these 7 VOCs was 85% of that of the total VOCs detected.
- About 65.2% of the VOCs were emitted within the first 4 h, and the emission then slows down and persists for a long period. After 10 days, about 99% of the VOCs were released to indoor air.
- The substrates with high adsorption capacity act as a secondary source for VOCs emission, and such effects may prolong the decay of VOCs.

Although the emission and sorption of many VOCs pollution sources have been investigated experimentally and numerically, the following need to be researched further:

- Some hypothesises have been adopted in the numerical models, such as one-dimensional mass transfer, constant physical properties, and uniform materials. Many materials actually do not meet these hypothesises.
- Excessive VOCs do damage human health, but the damage of individual VOCs in pathology is lack of research. Moreover, it is not clear that the effect mechanism of VOCs to human body,

and the influences of exposure concentrations and exposure time on human health are uncertain.

2.2.2. *Secondary gaseous pollutants*

The mix of pollutants in indoor environments can be transformed as a consequence of chemical reaction. Reaction between ozone and some unsaturated hydrocarbons is an important source of indoor secondary pollutants which mainly include free radicals, aldehydes, ketones, alcohols, carboxylic acids, and fine particulate matter (Sarwar et al., 2003). Secondary pollutants may be more irritating than the original reactants (Wainman et al., 2002; Rohr et al., 2003). During the past few years, many investigations were conducted on indoor secondary pollution due to ozone reacting with limonene (Clausen et al., 2001; Schell et al., 2001; Knudsen et al., 2002; Nøjgaard et al., 2005; Sirakarn et al., 2005; Tamás et al., 2006; Sarwar and Corsi, 2007), terpene (Knudsen et al., 2002; Weschler and Shields, 2003; Kleno and Wolkoff, 2004; Sarwar et al., 2004; Fiedler et al., 2005; Nøjgaard et al., 2005), α-pinene (Fick et al., 2003; Pommer, 2003; Pommer et al., 2004), VOCs (Fan et al., 2003; Liu et al., 2004), organism deposited on a dirty filter (Bekö et al., 2003; Hyttinen et al., 2003), and airborne particulate (Mølhave et al., 2004, 2005). Much significant research has occurred in three subtopics:

- Confirming the importance of hydroxyl radical in indoor transformations. Hydroxyl radical is a product of ozone/terpene reactions and goes on to react with other products. Hydroxyl radical is responsible for a large fraction of oxidized products, including certain products that cannot be made by ozone pathways alone.
- Chemical reactions that occur on indoor surfaces. Such reactions may have larger impact on IAQ than those that occur in the gas phase because of the large indoor surface-to-volume ratio.
- The impact of secondary pollutants on occupants. A major limitation in evaluating the impact of secondary pollutants is the inability to measure many of the reaction products. Sensory measurements are useful in detecting changes derived from indoor chemistry and changes missed by the analytical methods routinely used to evaluate indoor air.

Indoor secondary pollutants have significant impact on comfort and human health, but the degree of impact and the frequency of occurrence are uncertain at present. In addition, many secondary pollutants cannot be measured because of the complexity of composition, and it is necessary to improve the measure level.

3. Air-conditioning systems

3.1. *Air-conditioning systems*

Many kinds of AC systems are used to improve indoor thermal comfort and IAQ. Recent research is focused on dedicated outdoor air system (DOAS), independent control of temperature and humidity system (ICTHS), and cooling ceiling and displacement ventilation systems (CC/DV).

3.1.1. *Dedicated outdoor air system (DOAS)*

With the occurrence of SARS, avian flu and anthracnose in some countries, the safety of AC systems becomes more important. DOAS, an effective measure to realize ‘‘immune building’’, has gradually been appreciated by international AC industry (Mumma, 2001). The reason why DOAS is called ‘‘new concept’’ AC system is that the techniques used in DOAS have widely been applied but are subtly combined to show its broad prospect. DOAS results in a significant revolution in air-conditioning industry.

Typical DOAS, shown in Fig. 1, consists of the following several parts (Yin and Mumma, 2003):

- Cold source: As the outlet air temperature of the outdoor air producer is required to be no more than 7 °C, its inlet water temperature should be no more than 4 °C. Though the conventional chiller could be used as the cold source of DOAS, the outlet water temperature of the chiller should be no more than 5 °C. So the chiller should be redesigned. The optimal cold source will be the ice-storage system.
- Outdoor air processor: To ensure that indoor terminal devices run in dry condition, outdoor air heat load, total latent heat load and partial sensible heat load are removed by

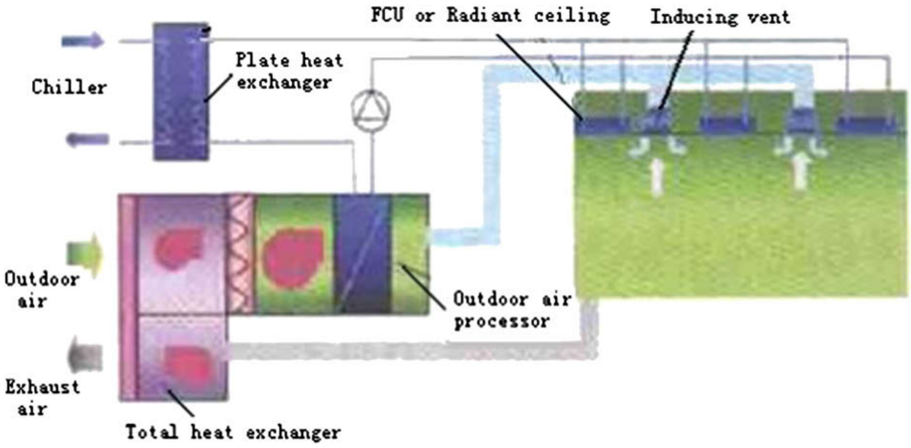

Fig. 1 – Schematic diagram of typical DOAS.

outdoor air processor whose outlet air temperature should be no more than 7 °C.

- Sensible heat removing terminal device (SHRTD): The residual sensible heat load is removed by SHRTD which includes cooling ceiling (CC), fan coil unit (FCU), and unitary air conditioner. Among them CC is the best one. DOAS using CC as SHRTD can save the primary energy by 18%, compared with DOAS using FCU as SHRTD (Li and Zhang, 2007).
- Total heat exchanger: Outdoor air is dehumidified by solid dehumidizer in desiccant wheel, and then exchanges total heat or sensible heat with exhaust air in heat recovery wheel to recover the energy of exhaust air.
- Automatic control system: Automatic control system is necessary for DOAS. The controlled parameters mainly include the outlet water temperature and the cold water flux of outdoor air processor, cold water flux and inlet water temperature of SHRTD, indoor dry-bulb temperature and dew-point temperature.

The inlet water temperature of SHRTD is controlled based on indoor dew-point temperature, and the total latent heat load is removed by outdoor air processor. Therefore, SHRTD runs in dry condition completely and there is no need to worry about the condensing water. Moreover, DOAS is an all air system without return air, and it eliminates intercrossing infection existing in all air system with return air. DOAS also exhibits better effect of energy saving. When the effectiveness of total heat exchanger is 65%, DOAS using CC as SHRTD can save the electric energy by 42%, compared with conventional VAV systems (Jeong et al., 2003). As the energy consumption of DOAS highly depends on the efficiency of total heat recovery devices, it would be important to develop the heat recovery devices with high efficiency. In addition, to ensure that DOAS runs effectively and safely, further work needs to be done to improve automatic control system, and to enhance the compatibility among different parts of DOAS.

