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A review of the advance of HVAC technologies as witnessed in ENB publications in the period from 1987 to 2014

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Abstract: Applying energy-efficient HVAC systems in building to reduce the building energy consumption is widely accepted as the most promising way of relieving the increasing world energy crisis. As one of the top journals in building energy use area, *Energy and Buildings* dedicated every effort to encouraging studies and proven practice of advanced, energy-efficient HVAC systems since its founding. In this paper, a critical review on the development of advanced, energy-efficient HVAC systems in the past 30 years is presented. Specifically, attention is paid on stratified ventilation, heat recovery ventilation and thermal storage in air-conditioning, indirect evaporate cooling technology, and the independent control of temperature and humidity, including radiant cooling system and solid/liquid desiccant system. Focused studies include but are not limited to mechanism investigation, numerical model development, experimental verification/calibration and equipment upgrade. The emphasis of previous work was summarized and discussed. Area that had not yet been studied in-depth was posed. The future prospects and application potentials are also discussed.

Keywords: radiant cooling, solid and liquid desiccant, indirect evaporative cooling, heat recovery ventilation, thermal energy storage, stratified air-conditioning.

1. Introduction

Building is the most indispensable element in our daily lives. Building energy consumption is the top components of the total energy consumption in a modern society, which takes a proportion of over 30% [1]. As the reflection of people's living standard and economic prosperity, building energy consumption will no doubt be growing rapidly. Since the "Energy Crisis" in the 1970s, the energy saving concept has been widely accepted as a

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necessary initiative for sustainable development. Saving energy from building sector is considered to be the most effective and productive alternative, thus received much attention.

HVAC consumed energy accounts for over one fifth of the total building energy consumption in developed countries and a rapid growing proportion in developing countries [1]. How to maintain a comfortable indoor environment yet consume lower energy is a challenging topic. In the past four decades, as the development of industrial technology and interdisciplinary communication, the bursting out of large amount of new ideas stimulates many novel system styles. Within all these newly-developed systems, some have been commercialized and widely applied, some have been proved feasible and waiting for deeper investigation, some are just crazy thoughts that require verification. As a well-recognized top-rated academic journal, *Energy and Buildings* was among the first choices for professionals, in which all the important discoveries and developments in HVAC systems were collected and recorded.

In undertaking this review of the HVAC technology development, the authors firstly browsed the titles of all the published papers in *Energy and Buildings* from 1987 to 2014, during which period the Journal developed rapidly and most paper were published. Though the journal was started from 1977, only less than 300 papers were published in the first 10 years. A total of 4733 papers were published during the year 1987 to 2014, which could be considered as the most presentative and rapid-developing period for the journal. A total of over 240 papers pertaining to HVAC systems were and selected for further review, which were further classified into five technology categories as depicted in Table 1 and Figure 1. The five most representative technologies are independent control of temperature and humidity, stratified ventilation, thermal energy storage, heat recovery and indirect evaporate cooling. Judging from the number of publications, apparently the independent control of temperature and humidity has been in the spotlight during the reviewed period: of all the literatures collected, over half are about this specific system configurations. If further classifying this category into temperature control section (radiant cooling) and humidity control section (solid and liquid desiccant).There are relatively a smaller number of studies about heat recovery and indirect evaporative cooling technologies. The reason may lie in the characteristics of these two technologies, both of which can be either a component of a complete HVAC system or some stand-alone equipment. Many studies on these two technologies were more likely to be published in other journals that more focus on the heat and mass transfer processes. Detailed review of individual technologies is presented in the following sessions, and their future application potentials will also be discussed.

Table 1 Number of literatures reviewed on each topic

Topic	No. of Literatures	Topic	No. of Literatures
Stratified ventilation	37	Indirect evaporative cooling	13
Heat recovery	20		
Thermal energy storage	37	Stratified ventilation + radiant cooling	8
Radiant air-conditioning	44		
Solid desiccant	37	Thermal energy storage + radiant cooling	4
Liquid desiccant	36		

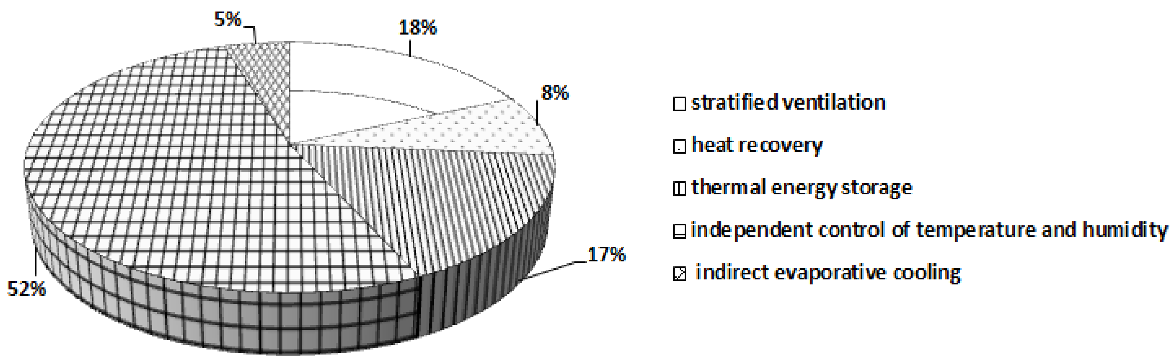

Figure 1 Statistics of the number of literatures reviewed on each topic

2. The temperature and humidity independent control air-conditioning system

The temperature and humidity independent control air-conditioning system is probably the greatest development in the indoor environment control area in the past 25 years, and it will no doubt become one of the major air-conditioning system types in the future.

