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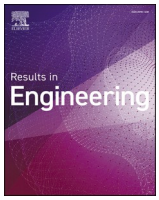

Review article

Multitarget control models for building thermal comfort and indoor air quality - A critical review☆

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ABSTRACT

The control techniques in buildings contribute significantly to thermal comfort and indoor air quality (IAQ). However, the gaps are existing for multitarget controls considering both thermal comfort and IAQ. They are: (1) both experimental and modeling control studies were conducted for thermal comfort, focusing on temperature and humidity. (2) All three (physical, grey-box, black-box) modeling approaches were investigated for temperature control. (3) Physical and grey-box modeling approach were adopted for humidity control. (4) physical models were developed for VOCs and CO2 control. (5) grey-box and black-box models were lacking for VOCs and CO2. (6) Multi-target controls were lacking for temperature, humidity and CO2s. (7) Limited studies are available for multi-target controls for temperature, humidity, and VOCs. (8) Multi-target controls are not available yet for temperature, humidity, VOCs, and CO2.

1. Introduction

1.1. Background

The building sector is responsible for 40 % of energy consumption, 75 % peak power demand, and 22 % of carbon emissions [1]. During the past 20 years, building science research has focused more on energy consumption. Starting in 2020, building decarbonization has gained attentions. For building science research, remaining challenges include how to make buildings more energy-efficient and carbon-neutral while maintaining the desired indoor air quality (IAQ) and thermal comfort.

Control is an extremely important research topic for buildings. Abundant control studies exist for buildings. Control loops can be classified into three groups [2]: supervisory control, local control, and rule-based control. Considering the control targets, building control has (1) temperature control, (2) humidity control, (3) VOCs control, and (4) carbon control respectively [3]. Temperature and humidity control are closely related within the context of thermal comfort. The VOCs and CO2 controls are in the context of IAQ. A summary for each control target can be summarized as:

1) Temperature Control

Maintaining the desired indoor air temperature is the first control target for HVAC systems. Based on ASHRAE Standard 55–2017 [4], the recommended temperature range for indoor environment is 67°F (19.44 °C) to 82°F (27.78 °C). The engineering practice is 75.2–78.8°F (24 –26 °C) for a cooling set point and 69.8 – 71.6°F (21 – 22 °C) for a heating set point. There are already a rich literature studies available for temperature controls of buildings. A review study [5] concludes that multiple types of controls already being used in buildings: PID control [6,7], On/Off control [8], MPC control [9–11], adaptive control [12], fuzzy logic control [13,14], artificial intelligence control [15,16]. Those controls have their own advantages and disadvantages. PID control and On/Off controls are the classic control strategies for buildings.

2) Humidity Control

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Nomenclature

Abbreviations

CFD	computational fluid dynamics
COP	coefficient of performance
HVAC	heating, ventilation, and air-conditioning
IAQ	indoor air quality
ODE	ordinary differential equation
RTU	remote terminal unit
TEAM	Total Exposure Assessment Methodology
TVOCs	total volatile organic compounds
VAV	variable air volume
VOC	volatile organic compound

Units

°C	degrees Celsius
°F	degrees Fahrenheit
J/(kg·K)	joules per kilogram-degree Kelvin
kg/s	kilograms per second
ppm	parts per million
W	watts

Variables

$\dot{Q}_{thermal}$	thermal capacity of the zone needed to maintain the set point (W)
f	schedule of the temperature control loop, within the range of [0, 1]
cp	specific heat of the system [J/(kg·K)]
$\dot{m}$	supply air flow rate to the zone (kg/s)
Tzone	zone temperature (°C)
Tspt	temperature set point (°C)