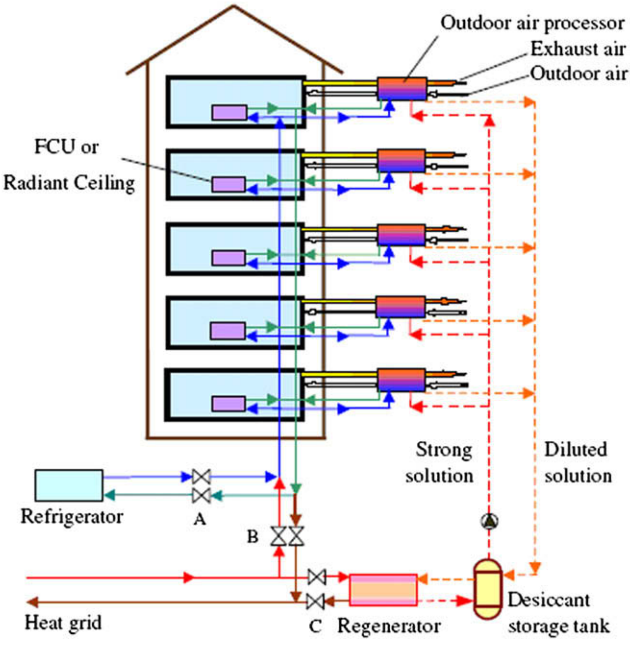

Fig. 2 – Schematic diagram of ICTHS.

3.1.2. Independent control of temperature and humidity system (ICTHS)

Conventional AC systems firstly cool air below the dew-point temperature in order to condense moisture out, and then reheat it to the supply comfortable temperature before delivering it to the occupied spaces. This leads to low evaporating temperature, a poor COP value for the chiller, and higher energy consumption. Moreover, the FCU may become the hotbed of many kinds of mildew due to the existence of condensing water, which will deteriorate IAQ. The reason for all these problems is that the cooling process and the dehumidifying process are in the same unit and at the same time, but there is an essential difference between the two processes (Chen et al., 2004). ICTHS can realize the independent control of temperature and humidity, and resolve the problems above.

An ICTHS is shown in Fig. 2 (Liu et al., 2006). The ICTHS consists of a liquid desiccant system and a cooling/heating grid system. The liquid desiccant system is composed of outdoor air processors (serving as dehumidifier in summer and humidifier in winter), a regenerator, and a desiccant storage tank. LiBr solution is used as liquid desiccant in the system, and the regeneration temperature is about 60 °C. The cooling/heating grid system is composed of the power driven refrigerator, the heat grid, and the FCU or radiant ceiling. In summer operations, valves A and C are turned on and valve B is turned off, and the ICTHS performs dehumidification and cooling of the air. Chilled water with temperature of 15–18 °C flows from the refrigerator into the outdoor air processors and the indoor terminal devices. The outdoor air processors remove the total latent load and a portion of sensible load of the occupied space, while the indoor terminal devices deal with the remained sensible load. IAQ is greatly improved because of the following two main reasons: (i) indoor terminal devices operate in dry condition, and no condensing water will be produced on the surfaces of the AC system; (ii) the liquid desiccant can remove a number of pollutants from the air stream. In winter operations, valves A and C are turned off and valve B is turned on, and the ICTHS performs humidification and heating of the air. Hot water from the heat grid flows into the outdoor air processors and indoor terminal devices. The operating principle of the outdoor air processor is shown in Fig. 3. The outdoor air processor consists of two parts. The left of the broken line is a three-stage total heat recovery device using liquid desiccant, and the right of the broken line is a single-stage spray unit (Li et al., 2003).

The ICTHS can not only improve IAQ but reduce energy consumption and operation cost. In summer, when the latent load of the building covers from 10% to 50%, the primary energy consumption of the ICTHS is 76–80% and the operation cost is about 75% of that of the conventional AC systems. In winter, when latent load of the building are 5%, 10% and 15%, the primary energy consumption of the ICTHS is 77%, 62% and 45%, respectively, and the operation cost is 75%, 57% and 42%, respectively, compared with that of a conventional AC systems (Liu et al., 2006). If solar energy or waste heat is used to regenerate desiccant, and ground water is

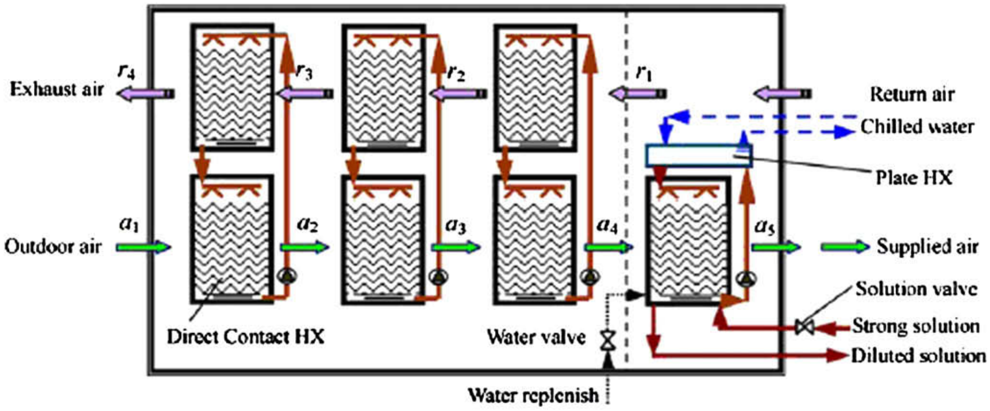

Fig. 3 – Principle of outdoor air processor in summer.

used to cool indoor air, more energy and operation cost would be saved. However, the FCU in ICTHS is only used to cool indoor air and is different from the FCU in conventional AC systems. So the FCU in ICTHS needs to be redesigned.

3.1.3. *Cooling ceiling and displacement ventilation systems (CC/DV)*

DV system performs well on eliminating indoor pollutants and improving IAQ, but it sometimes is incapable of meeting indoor cooling load due to the limitation of temperature and velocity of air distribution, which may lower the indoor thermal comfort. CC system performs well on indoor thermal comfort, but it cannot improve IAQ due to its configuration. So it can be found that DV system and CC system can offset the disadvantages each other. In combined CC/DV systems, the CC panels remove part of sensible cooling load by convection and radiation, while DV system removes indoor pollutants, latent cooling load and the other part of sensible cooling load.

For combined CC/DV systems, the vertical temperature gradient should exist because it indicates stratified airflow pattern and vertical stratification of pollutants. On the other hand, the temperature gradient should be small for an acceptable thermal comfort. Table 1 presents the vertical temperature gradient in the occupied zone (0.1–1.1 m above the floor) obtained from several studies. The temperature gradient in the occupied zone varies from 0 to 2 K m^{-1}, which implies that it is almost completely uncertain. These differences are due to different experimental thermal conditions and fluid flow conditions, such as cooling loads, ventilation rates, supply air temperatures and CC panel temperatures. Velocity is another important thermal comfort parameter. Loveday et al. (1998) reported that a low CC temperature, which increased the CC cooling capacity, could increase air velocities in the occupied zone. The increase in velocity was due to the downward airflow motion caused by the negative buoyancy force from the CC. For a cooling load of 62 W m^{-2} and CC temperature in range from 21 to 14 °C, Loveday et al. (1998) measured maximum air velocity of 0.11 m s^{-1} in the occupied zone. Behne (1995) measured the air velocity of 0.11–0.16 m s^{-1} for the same cooling load. In both studies, the velocities were far below the velocity that can cause draft. According to Behne (1995) and Fitzner (1996), there was no risk from draft caused by CC if the total cooling load in a space was less than 100 W m^{-2} (floor area).