In the year 2002, Niu et al. present their idea about the independent control of temperature and humidity for the first time in the journal *Energy and Buildings*. They had been working on radiant cooling and desiccant system individually. In their proposal, they combined their previous work together and made a hourly simulation to predict the annual energy consumption of their proposed system. Their result indicated a 44% primary energy saving potential [2]. As the largest developing and energy consuming country, China showed great interest on the temperature and humidity independent control air-conditioning system. Chinese scholars devoted much effort for research and application of this novel system. The research group led by Professor Jiang of Tsinghua University did an outstanding job not only in the laboratory, but also in practice. Zhao et al. reported a practical application in an office building at Shenzhen, which involved a liquid desiccant system, dry fan coil and radiant panel. In the year 2009, an energy saving of 60% was achieved with a total COP of 4.0 [3]. Zhang et al. made a detailed performance investigation on a temperature and humidity independent control air-conditioning system applied in an airport terminal in Xi'an. The system consisted of a radiant floor system and a liquid desiccant fresh air supply system. Their investigation indicated that the temperature and humidity independent control air-conditioning system could maintain a comfortable indoor environment with relatively low energy consumption, during the year 2012, the energy efficient ratio of the cooling plant was 2.62 [4]. Besides China, researchers from other countries also made some significant moves on the development of the system. López et al. discussed a combination of solar energy application and the temperature and humidity independent control air-conditioning system. In their study, the solar energy was utilized for the regeneration of the desiccant wheel. They claimed that a 35% energy saving could be achieved compared with conventional system [5]. A temperature and humidity independent control air-conditioning system includes two parts, sensible load handling unit and latent load handling unit (dehumidification system). For sensible load handling unit, the most typical choice is the radiant cooling system (chilled ceiling in most cases). For dehumidification system the common choice is multiple, above which the most popular ones are desiccant wheel and liquid desiccant.

2.1. Radiant cooling system

As early as the year 1995, Niu et al. started to investigate the energy saving potential of the cooled-ceiling system. They conducted a series of simulation on the performance of the cooled-ceiling system under Dutch climate, trying to make an evaluation on the annual energy consumption and the indoor thermal comfort control ability of the cooled-ceiling system. Their result illustrated that under Dutch climate, the energy consumption of cooled-ceiling system was equivalent to that of the conventional VAV system while the indoor comfort level was maintained the same. They further concluded that in hot and humid area, a much higher energy saving potential could be expected from the cooled-ceiling system [6]. Hirayama and Batty conducted a further study on the applicability of the radiant cooling system in hot and humid climates. Based on data from a series of experiments in a climate chamber, they developed a mathematical model describing the heat transfer process within a room under radiant cooling. With the help of their model, they got several very important conclusions which were considered the principle for radiant cooling design. Their calculation indicated that in radiant cooling, radiant heat transfer took around 55% of the total heat transfer amount, while convection took the rest 45%. They suggested that the radiator had an immediate effect on the target, which indicated a potential of a higher air temperature set-point. They also suggested that the ventilation design was the key factor that affected the energy and comfort performance of the radiant cooling system, which should be considered as the top emphasis during design stage [7]. The conclusions in [6] and [7] were both reflected in Stetiu's study which focused on the energy saving potential of radiant cooling system in office building. According to Stetiu's simulation result, the application of radiant cooling could achieve an energy saving of around 30% in U. S. office building compared with conventional air-conditioning system. The saving varied with the climates, while different ventilation methods should be referred in different climates to ensure the energy saving effect [8]. Sodec investigated the economic viability of the radiant cooling system and claimed that there existed a cooling load break-even point for the radiant cooling system to be more cost effective than conventional VAV system due to the high investment. Sodec suggested that in Germany, if the cooling load was higher than 45-55 W/m2, applying cooled ceiling system would be a better choice [9]. Tian et al. measured the actual cooling capacity of the radiant cooling panels under different window-wall ratios and indoor air velocities. They gave a series of correction coefficients to more precisely represent the cooling capacity of the radiant cooling panels for system design [10]. Vangtook and Chirarattananon highlighted the importance of system design in an experimental investigation. They stated that to avoid the condensation, a higher chilled water temperature was required, which resulted in a larger radiant surface, which stand for a larger investment [11].

Most of the early studies focused on the energy consumption of the radiant cooling system. As the system's energy-efficient features had been proved by various research cases, people also noticed the thermal comfort issue under radiant cooling. Imanari et al. conducted an occupant voting experiment to assess the thermal comfort under radiant cooling. Their result indicated that thermal comfort level was significantly improved due to smaller vertical temperature difference and lower supply airflow rate [12].

The calculation of cooling load under radiant cooling system is an important constraint that affects the promotion of the system, thus attracted much attention. Causone et al. proposed an equivalent heat transfer coefficient method for the calculation of space load. They also conducted an experiment for the selection of room reference temperature. According to their measurement result, the operative temperature at 1.1m height was the most suitable as the reference temperature for space load calculation with their proposed method [13]. Later, they further improved their calculation method by calculating the solar radiation separately [14]. However, the research conducted by Andrés-Chicote et al. proved that the method proposed by Causone et al. was not generally applicable.

They claimed that in order to achieve an accurate result, radiation and convection should be considered separately [15]. Strand and Baumgartner developed a numerical model for the simulation of the radiant cooling system. They prospectively constructed their model in a generic way so that their model could be applied in any kinds of building with any kind pf associated systems under any kinds of simulation programs. Their model was later evolved into the simulation algorithm for the world famous software EnergyPlus [16]. Tian and Love made some validation on the model described in [16] with on-site measurement. They discovered that though the model could predict the annual cooling load within acceptable error, it could not allocate the instantaneous cooling load precisely, which may be attributed to the lack of control strategy [17]. Wang et al. proposed a CFD based simulation model for the evaluation of the radiant cooling system. With their model, they investigated the energy consumption of the system from the exergy point of view [18]. Tye-Gingras and Gosselin conducted a numerical investigation on the impact of the tube layout within radiant panel during the heat transfer process. They constructed a 2D finite volume model for the full temperature field calculation on the radiant panel and received a no more than 2% error within all the simulation cases. Their conclusion could largely improve the calculation speed in radiant panel simulation cases [19]. Feng et al. investigated the difference between cooling loads of radiant cooling system and conventional air-supply system through a simulation study with the improved model of [16]. They claimed that actually, the cooling load under radiant cooling system was 5% to 15% higher than that under conventional air-supply system, which should not be ignored in the design stage [20]. Sui and Zhang conducted a simulation study on the cooling capacity distribution feature of a hybrid air-conditioning system which combined radiant cooling system with conventional air supply system. They discovered that the distribution of sensible load handling capacity of the two subsystems would affect the selection of the ventilation style from energy-efficiency point of view [21].