The moisture could be adjusted through dehumidification and humidification depending on occupant needs. Based on ASHRAE recommendations [4], the comfort range of relative humidity is approximately 40 %–65 %. According to a review study [17], two types of dehumidification control exist: condensate dehumidification (or mechanical dehumidification) and desiccant dehumidification. Both technologies can be integrated with conventional HVAC systems to modify the supply air flow rate and supply air temperature to remove extra moisture. The desiccant control and optimization was conducted by a study [18] that optimized input parameters that needed to be obtained through an optimization approach for the best system efficiency using a genetic algorithm. Another recent study [19] developed an innovative centrifugal-type humidifier, in which the experimental results showed good agreement with modeling results. A novel environmental control system focusing on humidity control of aircraft cabins [20] demonstrated modeling and experimental consistency. Their results showed that smooth cabin humidity increased to 27.9 % for the cruising state and 1 % decrease of fuel penalty from this new system. Another membrane humidifier was developed [21]. An innovative vapor compression cycle–based dehumidification system integrated with a membrane-based heat exchanger was proposed and modeled [22].

3) VOCs Control

There are two types of indoor pollutants [23]: particle pollutants and gaseous pollutants. Particle pollutants are fine or extra-fine particles harmful to indoor occupants. A typical example is PM2.5, which is common in outdoor environments, entering indoors through the doors or windows. Other sources of particle pollutants are from smoking, cooking, the ventilation system, sweeping, or vacuum cleaning. The particle pollutants are produced by occupants through three methods [24]: respiration, skin, and alimentary actions. Gaseous pollutants are chemical molecules or chemical compounds in the air within the indoor environment. The dominant gaseous pollutants are CO, CO_2, SO_2, NO_x, O_3, radon, and volatile organic compounds (VOCs). VOCs are chemical compounds with high vapor pressure and low water solubility. Major sources of VOCs are human-made chemicals that are used in manufacturing paints, pharmaceuticals, and refrigerants. VOCs are typically industrial solvents, such as trichloroethylene; fuel oxygenates, such as methyl tert-butyl ether; or by-products produced by chlorination in water treatment, such as chloroform. VOCs are often components of petroleum fuels, hydraulic fluids, paint thinners, and dry-cleaning agents. Limited models were found for VOCs under the impacts of outdoor airflow and supply airflow within an indoor environment [25,26]. One study proposed an analytical control model for the mass transfer of VOCs within indoor environment [25]. Another study developed an analytical model for the building materials [27]. The majority studies focus on VOC absorption, which is based on innovative material

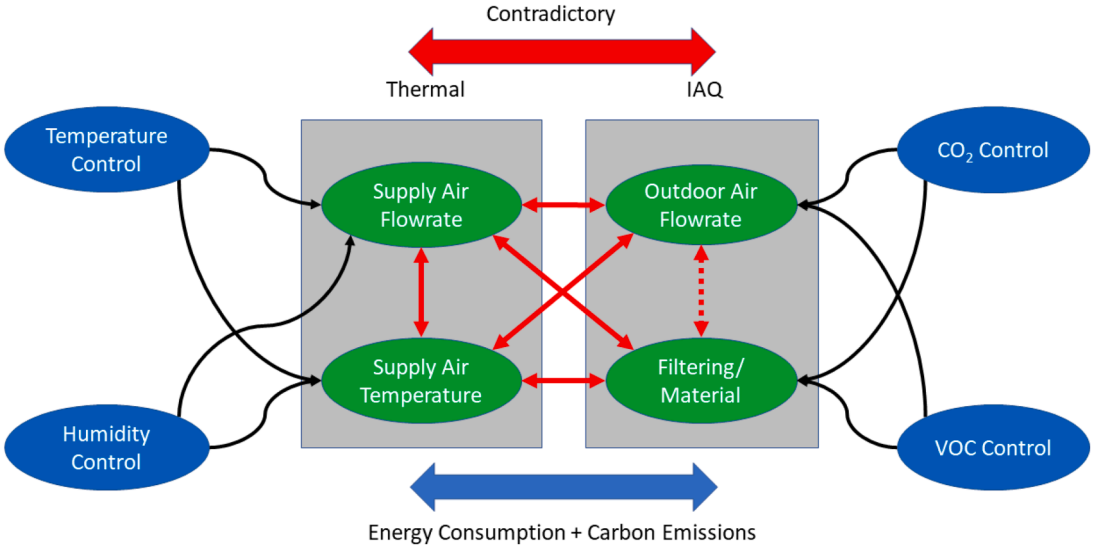

Fig. 1. Control dilemma.