Table 1 – The vertical temperature gradient in occupied zone (0.1–1.1 m)

Researchers	Temperature gradient (K m^{-1})	Research approach
Niu and Kooi (1993)	2	Simulation
Kruhne (1993)	0	Experiment
Kulpmann (1993)	1.5	Experiment
Fitzner (1996)	0	Experiment
Alamdari (1998)	1.2–1.7	Experiment and simulation
Behne (1999)	0.4–1.2	Experiment

Downward convection below CC, downward convection near cold walls and upward thermal plumes from heat sources have important effects on the height of the stratification boundary, and the air quality in occupied zone in a room with CC/DV (Fig. 4). The downward convection below CC may reduce the height of the stratification boundary in CC/DV systems. According to Loveday et al. (1998), the stratification boundary appeared at a height of about 2.0 m regardless of cooling load (from 25 to 52 W m^{-2}) in his experiments. However, when CC system was on, the boundary layer was suppressed to 1.5 m above the floor for a cooling load of 62 W m^{-2}. The downward motion from CC might suppress the stratification boundary into the occupied zone, especially in room sections without heat sources. This causes unexpected reverse effects on the air quality. Fitzner (1996) analyzed the influence of heat source and upward convection on local air quality, and found that sitting person might have remarkable improvement of the inhaled air quality due to the buoyancy which drives the transport of fresh air from the layer near the floor to the person's nose (Fig. 4). Alamdari (1998) reported that, for a cooling load of 60 W m^{-2}, upward convection was dominant in the vicinity of the occupants even with the strong downward air motion from the cooling panels. This study also showed that the downward convection near the sidewalls with low wall temperatures could cause

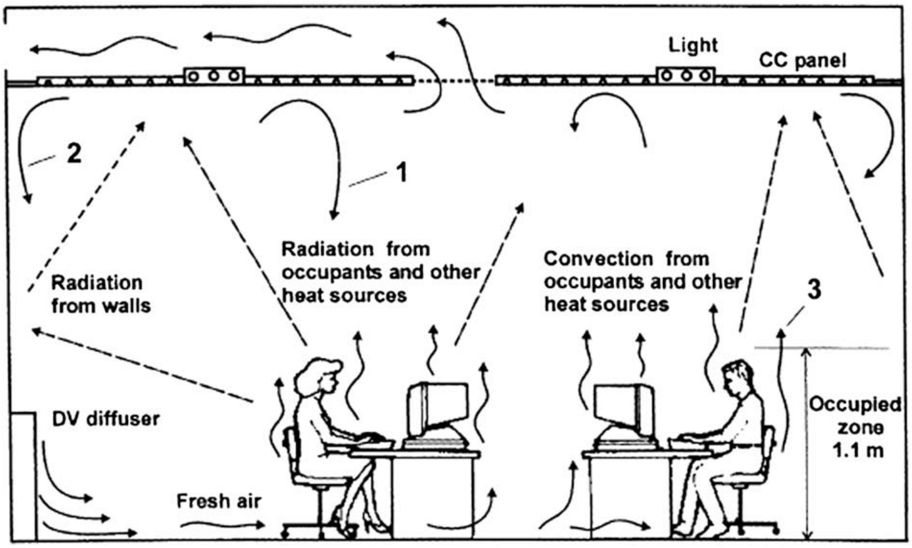

Fig. 4 – The combined CC/DV systems performance: (1) downward convection below CC, (2) downward convection near cold walls, and (3) upward thermal plumes from heat sources.

a transport of pollutants from the upper mixed zone directly into the air supply layer with clean air.

The occurrence of condensing water is not allowed absolutely on the surfaces of CC panels, so it is necessary to develop accurate control technique to prevent condensation. In addition, the ratio of the cooling load removed by DV to the cooling load removed by CC has significant effects on thermal comfort and IAQ, which deserves further study.

3.2. *Air supply modes*

Prominent airflow distribution as well as outstanding AC systems is necessary in order to achieve a comfortable and healthy environment in occupied zone. Air supply mode is the main influence factor of airflow distribution. Recent research is mainly focused on displacement ventilation (DV), personalized ventilation (PV) and under-floor air distribution (UFAD).

3.2.1. *Displacement ventilation (DV)*

DV is a new type of air supply mode, and it only improves the environment in occupied zone and not all the spaces. Hence DV not only saves much energy but keeps better IAQ. Indoor airflow pattern and distribution profiles of temperature and contaminant concentration are shown in Fig. 5. Air temperature is rather uniform at horizontal level except in the region near the air supply diffusers. Vertical temperature gradients always exist in the space with DV system and they are not linear in all the space height. DV, compared with mixing ventilation (MV), has higher ventilation efficiency and IAQ due to its piston flow effect and temperature stratification. However, DV may not provide better IAQ than MV if the contaminant sources are not associated with heat sources, such as VOCs from building materials (Lin et al., 2005; Cheong et al., 2006). Additionally, DV system is not suitable for removing ground level contaminants, or where the main contaminants are emitted at the ground level, because the contaminants would simply be displaced into the breathing zone. For gaseous contaminants, the displacement effect of DV system is probably dependant on the molecular weight of contaminants. Since VOCs have greater mass, the displacement effect is significantly less than that for CO_2.

There are many factors that affect the design and the performance of DV system. The door and window have

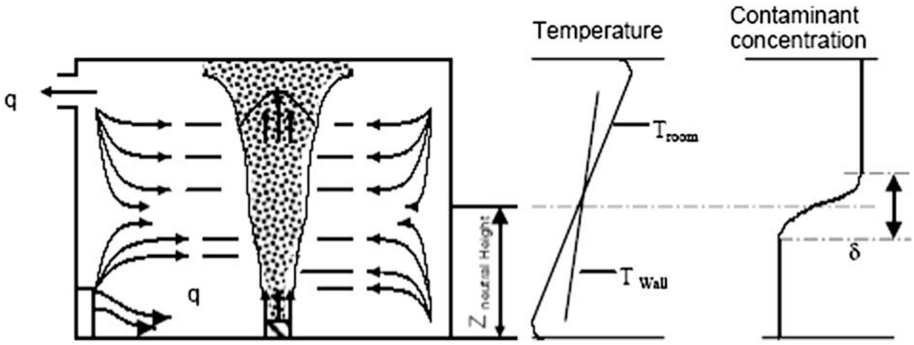

Fig. 5 – Indoor airflow pattern and distribution profiles of temperature and contaminant concentration.

significant effects on the displacement effectiveness of DV system (Lin et al., 2007). The displacement effectiveness for CO_2 and VOCs are significantly reduced by the door opening due to the change in airflow pattern. The added momentum from the incoming air causes pollutants to be displaced into the breathing zone. The lateral displacement of the air due to the window heat transmission may result in disruption of the displacement effect, which reduces the effectiveness of DV system in removing contaminants. The influence of furniture is related to the location and distribution. Furniture has minimal impact on thermal comfort and IAQ when they do not obstruct the airflow from diffusers (Lau and Chen, 2007).