With the development of simulation tools, the impact of different parameters on the performance of the radiant cooling system and their affection mechanism became more and more clear. Professionals started to make improvement on the device under the guidance of simulation outcome, aiming at enhancing the cooling capacity of the radiant cooling system. Zhang et al. tested the cooling capacity of a new type of suspended metal radiant panel with inclined aluminum fins by conducting a comparative experiment in two identical test rooms. Their experiment result indicated that the new type panel gave a 19% higher cooling capacity compared with conventional type [22]. With the application of environmental chamber, Tang and Liu analyzed the optimum design for the radiant panel surface to decline and delay the dew formation. With the assistance of simulation tools, they were able to conduct a series of calculation cases to get the ideal contact angle for the panel surface material [23].

2.2. Dehumidification system

2.2.1. Solid desiccant

Desiccant wheel is the core component for the solid desiccant system. The precise description of the heat and mass transfer process within the desiccant wheel has been the research focus since late last century. Cejudo et al. (2002) presented two models for the simulation of desiccant wheel. The first model was a conventional mass/energy-balance-based numerical model which was solved by finite differences techniques. The other model was a black box model based on neural network training. An experiment was also prepared to provide data for numerical model validation and neural network model training. The simulation result from neural network model displayed a higher accuracy compared with the numerical model, which indicated that it was necessary to consider the heat loss between the wheel and environment for better numerical simulation [24]. Vitte et al. developed a numerical model which was inspired by rotating sensible heat exchangers. They introduced in some previously published measurement data to validate their model, and applied their model in a simulation study of desiccant wheel control strategy. They claimed that as long as the regeneration airflow rate was not much higher than the process airflow rate (less than 1.2 times), their model was reliable (less than 3% error) [25]. Panaras et al. presented an analogy-based simplified algorithm to improve the convenience of numerical model. They claimed that through their approach, the operation parameters of the desiccant wheel could be predicted from the manufacturers' data accompanying their products [26]. Antonellis et al. proposed that the temperature and velocity distribution along the air tunnel within the wheel should also be considered in the numerical model. They conducted a series of experiments which proved that the accuracy of their model was slightly better than previous model [27]. Parmar and Hindoliya made some further investigation on the neural network model of desiccant wheel. They compared several different data training algorithms and claimed that a "Levenberg–Marquardt back propagation" training algorithm could obtain a least mean square error [28]. Nóbrega and Brum conducted a simulation study to discuss the different impacts of heat and mass transfer within desiccant wheel on the system efficiency of the desiccant system. They claimed that in a passive system, the heat and mass transfer had conflicting influences on the system efficiency, while in more common active dehumidification system, heat and mass transfer had cooperating effects [29]. Sheng et al. developed a simple methodology for desiccant wheel dehumidification efficiency prediction. They applied multiple linear regression theory between the evaluation indexes and design variables to give a direct display of the relationship, which was supported by their experimental data [30]. Ghazal and Ghiaus proposed a gray-box model to identify the heat and mass transfer coefficients between the fluid flow and the porous materials within the desiccant wheel. They claimed that their model was a dynamic model in a state-space expression. Validation result indicated a less than 10% error between their model and previous more complicate models [31].

Heat is needed for the regeneration of desiccant material, in lieu of the cooling energy consumption in a condensation-based dehumidification process. Utilization of low-grade heat source for the regeneration is the most common idea of saving energy in the dehumidification system. Casas and Schmitz reported their experiment system, in which gas was applied for the regeneration of desiccant wheel. The operation data for the 2002 cooling season was presented, which indicated a 40% primary energy saving could be achieved from the desiccant system compared with conventional condensation dehumidification [32]. Aynur et al. introduced a solid desiccant system in which applied electric vapor compression heat pump as the regeneration heat source. They compared the energy consumption and efficiency of desiccant ventilation system with that of a heat recovery ventilation system, and claimed that the desiccant system could achieve an energy saving of over 25% at a COP of around 5-6 [33]. Hürdoğan et al. added an extra heat exchanger between the regeneration air entrance and the exhaust air to make further energy reduction. Their experiment displayed a 10% saving in the heating requirement [34]. Ge et al. designed a heat pump-assisted desiccant wheel system in which cooling coil and desiccant wheel were coupled to handle the latent load together. An air source heat pump system was applied to supply regeneration heat from condenser dissipated heat. The operation result showed that the primary energy consumed for regeneration could be saved by 50%, while the total system energy consumption could be reduced by 37% [35]. Fong et al. proposed the application of solar energy as the heat source in the desiccant wheel. They simulated six different hybrid systems to test the applicability and energy saving potential of the solar-assisted solid desiccant system they imaged and concluded that an over 30% energy saving could be expected [36]. Hatami et al. developed a methodology for the optimization of solar collector surface. Major parameters during the system operation were considered, such as airflow rate, wheel size and rotating speed, environment air status, regeneration air status as well as the solar radiation [37]. Li et al. designed a solar-assisted two-stage desiccant wheel system. Operation measurement result showed that the system's average moisture removal level could reach as high as 11.9 g/kg while the thermal efficiency of the solar energy utilization was over 40%, which indicated that the system could satisfy the dehumidification need under most weather condition [38]. Enteria et al. analyzed the roles of each component on the total system efficiency of a solar-assisted desiccant wheel system. They claimed that the solar collector was the key component that affected the system's total efficiency, to which an energy loss of over 50% and an exergy destruction of over 70% could be attributed [39]. Baniyounesb et al. reported a year-round operation measurement of a solar-assisted desiccant wheel system in subtropical climate. The reported system worked at an average COP of 0.5, reducing the annual primary energy consumption by 18% [40].