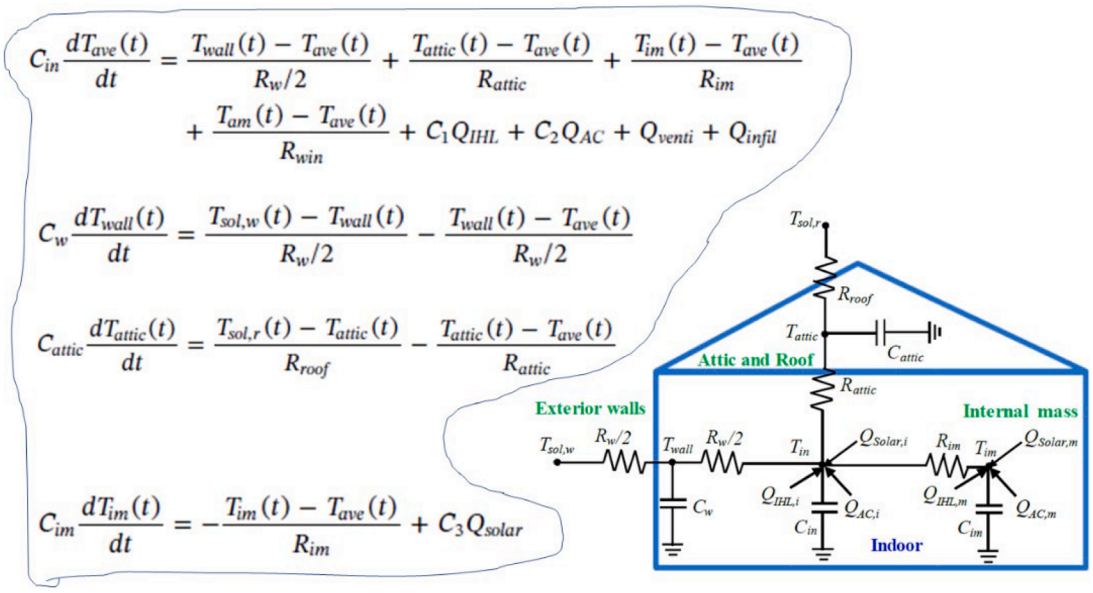

Fig. 2. A Grey-box model for buildings [53].

perspective [28,29].

4) Carbon Control

Carbon control is to maintain the zone CO2 emissions below certain levels. For carbon control, there is two approaches: direct carbon capture (DAC) and passive carbon reduction. The DAC is using chemical or physical processes to extract CO2 directly, which was systematically reviewed in this study [30]. The DAC is not within the scope of this study. The passive carbon reduction is to dilute the CO2 emissions through ventilation technologies, such as demand control ventilation [31–34]. Two major methods can reduce zone CO2 concentration: outdoor air ventilation or CO2 filtering. The outdoor air has a relatively constant CO2 concentration around 400 ppm. Outdoor air ventilation consumes a lot of energy, especially in cooling or heating seasons. A majority of studies of building CO2 filtering are experimental approaches using sorbent materials [35]. There are studies capturing zone carbon through ventilation strategies [36–38].

1.2. Motivation and research objective

However, those control studies are only focusing on individual control itself. Temperature and humidity control are focusing on thermal comfort of buildings. VOCs and carbon controls are focusing on the IAQ of buildings. Underlying thermal comfort and IAQ controls, there are four major (control/decision) variables within the building context: supply air flowrate, supply air temperature, outdoor airflow rate, filtering materials. Fig. 1 demonstrates the relationships of control variables and control targets for those four types of controls. For example, the ventilation increase can lead to better IAQ but more energy consumption. Humidity control is relying on lower supply air temperature which leads to higher cooling energy. A study investigated temple buildings [39] (e.g., churches and mosques) for energy consumption, IAQ, and thermal comfort and concluded that limited studies have investigated the correlation of energy, thermal comfort, and IAQ. Another study [40] showed natural ventilation and mechanical ventilation are better than air conditioning for lower energy consumption with improved thermal comfort. Multi-target controls are important considering thermal comfort, indoor air quality, energy consumption, and carbon reductions simultaneously. There is a gap in balancing the demands of the four targets. To the best of the authors' knowledge, limited studies investigated multi-target controls, including temperature, humidity, carbon, and VOCs, simultaneously. This review study aims to identify the research gaps for multitarget control for buildings.