Stratification boundary is the interface between the upper mixing zone and the lower zone with unidirectional flow. The air of occupied zone will be sanitary only when the height of the stratification boundary is above the occupied zone. Therefore, the height of the stratification boundary is a very important parameter in DV system. Lee and Lam (2007) calculated the height by simulation and found that with a room height of 2.4 m and design room temperature of 25.5 °C (defined at 1.1 m above floor level), under the normal load to airflow ratio of 12,000 $\mathrm{W\,m^{-3}\,s}$ and minimum supply temperature of 18 °C, the height was 2.2 m, and was above normal breathing level. There are many factors that affect the height. The height decreased as the room load increased, but the height increased as the room load increased further when the room load was greater than about 45 $\mathrm{W\,m^{-2}}$ (Xing and Awbi, 2002). The height increased as the flow rate increased for a given heat source at a fixed surface temperature. For a fixed flow rate and a given heat source diameter, the height decreased as the heat source temperature increased (Bouzinaoui et al., 2005). DV system is quite suitable for large size room due to its stratification characteristics. Future research could explore the possibility to apply DV system in ordinary rooms.

3.2.2. *Personalized ventilation (PV)*

PV is a special DV system, and it really embodies the central status of occupants. PV is able to provide occupants with improved IAQ, thermal comfort and individual control of the micro-environment. Through adjusting the personalized airflow rate, direction, temperature and turbulence intensity, occupants can achieve their preferred individual micro-environment, which is impossible in conventional air-conditioning systems.

There are many types of PV system. For the desk-edge-mounted PV system, it was possible to obtain an air change effectiveness of approximately 1.5 when the supply flow rate was 3.5–6.5 $\mathrm{l\,s^{-1}}$, which represented a 50% increase in effective ventilation rate at the breathing zone (Faulkner et al., 2004). Niu et al. (2007) proposed a chair-based PV system (Fig. 6), and the position of the fresh air supply nozzle can be adjusted by the seated user. The experimental results showed that up to 80% of the inhaled air could be composed of fresh personalized air with a supply flow rate of less than 3.0 $\mathrm{l\,s^{-1}}$. Perceived air quality was improved greatly by the chair-based PV system. Zhao and Guan (2007) investigated the dispersion characteristics of particles with aerodynamic diameter of 0.5–10 μm in a room ventilated by a PV system by computational fluid dynamics (CFD). The results showed that PV was effective to remove particles smaller than 2 μm, and that PV might not be the best ventilation mode for particles bigger than 7.5 μm due to resulting obvious particle accumulation on the floor.

Compared with total volume ventilation, PV is advantageous for many practical applications. Research is needed on exploring the potential of PV and ensuring its optimal performance. Some of this research is outlined as follows (Melikov, 2004):

- Impact of airflow temperature and velocity on thermal comfort and perceived air quality, and occupants' compromise between thermal comfort and perceived air quality.
- Airborne transmission of infectious agents, and dispersion of large-droplet aerosols exhaled by occupants.
- Development of the supply air terminal devices (ATD) with high efficiency and of the technical solutions to installation of PV in practice.
- Development of PV systems with high performance for use in crowded spaces such as theaters and cinemas.

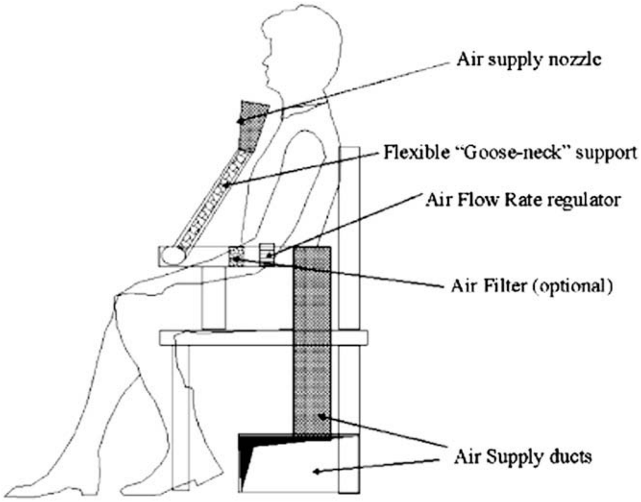

Fig. 6 – Schematic diagram of chair-based PV system.

3.2.3. *Under-floor air distribution (UFAD)*

UFAD system is a new type of air supply mode with the advantages of better flexibility, energy saving and improvement of IAQ (Webster et al., 2002). Its operating principle is

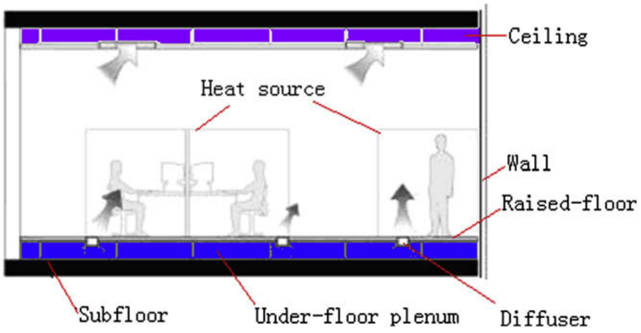

Fig. 7 – Principle of UFAD.

shown in Fig. 7. Now it has been applied in Europe, Hong Kong, Japan, South Africa and America.

At present, the studies on UFAD are focused on its airflow characteristics, IAQ, thermal comfort, thermal characteristics of under-floor plenum, and system energy consumption. Since the airflow characteristics are significantly affected by the diffusers, different types of diffusers have been the research focus of many investigators. Lian et al. (2004) experimentally compared swirl diffusers with cylinder diffusers, and found that with less quantity of swirl diffusers (about 0.4 m^{-2}), the airflow in room would be more uniform. However, Webster et al. (2002) pointed out that airflow characteristics in room were more affected by swirl diffusers than by grille diffusers. PMV (Predicted Mean Vote), PPD (Predicted Percentage of Dissatisfied) and PD (Predicted Dissatisfied), presented by Fanger at Copenhagen University in Denmark, are still used as the main standard in the studies of thermal comfort. When the rate of ventilation was 6 h^{-1}, the maximum velocities at the head of occupant and on the top of computer were 0.25 $m\,s^{-1}$ and 0.45 $m\,s^{-1}$, respectively, which still satisfied the thermal comfort demand. Zagreus et al. (2004) developed a web-based survey and accompanying online reporting tools to gather the information about users' evaluation of UFAD. The results showed that about 95% of the surveyed people showed their satisfaction towards UFAD, and nearly 2/3 of them indicated a preference for UFAD over conventional overhead air distribution. Under-floor plenum is one of the most important parts of UFAD. Linden et al. (2004) suggested that the flow in the plenum be regarded as 2-dimension flow for plenum with small ratio of height to length. Further studies of thermal characteristics of under-floor plenum were carried out by Hui et al. (2006) and Daly (2002). Daly (2002) suggested that the use of ventilation pipe be avoided, that the air leakage be reduced, and that the variable air volume system be used in under-floor plenum. CBE (Center for Building and Environment) (2006) reported that for adiabatic floor about 20–30% heat load entered under-floor plenum, while for un-adiabatic floor it would be about 30–40%, and the value would be larger with higher vertical temperature gradient. The thermal decay in under-floor plenum has disadvantageous effects on UFAD system:

- The useless heat load from sub-floor increases the cooling load and the energy consumption of air-conditioning system.
- The thermal decay results in non-uniform temperature distribution of air in under-floor plenum, and temperature difference of supply air from different diffusers.
- The rise of supply air temperature weakens the temperature stratification and pollutant concentration stratification of indoor air, which could increase the energy consumption of air-conditioning system and badly affect the improvement of air quality in occupied zone.