2.2.2. Liquid Desiccant

As early as the year 1997, Isetti et al. presented a concept of triggering dehumidification process by creating a vapor partial pressure difference. They placed a kind of hydrophobic synthetic membrane between a hygroscopic solution and moist air, which was not liquid desiccant in a strict sense though, some of the principle and theory were common [41]. Li et al. analyzed the algorithm of the ideal dehumidification energy efficiency calculation. They compared the ideal energy efficiency of various dehumidification processes on removal of the same amount of moisture and claimed that it is the easiest for the liquid desiccant cycle to approximate the ideal reversible dehumidification process [42]. Wang et al. assumed an ideal liquid desiccant system and conducted an exergy analysis on important parameters, aiming at serving as a reference for future system design and device upgrading [43]. Ge et al. paid attention to the control strategy for the liquid desiccant system. They conducted a series of simulation first to evaluate the effect of controlling different parameters in the air dehumidification process and solution regeneration process. With the evaluation result, they proposed two different control strategies, variable strong solution inlet temperature method and variable strong solution flow rate method. A simulation study was then performed which indicated that the variable strong solution inlet temperature method was more effective because the system's dehumidification capacity was more sensitive to the temperature [44]. Li et al. developed a novel mass transfer model based on kinetic theory to better explain the dehumidification reverse phenomenon that constantly observed in experiments. Corresponding experiments were conducted to verify the model's accuracy and a satisfactory result was achieved [45]. Gao et al. conducted an experimental study on the internally cooled dehumidifiers. They claimed that the internally cooled dehumidifier had higher dehumidification effectiveness and moisture removal rate compared with conventional adiabatic dehumidifier. They also claimed that the optimal solution temperature of internally cooled dehumidifiers was around 5℃ higher than that of adiabatic dehumidifier

[46]. Meanwhile, Qi et al. (2013) developed a simplified model to predict the operation parameters of internally cooled/heated liquid desiccant dehumidification system, which was based on multiple linear regressions. They compared the predicted data with previous experiment result and claimed that an average difference of 14.5% for dehumidifiers and 6.8% for regenerators in outlet air moisture content and water temperature occurred between their predicted result and previous experiment data [47].

In 2007, Lazzarin and Castellotti reported a liquid desiccant application in a supermarket in Italy after decades' deeper investigation and improvement, in which temperature and relative humidity were key factors not only for thermal comfort, but also for product preservation. Electric heat pumps were used as the re-generation heat source. They claimed that a 12% to 21% saving was achieved from the supermarket's total energy consumption, and that, if considering air-conditioning system only, the energy saving could be as high as 60% in some cases [48]. Zhu et al. presented the operation data of the year 2007 for a heat pump-coupled liquid desiccant system in a Shanghai office building. An average COP of as high as 6.24 could be calculated from the published data, while an overall air-conditioning system COP of 5.28 was achieved during the operation period, both of which were notably higher compared with other air-conditioning systems at that moment [49]. Zhang et al. performed a system upgrading for the heat pump driven liquid desiccant system. They added an auxiliary condenser to the regeneration air path to exhaust extra heat from the original condenser. The result indicated that, at least, 18% improvement in COP could be obtained. If a water-cooled condenser was applied, which used cooled water from evaporation of the exhaust air, the improvement could be as high as 35% [50]. Yin et al. proposed a liquid desiccant system which utilized the waste heat from hot exhaust air for regeneration. Their simulation showed that this kind of system was feasible as long as the inlet solution temperature was high enough to avoid air dehumidification within regenerator [51]. Katejanekarn and Kumar presented their design of the solar-assisted liquid desiccant system, in which the weak solution was sent directly under a solar collector for regeneration. They carried out a simulation to analyze the impact of different operation parameters, and their conclusion was that solar radiation was a key factor for the performance of the system, which is quite similar to the solar-assisted solid desiccant system. They also discovered that the water balance between dehumidifier and regenerator was critical for the stable operation of the liquid desiccant system [52]. One major concern for the solar-assisted liquid desiccant system was its dependence on the solar radiation. Qi et al. proposed the coupling of thermal energy storage with the solar-assisted liquid desiccant system. They conducted a simulation study with the cooling load profile of Hong Kong to calculate the minimum required solar collector area and the potential energy saving for different seasons. Their result indicated a up to 90% saving could be achieved in winter while in summer the saving was still over 10% [53]. Cheng et al. proposed another possible way of store solar energy which involved the application of photovoltaic- electrodialysis as the regeneration method. An experiment study was also conducted, which indicated that the electrodialysis regenerator could be applied in liquid desiccant system. They claimed that a further analysis would be conducted to investigate the energy features of the electrodialysis regenerator in detail [54]. Yang et al. proposed the application of ultrasonic atomization in the liquid desiccant system. They claimed that after ultrasonic atomization, the desiccant solution would be broken into droplets with diameter of around 50 μm, which would significantly improve the solution's specific surface area. Their experiment indicated an improvement of average dehumidification effectiveness from 20.8% to 66.5%. A 46% solution flowrate reduction was also observed. It was also concluded from the experiment that with ultrasonic atomization, the concentration of the solution could be as low as 26%, compared with the 38% of conventional system [55].

2.3. Brief summary

From the above review of literatures, it could be concluded that compared with conventional systems, the temperature and humidity independent control air-conditioning system possesses several outstanding advantages:

1. In a conventional system, the sensible load and the latent load were handled simultaneously. The dehumidification of fresh air required a much lower chilled water temperature. Besides, the ratio of sensible load and latent load was affected largely by climate, occupant behavior and the type of buildings. These factors resulted in a frequently appeared "over-cooled" phenomenon inside buildings, which not only caused higher energy consumption, but also affected the occupants' thermal comfort experience. With the application of the temperature and humidity independent control air-conditioning system, the above-mentioned problem could be solved perfectly.