The remaining sections of this review study are organized in three parts. Section 2 discusses single-target controls for temperature, humidity, CO_2, and VOCs. Section 3 discusses multi-target control studies in buildings. Section 4 presents the conclusions with research gaps for multitarget controls in buildings.

2. Single target controls

2.1. Temperature control

From modeling perspective, the temperature control can leverage the robustness of physical models, black-box model, and grey-box models.

2.1.1. Physical model

There are already many studies focusing on physical model controls [33,41–43]. This study proposed a simplified physical model using model predictive controls for building temperature [44]. Similarly, another study [45] predict the zone average temperature in heating mode using reduced-order physical models. Because of the nonlinear relationships in building thermal states, another study developed a linear physical model for building [46]. The details of those controls are not necessary to be given here. The basic principle of temperature control is to remove (cooling) or add (heating) equal amount of thermal energy to the indoor environment by using building mechanical systems to meet the temperature set points.

2.1.2. Black-box model

The black-box model for temperature control basically uses machine learning algorithms to calculate the zone temperature. A large body of literature already exists using machine learning to control building temperature [16]. The dominant machine learning type is reinforcement learning. This study [47] reviewed the reinforcement learnings in buildings and evaluated the challenges of reinforcement learnings. One study [48] investigated the zone temperature predictions using grey-box models compared with that of black-box models. The conclusion was the machine learning model works better than grey-box models with smaller accuracy. Another study used machine learning to predict the cooling

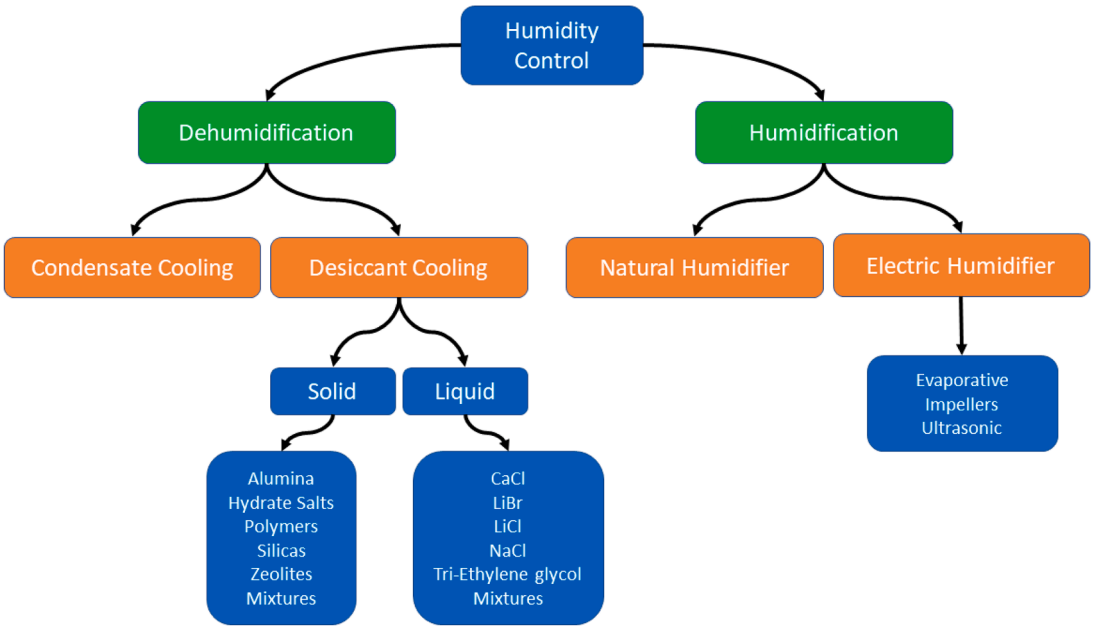

Fig. 3. Humidity control categories.

demands in office buildings [46]. A latest study pointed out the promising of machine learning controls in buildings [49]. The strengths of machine learning controls are: (1) scalable and suitable for different buildings. (2) does not rely on the physics of buildings. The major drawbacks of machine learning controls are: (1) is relying on large amount data. (2) bad data leads to bad predictions for controls.