Therefore the thermal decay in under-floor plenum should be reduced or avoided. The introduction of flexible and adaptive UFAD systems in office buildings was approaching 10% of the new construction market, and would continue to grow because of performance gains, including equal or lower first costs, thermal comfort and indoor air quality gains, and 20–35% energy savings (Hartkopf and Loftness, 1999; Hartkopf et al., 2002; Loftness et al., 2002).

UFAD needs to be researched further in several aspects: individual control of thermal comfort, thermal characteristics of under-floor plenum, development of new types of diffusers, impact of radiation on thermal comfort and indoor airflow characteristics, load calculation, and system control.

4. Control of IAQ

In order to provide a comfortable and healthy indoor air environment, measures must be adopted to control the concentration level of indoor pollutants and improve IAQ. The current methods mainly include control of pollution sources, ventilation and indoor air purification. The recent research on ventilation has been described in Section 3.

4.1. *Control of pollution sources*

It is a most economical and effective approach in improving IAQ to eliminate or reduce indoor pollution sources (Guo et al., 2003). The best ways of controlling indoor air pollution are to use pollution-free or low-pollution materials and to adopt the design and maintenance measures that avoid producing indoor pollutants. They are outlined in detail in the following (Li et al., 2004; Zhang et al., 2005a; Zhang et al., 2006b):

- Filtrating the outdoor air to prevent outdoor pollutants from entering the room.
- Isolating the sites that may form pollution sources (e.g., copycat rooms, printer rooms, kitchen and toilet) in order to avoid intercrossing infection, and using the enforced ventilation when necessary.
- Making full use of pollution-free or low-pollution building materials and decorating materials. Preventing building products with high pollution from entering market by government legislating and setting up industry standard. For the products in markets, government can label them with different grade. The building materials and decorating materials with high pollution can be eliminated by market mechanism.
- Dust and liquid drops are the important medium for bacteria to spread. It is necessary to termly clean the components that are easy to be infected in air-conditioning systems (e.g., filter, heat exchanger and muffler) and to replace them in time in order to avoid the aggradations of pollutants. Moreover, the condensing water should be eliminated in time or ICTHS is employed in air-conditioning systems to prevent bacteria from propagating.

In addition, occupants' behavior is also an important origin for indoor pollutants, so we should form better customs such as no high strength activities in room, keeping better individual sanitation, no smoking in room, and avoiding using pressurized spray and cosmetic. Researchers should keep on investigating chemical pollutants' releasing characteristics of materials used indoors and exploiting new types of materials without release of pollutants.

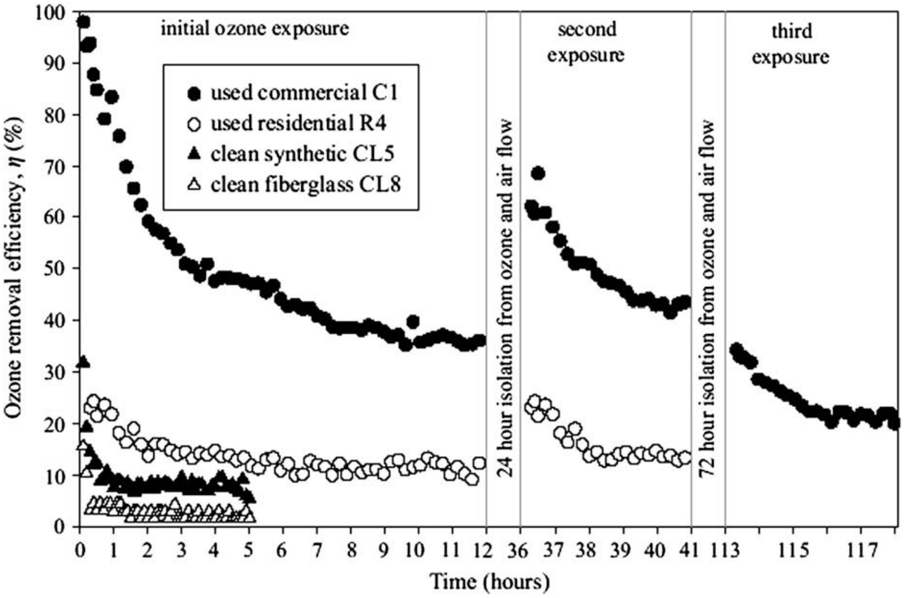

Fig. 8 – Zone removal efficiency.

4.2. *Indoor air purification*

Indoor air purification is an important method of removing indoor pollutants and improving IAQ under the circumstances that the ventilation and the control of pollution sources are impossible. The major methods of indoor air purification include filtration, adsorption, photocatalytic oxidation (PCO), negative air ions (NAIs), and non-thermal plasma (NTP).

4.2.1. *Filtration*

Filtration is a quite economical and efficient method of improving IAQ. Filters are important components in all AC systems. It has been found that AC filters can remove ozone significantly at steady state (Hyttinen et al., 2003, 2006; Bekö et al., 2005, 2006). Zhao et al. (2007) measured the ozone removal efficiencies of clean filters and field-loaded residential and commercial filters in a controlled laboratory (air temperature 22–26 °C, 45–60% RH). The steady-state ozone removal efficiency varied from 0% to 9% for clean filters. The mean steady-state ozone removal efficiencies for loaded residential and commercial filters were 10% and 41%, respectively. From the results above it can be seen that the particles deposited on the filters can increase the ozone removal efficiencies. Zhao et al. (2007) also observed a partial regeneration of ozone removal efficiency after filters were isolated from ozone and treated with clean air, nitrogen, and/or heat (Fig. 8). The ozone removal efficiency of AC filters appeared to decay with time (Hyttinen et al., 2006; Bekö et al., 2005, 2006). Bekö et al. (2006) found that the initial ozone removal efficiency was 35–50%, only 5–10% after an hour. The removal of ozone from indoor environments is generally desirable. However, the ozone removal on AC filters is mainly due to the chemical reactions between ozone and the particles deposited on the filters, which can lead to oxidation products such as formaldehyde, carbonyls, formic acid, and ultra-fine particles (Bekö et al., 2005; Hyttinen et al., 2006). Processes involved in the removal of ozone on HVAC filters include: (i) ozone advection through the filter, (ii) ozone diffusion into the boundary layer near particles, (iii) ozone diffusion into particles, (iv) diffusion of reactive organic compounds out of particles, and (v) ozone reactions with reactive organic compounds. Based on time scales analysis, it appeared that the diffusion processes of ozone and reactive organic compounds were the limiting factors for ozone removal in filters. The speed of the two processes depended largely on the composition of deposited particles (Zhao et al., 2007). Further research is needed to identify and quantify time-dependent emissions of oxidized products and their potential significance with respect to IAQ.