2. The temperature and humidity independent control air-conditioning system did not utilize condensation to achieve dehumidification and there was no wet area occurred within the system, which eliminated the breed of mildew. The fresh air supplied in the system was only for the removal of moisture, carbon dioxide and peculiar smell, which indicated a way smaller airflow rate compare with VAV system. These two features would significantly improve the indoor air quality.

3. In a temperature and humidity independent control air-conditioning system, since the sensible load was handled separately, the chilled water temperature could be much higher at around 18℃ instead of conventional 7℃. The high chilled water temperature suggested a higher COP. It also made the application of low-grade cooling source or even free-cooling possible.

3. Stratified ventilation

Stratified air-conditioning is a novel idea for more energy efficient indoor thermal environment control through delicate engineering of the indoor airflow. The basic principle of stratified air-conditioning is to consider the occupied zone, which is normally around 2m high, and the upper zone separately. Certain airflow pattern such as displacement ventilation is applied to artificially maintain the occupied zone, while the upper space is left uncontrolled or as a path for heat exhaust.

Compared with well-mixed air-conditioning concept, a stratified system only handles part of the space cooling load (cooling load that occurs in the occupied zone), which could significantly reduce the equipment investment as well as the energy consumption during operation. Besides, for the stratifying purpose, fresh air is supplied directly into the occupied zone, which is also favorable for better inhaled air quality for occupants.

3.1. System cooling load calculation

One of the key issues to fully take the advantage of the stratified system is the calculation of the space cooling load, which is the foundation of the system design. For a stratified air-conditioning system, the system load mainly consists of two parts. The first part is the heat gain from occupied zone, including occupant, equipment as well as the building envelope. The second part is the load that transferring from the un-occupied zone, including convection heat gain caused by air flow and the radiation heat gain. Since the indoor air flow and the transient heat transfer interact with each other, the indoor air flow and the space load should be considered simultaneously. In 1990, Chen and Kooi proposed a simplified method to predict the indoor airflow pattern and the space load of a displacement ventilation system. They applied the κ-ϵ turbulence model to calculate the indoor airflow distribution, and then utilize the air temperature distribution to calculate the space load [56]. Xu and Niu proposed numerical method to calculate the energy consumption of the stratified system, which involved a combination of FLUENT, a CFD simulation and ACCURACY, a dynamic cooling load simulation. First, ACCURACY was applied to calculate the surface temperatures of the building envelope, which was utilized as a boundary condition for CFD simulation, so that an indoor air temperature distribution could be received. Then, the indoor air temperature distribution was considered as an input for a revision in ACCURACY, from which an updated supply air and envelope surface temperatures could be achieved. The updated supply air and envelope surface temperatures were then used again as the boundary condition for a second round CFD simulation. The indoor air distribution calculated from the second round CFD simulation was then applied in ACCURACY to calculate the supply and exhaust air temperature, which were eventually used for cooling load calculation [57], and the effective cooling load factor was defined as the ratio of cooling load in the occupied zone and the total space cooling load. CFD simulation tool was applied to calculate the effective cooling load factor of each heat source separately, while the space cooling load could be acquired from conventional calculation method. Lee and Lam developed a numerical model which was based on the thermal plume rise theory to predict the room air temperature distribution under stratified air-conditioning system. They claimed that the difference between the calculation result from their model and the test result could be within 6% in most case [58]. Schiavon et al. proposed a simplified cooling load calculation method for stratified system. They defined a parameter named cooling load ratio, which stand for the ratio of design cooling load of conventional overhead mix-type system and the cooling load of stratified system. The cooling load ratio could be expressed as a function of several key factors, such as floor level, zone orientation and the window-to-wall ratio, etc. [59]. Cheng et al. further clarified the association between the conventional space cooling load and the AHU cooling load, and developed a new formula that links the reduced air-conditioning load in terms of the percentage of the conventional total space cooling load with the outdoor air ratio and temperature difference between the exhaust air and outdoor air [60]. Later, they conducted an experimental study to validate their CFD model. With their improved model, they further investigated the impact of supply, return and exhaust grille location on the indoor thermal comfort [61]. Lin et al. conducted a detailed simulation study to test the annual energy performance of a unique stratum air-conditioning system in Hong Kong. Different energy sources, equipment and supply air terminal positions were considered. Their simulation result indicated an at least 25% reduction in annual energy consumption for stratum system compared to conventional system [62, 63].

3.2. Stable thermal stratification control

Another major barrier was the maintenance of the thermal stratification, which affected the system's actual space load. Li et al. claimed that the space air temperature distribution was a result of joint action by conduction, convection and radiation. They conducted a very important study on the effect of radiation on displacement ventilation. A series of experiments were first conducted to test the vertical air temperature distribution with different wall surface emissivity, and then a CFD-based numerical method was constructed to predict the air temperature distribution within the room, which was verified by the experiment data. From the result, they discovered that heat radiation had a negative impact on the displacement ventilation by heating up the floor surface, which weaken the stratification level [64, 65]. Nielsen conducted a series of experiments on the airflow rate from air terminal device in displacement ventilation. He discovered that the airflow velocity can be described by the Archimedes number. While the Archimedes number was above 4, a stable stratified flow could be achieved [66]. Lin and Tsai also studied the effect of supply air flow rate on the vertical temperature profile. Their measurement showed that the stratification height would rise as the supply airflow rate increased [67]. Chenvidyakarn and Woods did an interesting yet very useful investigation on how a distributed heat source and a localized heat source would affect the stratified effect for a stratified air-conditioned room, which perfectly imitated a meeting room or classroom with active speaker and a group of audience. They discovered that a thermally comfortable and stable indoor stratified environment was affected by both the supply air flowrate and the ratio of the distributed heating to the total heat flux. A model was developed and validated to calculate the design air flowrate under different heat source distribution [68]. Kong and Yu conducted a CFD simulation study on the effect of space load and supply air status on the stratification under displacement ventilation, which involved the application of κ-ϵ turbulence model. They introduced in a new parameter named buoyant jet length scale to describe the properties of the plume formed from supply air, which could be expressed as a function of space load, supply air velocity and flux. Their result indicated that as the buoyant jet length scale increased, the stratification weakened [69]. Schiavon et al. carried out a series of measurement to test the effect of different air diffusers on the stratification formation. They discovered that reducing the vertical velocity component of supply airflow could create a stronger stratification [70].