2.1.3. Grey-box model

For building temperature control, grey-box models are also used substantially whenever needed. There are two types of grey-box models [10,50,51]: forward-approach and data-driven approach. The forward approach uses assumptions to simplify detailed physical models into simplified models, which are solved by using traditional white-box techniques (for example, discretization). The data-driven approach uses data-driven techniques to obtain the parameter values. Based on a published review study [52], the majority of literature studies applied the data-driven approach [53,54]. The diagram of black-box model is shown in Fig. 2.

2.2. Humidity control

There are two categories of humidification control models: humidification and dehumidification. Humidification is relatively easy. Normally, a humidifier would be used to increase the zone humidity levels. Dehumidification is more complicated, which is to remove extra moisture in the zone. A study discovered that the humidity increase can cause a virus survival decrease [55]; the study used a modeling study on CONTAM for the influenza virus, which is a common flu virus. The findings were that (1) an increase of moisture indoors leads to a decrease of influenza survival by 17.5 %–31.6 % when using a portable humidifier and (2) by distributing the water vapor through the zone, the relative humidity increases by 3 %–12 % above the baseline, and the associated virus survival rate decreases by 7.8 %–13.9 %. A diagram of humidity control is shown in Fig. 3.

2.2.1. Humidification models

(a) White-box models

The white-box model starts from the first principles for mass balance and energy balance. A humidification model was proposed for a general purpose humidifier [56], which presented the energy balance model and mass balance model in Eqs. (2) and (3):

$$C_h\frac{dT_h}{dt} = f_{sa}C_{pa}(T_{si} - T_h) + \alpha_h(T_o - T_h) \tag{1}$$

$$V_h\frac{dW_h}{dt} = f_{sa}(W_{si} - W_h) + \frac{h(t)}{\rho_a} \tag{2}$$

A desiccant wheel is traditionally used for dehumidification purposes. It is also suitable for humidification. Humidification uses the reverse process compared with a desiccant wheel dehumidifier system. The humidifier system absorbs the moisture from outside air and delivers the moisture to the supply air system for the building. A recent study proposed a desiccant wheel humidifier system [57], which was validated through experiments in real buildings.

The energy and water mass conservation in the desiccant material and adsorbed water is given as Eqs. (4) and (5):

$$(f_D cp_D + f_D c_{ad} W_D)\frac{\partial T_D}{\partial t} = (cp_v(T_a - T_D) + Q_{ads})h_m(X - X_W)P + h_T(T_a - T_D)P \tag{4}$$

$$\frac{\partial W_D}{\partial t} = \frac{h_m(X - X_\omega)P}{f_D} \tag{5}$$

The energy, water mass, and dry air mass conservation in the air stream are given by Eqs. (6–8):

$$\frac{\partial T_a}{\partial t} = -v\frac{\partial T_a}{\partial z} - \frac{h_T(T_a - T_D)P}{Cp_a\rho_a A} - \frac{h_m(X - X_W)PT_a Cp_v}{Cp_a\rho_a A} \tag{6}$$

$$\frac{\partial X}{\partial t} = -v\frac{\partial X}{\partial z} - \frac{Ph_m}{\rho_a A}(X - X_W) \tag{7}$$

$$\frac{\partial \rho_a}{\partial t} = -\frac{\partial(\rho_a v)}{\partial z} \tag{8}$$

For a membrane-based humidifier, a simplified model was proposed for fuel cells. The model [58] was based on the heat and mass transfer following the ε-Number of Transfer Units methodology, requiring mathematical iterations. Furthermore, the study validated the dehumidifier model through experiments [59], which showed good