Despite the fact that air filtration systems represent a good solution for the improvement of IAQ, they could become a source of contamination from micro-organisms harmful to human health. The organic/inorganic matter deposited on the filter contributes to microbial growth, which inevitably leads to a loss of filter efficiency and filter deterioration. Anti-microbial treatments of filters may be a solution to these problems (Verdenelli et al., 2003). It is possible to prevent the accumulation and dispersion of microorganisms by adding anti-microbial agents on the surfaces of filter, which contributes to the improvement of air quality. The filter sections stereomicroscope analysis on untreated and treated filter media showed that the anti-microbial treatments can reduce microbial colonization significantly (Cecchini et al., 2004). The active component of the anti-microbial agent is *cis*-1-(3-chloroallyl)-3,5,7-triaza-1-azoniaadamantane chloride. The incubation experiments indicated that untreated filter medium released microorganisms after 27 days, while release from the treated filter medium was delayed, after 67 days. The experimental results of Verdenelli et al. (2003) also showed that compared with untreated filters, the anti-microbial treatments could delay the deterioration of filter and result in a lower release of metabolic products. Verdenelli et al. (2003) experimentally investigated the pressure loss of the untreated and treated filters. The results showed that it increased by 34% in used and untreated filter, and by 22% in used and treated filter. However, the anti-microbial treatments of filter are still at a research stage. It is firstly needed to select anti-microbial agents with excellent performance and compatibility with the production process of filter before applied practically.

4.2.2. *Adsorption*

The adsorbents able to be used to purify indoor air mainly include activated carbon, zeolite, activated alumina, silica gel, and molecular sieves. Adsorption on activated carbon is an extensive method of purifying indoor air due to its large specific area and high adsorption capacity. At low concentration level, the advantages of activated carbon with abundant micro-pores are more prominent (Song et al., 2005). Activated carbon fibers (ACF) exhibit a higher adsorption capacity and have faster adsorption kinetics than granular activated carbon (GAC), 2 to 20 times faster than on GAC (Subrenat and Le-Cloirec, 2004). Moreover, ACF are easier to use than GAC since they can be formed in various forms such as cloth and felt. Therefore, ACF are more suitable as an adsorbent for removing indoor gaseous pollutants (Huang et al., 2003).

The production processes of ACF have remarkable effects on the microstructure, specific surface area, pore-size distribution and adsorption properties. For polyacrylonitrile-based ACF (PAN-ACF), proper oxidation temperature and time could increase the number of micro-pores. The surface area of PAN-ACF reached a maximum when the oxidation temperature was 270 °C (Sun and Wang, 2005). When carbonization temperature was more than 900 °C and carbonization time ranged from 50 to 90 min, the number of micro-pores also increased greatly (Sun et al., 2004). When activation temperature was 1000 °C, with activation time extending, the surface area of micro-pores in the PAN-ACF increased remarkably and reached 1234 $m^2 g^{-1}$ (Sun et al., 2006; Sun and Wang, 2006). A phenolic resin fiber was oxidized in air at 220 to 270 °C, subsequently carbonized at 900 °C, and activated by steam at 900 °C. The oxidation was found not to affect the chemical and physical properties of the carbonized fiber. The ACF produced from the oxidized fiber had almost the same pore structure as the ACF produced from the non-treated fiber. But the maximum yield of ACF produced from the oxidized fiber was 1.13 times larger than that of ACF produced from the non-treated fiber (Nakorn et al., 2003). For pitch-based ACF, air oxidation below 400 °C slightly modified the microporous structure together with a minor replacement of surface –C–O groups by –CO groups. However, oxidation above 500 °C increased the specific surface area gradually and induced the formation of surface functional groups greatly, especially the –COOH groups (Wang et al., 2004c). The oxidation activity of carbon could increase when magnesium oxide/hydroxide was deposited on pitch-based ACF. However, Mg deposition might reduce the specific surface area, pore volume, and average micro-pore width of the carbon (Wang et al., 2004b).

Methyl propyl ketone, methyl ethyl ketone, *n*-hexane, acetone, and methylene chloride were removed at 200–1020 ppmv (parts per million, volume), in a 40.0 slpm (standard liter per minute) air stream while using ACF cloth as adsorbent. The removal efficiencies were greater than 99.9% (Dombrowski et al., 2004). In addition, the effects of the adsorbate polarity on the adsorption capacity at lower concentrations were found to be more significant. ACF exhibited different dynamic adsorption and desorption characteristics for polar and non-polar gases due to surface oxygen complexes (Huang et al., 2002).

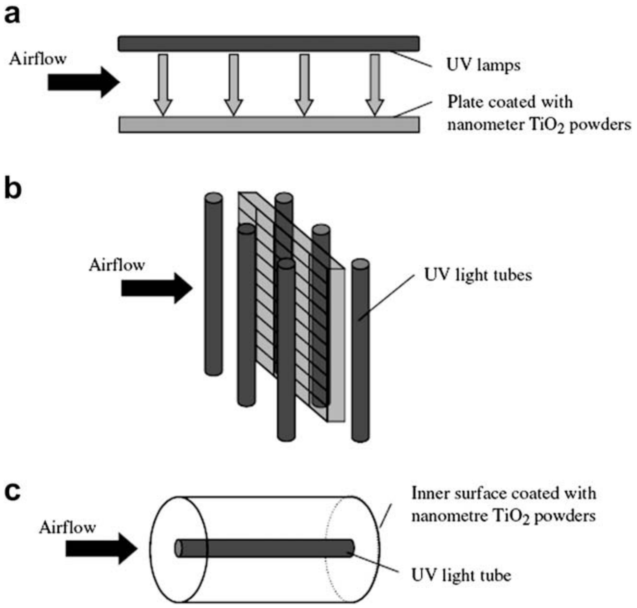

Fig. 9 – Schematics of three PCO reactors: (a) plate type reactor, (b) honeycomb type reactor, and (c) light-in-tube reactor.

However, activated carbon will lose its activity after used for a period of time, and its activity also will decrease after regeneration. Moreover, ACF is quite expensive, and its price is 5–100 times higher than that of GAC, which limits the wide application of ACF. In addition, individual adsorbent does not have the ability to adsorb all kinds of indoor pollutants, and only exhibits good adsorption effects on some kinds of pollutants. But the composition of indoor pollutants is quite complex, and their concentrations are greatly different. Hence the adsorbents with wide adsorption range need to be developed.

4.2.3. *Photocatalytic oxidation (PCO)*

PCO is an innovative and promising approach to purifying indoor air. Operating at room temperature, PCO can degrade a broad range of indoor pollutants into innocuous final products such as CO_2 and H_2O. Photocatalysts, a kind of semi-conductor, mainly include TiO_2, SnO_2, ZnO, CdS, Fe_2O_3, WO_3 and MnO_2. The schematics of three typical PCO reactors are shown in Fig. 9. The reaction rate is an important parameter to evaluate the efficiency of PCO. The reaction rate of PCO is dependent on the humidity, light source, inlet pollutant concentration, characteristics of the photocatalyst, and type of reactor.