3.3. Indoor thermal comfort and air quality

Indoor thermal comfort and air quality were also key factors that should be considered carefully for stratified air-conditioning system application and design. Sekhar and Ching stated that in a stratified system, the supply air terminals were installed directly in the occupied zone, which had a strong possibility to cause thermal discomfort for occupants nearby. They also observed a higher concentration level of dust in occupied zone [71]. Chung et al. studied the occupants' PMV levels under stratified system and conventional mix-type system, and claimed that to achieve a same comfort level in the occupied zone, the supply air temperature in the stratified system could be much higher than that in the conventional system, which showed a considerable potential of energy saving [72]. Lau and Chen conducted a series of simulation study on the stratified system under five major U. S. climates. They claimed that though displacement ventilation could save some energy compared to conventional system, the relatively high coil temperature resulted in poor dehumidification ability. They suggested an extra dehumidification system be installed to ensure a comfortable indoor environment [73]. Lee et al. also expressed similar concern on the supply air temperature set-point. They claimed that the supply air temperature should be selected carefully considering not only energy consumption but also thermal comfort [74]. Kim et al. studied the applicability of the stratified system in a huge space with a high ceiling. Their results showed that a stratified air-conditioning system could be a perfect selection for a huge space such as theater. The air velocity within the occupied zone was almost imperceptible, and the vertical air temperature difference was also reduced, which indicated a higher thermal comfort level [75].

3.4. Combination of displacement ventilation and chilled ceiling

A combination of displacement ventilation and chilled ceiling system is a popular design concept. Coupling the displacement ventilation and chilled ceiling allows larger load handling capacity and a higher thermal comfort level (by reducing vertical temperature difference and draft). Besides, since chilled ceiling also operated at a slightly higher temperature of around 17℃-19℃ compared with conventional air-conditioning system, its combination with displacement ventilation could be supplied with one high-temperature chilled water supply system, which show a great potential on energy and investment saving. Hodder et al. proposed a chilled ceiling displacement ventilation system for office as early as 1998. They constructed a full-scale experiment room and did some basic measurement on the vertical air temperature difference [76]. Taki et al. installed a honeycomb slat structure on the chilled ceiling to suppress the natural convection caused by the cool ceiling surface. A following experiment demonstrated the effectiveness of their measure [77]. Keblawi et al. presented a methodology on the optimized design of the chilled ceiling displacement ventilation system with an application of design charts containing correlation of system load and operational parameters such as supply air temperature and ceiling temperature [78]. Keblawi et al. proposed an online control predictive tool for the optimal control of the chilled ceiling displacement ventilation system. The optimized supervisory control strategy within the tool was based on the prediction of the instantaneous load change and the COP of the system [79]. Chakroun et al. developed a transient coupled thermal and contaminant transport model to assess the indoor air quality under a chilled ceiling displacement ventilation system. After validated by experiments, the model was applied to evaluate the energy saving potential under different fresh air fraction [80]. Later, they made an attempt of combing personalized evaporative cooler with chilled ceiling displacement ventilation system, and a series of numerical modeling analysis were developed to evaluate the energy and thermal comfort performance of the integrated system [81, 82].

4. Thermal energy storage (TES)

Thermal energy storage tends to make full use of the system's capacity un-occupied periods, stores cooling into ice, phase-change materials or other carriers, and releases it during peak load hours. In this way, thermal energy storage could reduce the peak cooling load of an air-conditioning system, potentially improve the total efficiency of the system and make a sufficient cut in investment. Ice was considered a primary choice for the thermal energy carrier with its high specific heat and cheap price. Thus most early TES systems were ice based. Due to the lack of real-time monitoring data and control experience, early designs of thermal energy storage often failed to meet the expectation. In some extreme cases, the actual electric energy saving was only 10% of the original estimate [83]. After carefully compiling the design, installation and operation of two application cases of thermal energy storage air-conditioning systems, Akbari and Sezgen argued that it was quite normal for a newly-developed system to not meet the expectations in the beginning. They found that all the operation problems could be solved by proper design in the first place [84]. At the same time, Meyer and Emery claimed that an optimal control strategy was important as well. They also claimed that the ambient humidity was the top factor that should be considered during the design of the control strategy [85]. Kizilkan and Dincer thought that the potential and availability of the thermal energy storage system should be assessed via an exergy analysis to give a more accurate result [86]. Sebzali et al. proposed a life cycle cost analysis method to assess the economic and environmental benefits of the thermal energy storage air-conditioning system [87]. Henze et al. reported a retrofitting project of introducing in a chilled water thermal energy storage system into a huge air-conditioning system for a pharmaceutical industry. They claimed that the application of thermal energy storage system could achieve a saving of up to 25% of the operation cost, while the reliability and availability of the total system could also be improved [88]. Rismanchi et al. evaluated the energy saving potential of applying thermal energy storage air-conditioning system in Malaysia through a survey on Malaysia's office buildings. Their calculation illustrated that the application of the system could reduce the annual cost of the air-conditioning system by up to 35%, and the payback period would be around 3 to 6 years [89].