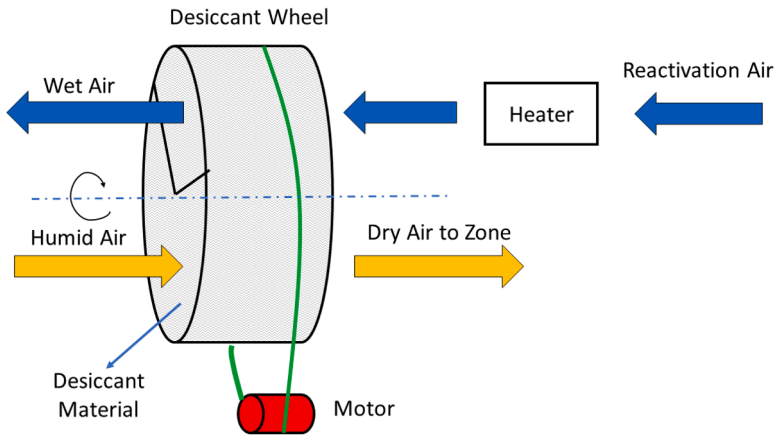

Fig. 4. Solid desiccant dehumidification diagram.

agreement between modeling and measurement results. The equations are shown in (9) and (10)

$$\varepsilon_L = 1 - e^{\left[\frac{e^{-NTU_L^{0.78}R_L}-1}{NTU_L^{-0.22}}R_L\right]} \tag{9}$$

$$\omega_{do} = \omega_{di} - \varepsilon_L \frac{(\dot{m}c_p)_{min}}{(\dot{m}c_p)_d}(\omega_{di} - \omega_{wi}) \tag{10}$$

(b) Grey-box models

Similarly, another study proposed a membrane humidifier model based on first principles [60] for fuel cell control using a grey-box approach. The steady-state and dynamic predictions were validated with experimental measurements. The saturation pressure of control volume is given in Eq. (11):

$$log_{10}(P_{1,sat}) = (-1.69e-10)\left(T_{1,out}^4\right) + (3.85e-7)\left(T_{1,out}^3\right)$$
$$-(3.39e-4)\left(T_{1,out}^2\right) + 0.143T_{1,out} - 20.92 \tag{11}$$

The relative humidity is given in Eq. (12):

$$RH_1 = \frac{P_{1,v}}{P_{1,sat}} \tag{12}$$

(c) Black-box models

To the best of the authors' knowledge, published articles were not found about using a black-box model for humidification.

2.2.2. *Dehumidification models*

There are two types of dehumidification: mechanical and desiccant.

1) mechanical dehumidification

Mechanical dehumidification is also called condensate dehumidification [61]. It works by decreasing cooling coil surface temperature below the dew point of air, which causes the water vapor inside the air to condense and accumulate on the cooling coil surface. The water vapor accumulates and becomes liquid to be removed. This method is usually composed of a compressor, condenser coil, and evaporator coil, with refrigerants cycling around the system, following the vapor compression cycle. Another recent study [62] proposed a 3D numerical model for the indirect evaporative cooler incorporated with air dehumidification. The modeling prediction had very good agreement with experimental data. Another recent study [19] developed an innovative centrifugal-type humidifier, in which the experimental results showed good agreement with modeling results. A novel environmental control system focusing on humidity control of aircraft cabins [20] demonstrated modeling and experimental consistency. Their results showed that smooth cabin humidity increased to 27.9 % for the cruising state and 1 % decrease of fuel penalty from this new system. Another membrane humidifier was developed [21]. An innovative vapor compression cycle–based dehumidification system integrated with a membrane-based heat exchanger was proposed and modeled [22].