Photocatalyst surface carries weakly or strongly molecular water, as well as hydroxyl groups created by the dissociative chemisorption of water. In the absence of water vapor, the photocatalytic degradation is seriously retarded and the mineralization to CO_2 does not occur. However, excessive water vapor on the catalyst surface will lead to the decrease of reaction rate because water molecules can occupy the active sites of the reactants on the surface (Zhang et al., 2003a). Wavelength and light intensity have important impact on the reaction rate of PCO. The shorter wavelength is, the higher energy will be. But it does not mean that the shorter wavelength is always better. 365 nm is more efficient than 254 nm when TiO_2/O_3/UV is used to decompose toluene (Zhang et al., 2003a). In the degradation process of trichloroethylene, 315–400 nm UV-light is more favorable to photocatalytic reaction than 200–300 nm UV-light. Theoretically, if light intensity becomes stronger, more photons will be produced, and reaction rate will be enhanced. However, with an increase in light intensity, the utilization rate of photons decreases greatly and the recombination rate of electron-hole pairs increases. Different inlet pollutant concentrations lead to different reaction rates. Within a certain range of concentration, reaction rate increases with inlet pollutant concentration. However, reaction rate decreases with an increase in inlet pollutant concentration after the concentration reaches a certain value (Zhao and Yang, 2003).

The photocatalysts used now have poor degradation efficiency and low utilization rate of visible light. The following methods could resolve the two problems.

- Photoexcited treatment on the surface of photocatalysts: The adsorption of photoexcited sensitizers (e.g., ruthenium-II) on the surface of photocatalysts can widen the stimulating wavelength range and enlarge the utilization rate of visible light (Cho et al., 2001).
- Addition of noble metal: The atomic radiuses of noble metal (e.g., Pt, Ag, Au) are bigger, so they are unable to enter the crystal lattice of photocatalysts. But they can improve the surface characteristics of photocatalysts, and restrain the recombine of electron-hole pairs (Daté et al., 2002; Zhang et al., 2005b). The microbial destruction performance of the silver ion doped TiO_2 photocatalyst is an order of magnitude higher than that of a conventional TiO_2 photocatalyst (Vohra et al., 2006).
- Addition of transition metal ion: A small quantity of multivalence transition metal ion, used as the capture traps of electron-hole pairs, is mixed into TiO_2, which can prolong the recombination time of electron-hole pairs, widen the available wavelength range, and increase the utilization rate of visible light. Fe^{3+}, Mo^{5+}, Ru^{2+}, V^{5+} and Rh^{2+} can improve the activity of photocatalysts. Among them the effect of Fe^{3+} is the most prominent. But Cr^{3+} is harmful to the activity of photocatalysts (Wilke and Breuer, 1999).
- Addition of inert elements: Asahi et al. (2001) found that the utilization rate of visible light could increase greatly when the oxygen of TiO_2 was partially replaced with nitrogen. TiO_2 improved with carbon possesses more micro-pores, and its degradation capability is two times higher than that of the ordinary TiO_2.
- Compound materials: Compound materials can enlarge the specific surface area, improve the reaction conditions, and widen the response range to light. The band-gap energy of $ZnFe_2O_4$ is lower, and it can absorb visible light. When the mass ratio of Zn to Ti in the compound materials of $ZnFe_2O_4/TiO_2$ is 0.05, it possesses the highest photocatalytic activity (Fuerte et al., 2002).

Many researchers have investigated the PCO reactors by experiments and numerical simulation. Zhang et al. (2003b) and Mo et al. (2005) developed the general models for analyzing the removal of VOCs by PCO reactors. They thought that the number of mass transfer units (NTU_m) was the key parameter which affected the removal performance of VOCs by PCO reactors. The NTU_m was a simple linear product of three dimensionless parameters: the ratio of the reaction area to the cross-sectional area of flow channel (A^*), the Stanton number of mass transfer (St_m), and the reaction effectiveness (η). Jo and Park (2004) experimentally investigated the five parameters (relative humidity, hydraulic diameter, feeding type for VOCs, PCO reactor material, and inlet port size of PCO reactor) in relation to the PCO degradation efficiencies. None of the target VOCs exhibited any significant dependence on the relative humidity. However, the other four parameters were important for better VOCs removal efficiencies. Jo and Park (2004) also found that the CO generated during PCO was a negligible addition to indoor CO levels. The measured maximum was 0.5 ppmv. Sekine (2002) developed an air cleaner using manganese oxide (77% MnO_2) as an active component. A mass balance study confirmed that a major product through the reaction between MnO_2 and HCHO was CO_2. Harmful byproducts (e.g., HCOOH and CO) were not found.

Further studies are needed before PCO is applied practically in indoor air purification. Some of them are outlined in the following:

- The reaction rate and the efficiency of PCO are comparatively low. It is needed to improve the performance of the photocatalysts used now, and to develop new-style photocatalysts.
- The intermediates produced during the PCO process are more harmful to human health, so the degradation rate should be improved further.
- It is necessary to investigate the reaction mechanism further, to explore the optimal reaction condition, and to develop PCO reactors with high efficiency.
- The composition of indoor pollutants is quite complex, and their concentrations are greatly different. But recent research on the degradation characteristics of PCO is mainly focused on the removal of single or several species of indoor pollutants. Future research could explore the degradation characteristics of PCO under indoor conditions.

4.2.4. *Negative air ions (NAIs)*

The generation of NAIs mainly includes corona discharge, droplet breakage, and radiation (Sakoda et al., 2007). NAIs air purifier usually uses the electric conduction fiber or the corona thread as the emitting electrode, which can not only increase the concentrations of NAIs but reduce the starting voltage of corona discharge. The life of NAIs is approximately 100 s, and is affected by humidity and temperature (Parts and Luts, 2004). The chemical composition of NAIs depends on air composition and age of NAIs. Superoxide (O_2^-) is the main component of NAIs, and is more stable than other primary NAIs. Other primary NAIs such as O^- and OH^- may exist but in lower proportions than O_2^-. Secondary NAIs such as CO_3^-, $O_2^-(H_2O)_n$, and $OH^-(H_2O)_n$ are generated by reactions between primary NAIs and components in air. For example, the hydration reactions produce complex cluster ions such as $O_2^-(H_2O)_n$ and $CO_3^-(H_2O)_n$ in moist air. Skalny et al. (2004) indicated that the cluster ions $O_2^-(H_2O)_n$ and $CO_3^-(H_2O)_n$ were dominant NAIs in moist air. However, if O_3 and NO_X existed in air, the dominant was $NO_3^-(HNO_3)_m(H_2O)_n$. Furthermore, when the concentration of O_3 was greater than 25 ppmv, O_3 completely suppressed the appearance of O_2^- and clusters involving O_2^-.

NAIs is commonly used to clean indoor air. NAIs can remove aerosol particles, airborne microbes, odors and VOCs in indoor air (Daniels, 2002). The mechanisms of particle removal by NAIs include particle charging by emitted ions and electro-migration. The charged aerosol particles and the electric field produced by the electrical discharge increase the migration velocity towards the indoor surfaces. Particles are finally deposited on indoor surfaces (Lee et al., 2004a,b; Mayya et al., 2004). The velocity of particle electro-migration depends on particle size, amount of particle charge and intensity of the electrical field. Lee et al. (2004a,b) indicated that the electro-migration velocity and removal efficiency of aerosol particles increased with an increase in NAIs emission rates. Conversely, if the NAIs concentrations were too high, an electrostatic shield on wall surfaces was produced that prohibited the deposition of charged particles, especially when surface materials had low-level conductivity. The reactions between VOCs and NAIs are slow and complicated, and involve the radical chain reactions in which H_2O and H_2O_2 participate. The reaction rate constant declines as the relative humidity increases. For example, the reaction rate constants of NAIs and toluene, measured by Wu and Lee (2004), were 2.66, 1.32 and 1.07 ppbv (parts per billion, volume) min^{-1} at 0%, 25% and 70% RH, respectively (indoor air temperature 25 °C). This is because O_2^- concentration decreases with an increase in relative humidity as mentioned above. The O_2^- and H_2O can be combined as cluster ions such as $O_2^-(H_2O)_n$, and the formation of the cluster ions reduces the reaction activity of NAIs. Actually the reaction mechanism may be more complex and further research is needed. Wu and Lee (2004) also found that no byproducts were detected at a discharge voltage below 16.0 kV, and that the concentrations of O_3 and NO_X increased with the discharge voltage when above 17.0 kV (Table 2).