4.1. Heat Transfer within a TES device

For a thermal storage device to be effective in terms of storage density and charging/discharging rate, the design and prediction of the transient heat transfer processes involved is critical. Tube in a tank and stratified water storage are the two commonly used TES devices. Zhu and Zhang constructed a dynamic simulation model to describe the melting process in an ice-to-coil tank with built-in tubes. The validation of the model only required data from two different cases, which largely reduce the effort for design and prediction of the system [90]. Navarro et al. experimentally investigated the impact of ice floating in an ice-to-coil tank. They summarized the experimental data and added two correlations to the existing mathematic model [91]. Wang et al. applied fuzzy sets theory combined with optimal weighting method, while Sanaye and Shirazi applied genetic algorithm respectively in their simulation analysis of the thermal energy storage system, trying to obtain the optimal design [92, 93]. Bruno et al. proposed an effectiveness and number-of-transfer-units (ε-NTUs) method to characterize the heat transfer within phase change material [94]. A more accurate and complete mathematic model is helpful for the design professionals to understand the key factors that affect the performance of a thermal energy storage system, and started to make improvement consciously. Chen et al. proposed a TES of using chilled water with a temperature of above 8℃, which is obtained by supercooling refrigerant before throttling. A counter flow supercooler was applied just before the throttling valve. The high-temperature water from water storage tank was utilized as the supercooling medium for the refrigerant so that the refrigeration output could be increased. The authors claimed that the system had a higher cool storage density than conventional chilled water system, while the efficiency as well as the reliability was acceptable [95]. Fang et al. reported an experiment of spherical capsules packed bed in the ice-to-coil tank. Their result indicated that the application of spherical capsules packed bed could enhance the heat transfer process during charging and discharging period [96].

4.2. Phase change materials (PCM) as TES media

With the development of material science and processing technology, phase change materials were considered as an excellent alternative for ice as TES media for air-conditioning systems. Compared to conventional ice-based TES system, phase change materials-based system could work at a relatively high chilled water temperature, which would mean a higher operation COP of the chillers. Besides, the initial investment and retrofitting cost of phase change material-based system were much lower than ice-based system. As early as 2006, Hammou and Lacroix reported a design of a hybrid solar and electric energy storage system, which applied a PCM as the storage medium. They developed a heat transfer model for their proposed system, and conducted simulation cases with two different PCMs, namely capric acid with a melting temperature of 301K and n-octadecane with a melting temperature of 303K. The simulation result indicated a at least 32% reduction in electricity consumption [97]. Later, Bony and Citherlet developed a numerical model with Finite Element Difference Scheme to better describe the heat transfer process between PCM and water in the storage tank. They did a measurement to validate their model and found a good agreement [98]. Parameshwaran et al. conducted a detailed on-site full-scale measurement on the annual energy consumption of a chilled water air-conditioning system combined with PCM-based thermal energy storage. They reported an on-peak total energy saving of up to 42% [99] during a peak day.

Researchers put much effort on the enhancement of the heat transfer between phase change material and the chilled water. It was discovered that increasing its surface area to volume ratio by encapsulating phase change material into microcapsules could significantly enhance the transient heat transfer, especially when microencapsulating phase change materials (MPCM) are dispersed into water to form the MPCM-in-water slurry. Diaconu developed a theoretical model for the heat transfer process within MPCM-in-water slurries, with his model, he managed to predict the enthalpy change around the melting-point of the PCM during a charging-discharging cycle and assess the impact of different factors on the enthalpy-temperature curve [100]. Parameshwaran and Kalaiselvam conducted an experimental study on the cooperation of thermal energy storage system which applied sliver-based PCM-in-water slurry and a VAV system. They claimed that a largest saving of 58% could be achieved during a peak day, while an annual saving of around 7.9% to 17.8% could be obtained [101].

Since a PCM-based thermal energy storage system could work at a relatively high temperature of around 14℃ to 20℃, it is considered to be a perfect match for the more energy-efficient air-conditioning system like radiant cooling system. Wang et al. proposed a hybrid system which involved the MPCM slurry for the storage of a night time free evaporative cooling for chilled water supply to cooled ceiling for space temperature control. They simulated the annual energy performance, proposed a method to estimate the availability of the free cooling and size the storage tank [102].

5. Heat recovery ventilation

Heat recovery ventilation system involves an additional heat exchange between the supply and exhaust air flow, so as to reduce the energy demanded in handling the precondition of fresh air. It was claimed that well-designed heat recovery could save as much as 50% of the total thermal loss from the building indoor environment [103]. Heat-recovery in ventilation was first noticed as a promising alternative for reducing energy use in 1970s, since then applying heat recovery system on exhaust air path was a quite popular design. There are two different types of heat recovery ventilation system, namely sensible heat recovery and total heat recovery.

5.1. Sensible heat recovery

The ventilation system with sensible recovery was quite simple, which involved a cross-flow or counter-flow air-to-air eat exchanger equipped between the supply and exhaust air path. In earlier studies, professionals discovered that shortcuts and leakage of the air handling units significantly impacted the efficiency of heat recovery from exhaust air [103, 104]. Several relating studies with the application of tracer gas were reported. Roulet et al. performed a measurement on 13 air handling units, trying to figure out the real global heat recovery efficiency. They discovered that the real global efficiency can vary from 10% to 80% depending on shortcuts and leakage [103]. Manz et al. developed a quantitative system to assess the efficiency of air handling units with heat recovery. They defined a parameter named the ventilation efficiency, which is now widely applied as the common approach. The ventilation efficiency could be expressed as the ratio of a fictitious airflow rate (which was proportional to the removal of contaminants) and the total supply airflow rate [104].

Fouih et al. conducted a simulation study on the applicability of the heat recovery ventilation system. They claimed that the applicability of the heat recovery ventilation system varied with the building type [105]. Ozyogurtcu et al. conducted a life-cycle analysis on a ventilation system equipped with exhaust air heat recovery in Turkey, their result showed that the proposed ventilation system could save up to 86% energy consumed for ventilation, and the payback period was 5 year and 8 month which was rather satisfactory [106]. O'Connor et al. designed a heat recovery integrated passive ventilation system and conducted a wind tunnel experiment to test the system's energy saving effect. Result indicated that the application did not affect the fresh air supply rate while an energy saving of up to 20% could be expected from the space heating. Moreover, a further energy saving could be expected if the efficiency was improved [107]. Rasouli et al. raised the importance of control strategy for the heat recovery in ventilation systems. They claimed that un-controlled heat recovery ventilator would make a negative effect on the energy consumption of air-conditioning system. With a series of simulation, they proposed an optimum control strategy for 4 different climate conditions in the U. S. [108].

5.1. Total heat recovery

Compared with that of the sensible heat recovery, the process of total heat recovery was a bit more complicated. A moisture transfer process is coupled with the heat transfer process, which indicated a complex heat and mass transfer characteristic and a higher requirement for equipment. Literatures discussing total heat recovery ventilation were quite rare in the journal of *Energy and Buildings*. Of all the 20 papers relating to heat recovery ventilation, only 3 papers focused on total heat recovery.

Zhou et al. developed a simulation model for total heat recovery ventilator. With the model, they conducted a series of simulation on the economic characteristic of heat recovery ventilator for northern China climate. They claimed that the climate and indoor temperature set-point affect the efficiency of heat recovery ventilator significantly. They also gave some quantitative analysis on the relationship of heat recovery efficiency, climate and indoor temperature set-point, but due to the limited data, the result is not quite accurate [109]. Liu et al. further introduced in the enthalpy efficiency. With the improved simulation model, they developed a weighting system to guide the design of heat recovery ventilator [110]. Jiang et al. designed an experiment to test the transient response of a heat recovery exchanger, aiming at developing a better control strategy for the heat recovery system. With their experiment result, they proposed the application of electronic expansion valve in the system, claiming that the electronic expansion valve-controlled system could reach the peak COP faster and more stably, while the peak COP was also 5% higher than the thermostatic expansion valve-controlled system [111].

6. Indirect evaporative cooling (IEC)

An indirect evaporative cooling system involves an extra heat transfer process between a secondary air which was cooled by conventional direct evaporative cooling and the primary air which was supplied into the indoor environment. In this case, relative dry supply air close to wet bulb temperature could be obtained. Indirect evaporative cooling can reduce the energy required from a conventional compression cooling, cut a considerable part of investment and also a good choice when coordinated to systems that work under higher chilling water temperature [112, 113].

As mentioned previously, due to the nature of this journal, publications focused specifically on the indirect evaporative cooling appear in this journal were quite limited. The first paper discussing indirect evaporative cooling appeared in the journal in the late 1990s. Alonso et al. proposed a mathematic model for the simulation study of indirect evaporative cooler, and introduced an equivalent temperature to describe the heat transfer between the primary air and the secondary air. The model was validated with experiment data and calculation result from earlier models [114]. Costelloe and Finn developed a method to assess the applicability of indirect evaporative cooling. With the annual weather data, they conducted an availability analysis in two European cities as a reference [112]. Later, they introduced the thermal effectiveness and conducted a sensitivity analysis on five operation parameters: cooling load, ambient adiabatic saturation temperature, primary water flow rate, secondary water and air flow rate. They discovered that the ambient adiabatic saturation temperature was the most significant factor that affects the Instantaneous energy consumption characteristic of indirect evaporative system, while the impact of the cooling load and the primary water flow rate could hardly be noticed [113].

Delfani et al. conducted an experiment study on the actual energy saving when an IEC was applied as pre-cooling for fresh air supply. They reported a 75% reduction in cooling load and a 55% reduction in electric energy consumption [115]. Indirect evaporative cooling has become a common component in low-energy air-conditioning system designs [116-118].

7. Concluding remarks

In this paper, a comprehensive review was conducted on the development of advanced energy-efficient air-conditioning system from 1987 to 2014. Literatures on five novel technologies, namely independent control of temperature and humidity, stratified ventilation, thermal energy storage, heat recovery ventilation and indirect evaporative cooling were collected, evaluated and summarized. Conclusion could be achieved as follows:

All these technologies concerned brought in reductions in energy consumption at different level in laboratory test. Techniques such as independent control of temperature and humidity had already taken a considerable share of the market by mature commercial product. Specific techniques such as the stratified ventilation and the independent control of temperature and humidity even performed dazzlingly in aspects of indoor air quality and thermal comfort control. These features would give a huge positive boost to the technological progress and commercial popularization.

Most papers published in the journal *Energy and Buildings* focused on the energy relating features of the technologies, while thermal comfort only attracted very limited attention. The majority of papers put the emphasis on the simulation study, aiming at developing a precise model to describe the heat and mass transfer process within the system or between the system and indoor environment. In these papers, experiments were only considered as an alternative to validate or verify the proposed models. With respect to those papers focused particularly on experiments or measurements, most were case studies while not many studies applied experiment as the major tool to conduct systematic research. This is also the reason why most of the systems' energy reduction figures appeared in laboratory test.

The independent control of temperature and humidity was the research spotlight at present. Its excellent compatibility and favorable cooling capacity allocating characteristic made it a perfect choice for combination of other energy-efficient HVAC technologies. More real-life operation data demonstrating the actual energy efficiency and better indoor environmental quality should be available in future publications.

The application of low-grade heat source was a major focus. In special, the direct collection and application of solar thermal energy would attract the most attention.

Though there had been some attempts on application of PCM in the thermal energy storage system, none practical reports were found in the journal. Existing papers put much effort on the development of accurate eat transfer models, trying to set a guide for seeking of new materials. MPCM slurry was considered a promising future alternative for not only thermal energy storage medium but even working fluid.

With the development of both mathematical models and computer technology, numerical simulation is becoming an extremely important and effective tool for the investigation and prediction of novel techniques. In the future, the parallel simulation of multiple simulation tools as well as the application of optimization algorithms and relating programs will be a considerable development direction.

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