Table 2 – Concentrations of O_3, NO, NO_2 and NO_X generated at different discharge voltage during 1 h electric negative discharge

Discharge voltage (kV)	O_3 (ppb)	NO (ppb)	NO_2 (ppb)	NO_X (ppb)
7,10,15,16	ND	ND	ND	ND
17	64.5	9.2	107	116
20	163	10.6	114	125
25	358	9.9	124	134
30	504	13.1	137	150

ND represents that no byproducts were detected.

Table 3 – Concentrations of O_3 and NO_X generated at different humidity

Energy density ($J L^{-1}$)	RH (%)	O_3 outlet concentration (ppmv)	RH (%)	NO_X outlet concentration (ppbv)
10	0	49.9	0	1500
	27	31.2	25	800
	45	26.6	50	500

When NAIs is applied to clean indoor air, there are several disadvantages, such as higher requirement to the emitter, re-suspension of the deposited pollutants, lower removal efficiency to low concentration pollutants, and generation of the harmful byproducts. Therefore, further studies need to be done to increase the generation of NAIs, and to enhance the removal efficiency of NAIs purifier by being combined with other purification methods.

4.2.5. *Non-thermal plasma (NTP)*

Non-thermal plasma (NTP) can be generated in different modes, such as direct current corona discharge, pulse corona discharge, dielectric barrier discharge and glow discharge. The pulse corona discharge is usually used to generate NTP because it can reduce the formation of O_3 in the discharge process (Wang and He, 2006). Atmospheric plasma discharges generate high energy electrons, while the background gas remains close to room temperature (Magureanu et al., 2005). The energetic electrons excite, dissociate and ionize gas molecules, which produce chemically active species such as atomic oxygen, hydroxyl radicals and ozone. These active species are capable to remove various indoor pollutants such as VOCs, aerosol particles and microbe.

However, NTP leads to the formation of byproducts (e.g., CO, O_3, NO_X and aerosol particles) in the process of indoor air purification. O_3 and NO_X production rates increased linearly as the energy density increased (Cooray and Rahman, 2005). Cooray and Rahman (2005) also found that the corona polarity strongly influenced O_3 formation. At an energy density of 50 $J L^{-1}$, ozone concentrations for positive and negative corona were 224 ppmv and 21 ppmv, respectively. Humidity has an influence on plasma characteristics, which is reflected by changing O_3 and NO_X production rates. Table 3 indicates that the production rates of O_3 and NO_X decrease as humidity increases (Van Durme et al., 2007).

NTP reactor operates unsteadily, and its efficiency is low. Some researchers considered that the following two approaches could resolve the problems: (i) improvement of discharge mode, including the structure of reactor, and the frequency and the voltage of power supply (Oda et al., 2001); (ii) combination with catalyst (Oda et al., 2002).

Individual of the five methods above has its disadvantages due to the complexity of indoor pollutants. The following is a summary of their disadvantages:

- Exhibiting good purification effects on some kinds of pollutants, but poor purification effects on other pollutants.
- Leading to secondary pollution and influencing the purification effects by the byproducts.
- Strongly dependent on environment.
- High energy consumption and low energy efficiency.

Therefore, many researchers began to explore the combination of several air purification methods, such as the combination of PCO and adsorption, and the combination of PCO and NTP (Sekine and Nishimura, 2001; Ao and Lee, 2003, 2005; Shiraishi et al., 2003; Chin et al., 2006; Delagrange et al., 2006; Zhang et al., 2006a; Van Durme et al., 2007). These air purification methods can offset the disadvantages each other. Recent research on combined purification methods is mainly focused on the removal of single or several species of VOCs, and few involved in indoor air purification. In addition, further studies are needed to improve the structure of combined purification devices, and to optimize the operation parameters.

5. Conclusions and future work

A comfortable and healthy indoor air environment is favorable to occupants. In recent years, indoor thermal comfort has been improved greatly due to the development of air-conditioning systems. However, health problems related to poor IAQ appear more frequently, and it is the indoor pollutants that lead to poor IAQ. Many researchers have widely investigated the composition of indoor pollutants, sources, physical and chemical characteristics, and effects on human health. However, a given symptom usually has different causes, and a given pollutant may result in (or trigger) many different symptoms. The biological effects of different pollutants may differ by orders of magnitude. Moreover, the composition of indoor pollutants is quite complex and their concentrations are greatly different. The chemical reactions among indoor pollutants may occur, which can produce more irritating secondary pollutants. Many secondary pollutants even cannot be measured for the moment. It is not clear that the effect mechanism of these pollutants to human body with exposure under low concentrations and short time levels. It is also uncertain that the impact of exposure amount and exposure time on human health. Only if these problems are resolved can indoor air environment be controlled accurately and reasonably.

Outstanding air-conditioning systems help to improve indoor air environment. DOAS and ICTHS realize the independent control of temperature and humidity, and ensure that indoor terminal devices (e.g., FCU, CC) operate in dry condition. These two kinds of air-conditioning systems not only eliminate microbial pollution but save energy. CC/DV system is a combination of CC and DV, which makes full use of each advantages of CC and DV. CC/DV system can not only provide an excellent indoor air environment but possesses prodigious potential of energy saving. The new-style air supply modes either possess prominent potential of energy saving or can provide a comfortable and healthy indoor air environment or both of them. Therefore, it could be concluded that comfort, health and energy saving are recent research topics and the direction of air conditioning in the future. However, usually there is a contradiction among comfort, health, and energy saving. Current air-conditioning techniques need to be improved further, and new air-conditioning techniques are expected to be proposed as soon as possible.

Indoor pollutants, in particular, VOCs, are harmful to human health. The mend of chemical pollutants' emission characteristics of building materials and decorating materials, and the development of new types of materials without chemical pollutants emission are the optimal approaches to control the pollution sources of VOCs, and improve IAQ. Indoor air purification is an important method of removing indoor pollutants and improving IAQ under the circumstances that the ventilation and the control of pollution sources are impossible. The methods of indoor air purification mainly include filtration, adsorption, PCO, NAIs and NTP. However, each individual of the five methods has its disadvantages due to the complexity of indoor pollutants, such as poor purification effects, high energy consumption, and secondary pollution induced by the byproducts. The combination of several air purification methods is a promising technique of indoor air purification, such as the combination of PCO and adsorption, and the combination of PCO and NTP. Much foundational research needs to be done before they are applied practically. The combination purification devices with excellent performance also need to be designed and optimized based on the results of foundational research.

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