2) Desiccant dehumidification

During the past 20 years, many efforts have been toward developing and researching desiccant dehumidification. Desiccant dehumidification uses desiccant materials (liquid or solid desiccants) to absorb moisture from the air. It was discovered in the 1930s by Hausen [63]. Desiccants chemical materials that can absorb the moisture contained in the air and then release under heating [64,65]. For desiccant materials, the driving potential for moisture absorption or release depends on the vapor pressure difference between the desiccant surface and surrounding air. The moisture transfers from the air to the desiccant material if the desiccant vapor pressure is lower than that of air. When the desiccant vapor pressure reaches that of air, dehumidification reaches equilibrium, or the moisture removal process stops. The desiccant materials remove moisture through chemical absorption and physical adsorption processes, and they are reusable. The typical way to reuse the material is through regeneration processes to extract the moisture from the desiccant materials. For solid desiccant dehumidification, regeneration occurs using a regeneration heat exchanger to blow hot and dry air through the desiccant materials to take away the moisture. For liquid desiccant dehumidification, the desiccants are regenerated through heating in a regenerator. For desiccant dehumidification, the regeneration is one of the key components to push out the moisture from the desiccant materials [66]. A study investigated three types of regeneration: solar radiation, microwave, and a combination of the two. For moisture removal, results showed the combination approach could yield 3.77 times higher regeneration than the solar radiation approach and 1.05 times higher regeneration than the microware approach. Another study proposed to use a solar thermal collector for the regeneration component for liquid desiccant dehumidification [67]. A solar-assisted liquid desiccant dehumidification system was proposed and modeled for greenhouse moisture controls in the Simulink [68]. Results showed that this type of system is capable of controlling the moisture effectively. The hybrid desiccant dehumidification is even more energy-efficient if integrated with a renewable source for the regeneration component.

One study reviewed humidity control technologies in buildings [17]

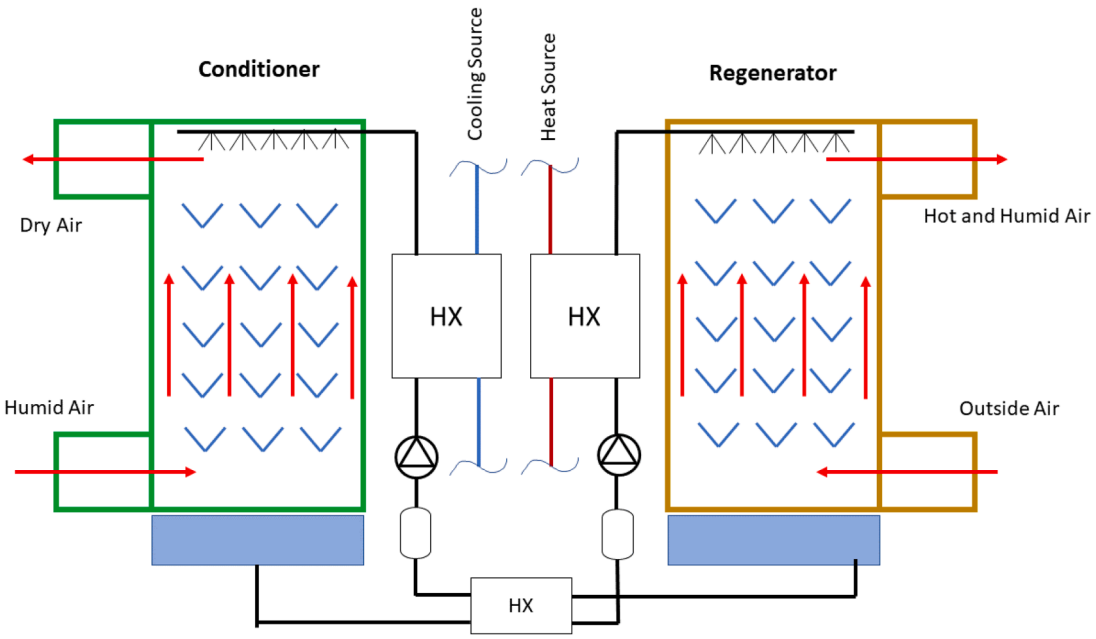

Fig. 5. Liquid desiccant dehumidification diagram.

and concluded that the liquid desiccant dehumidification was superior to the solid desiccant dehumidification. A system diagram for solid desiccant dehumidification is shown in Fig. 4. A system diagram for liquid desiccant dehumidification is shown in Fig. 5.

(a) White-box model

Solid desiccant–based dehumidification is an energy-efficient system that handles the latent load separately from the total thermal load. Such systems work by an adsorption process of the water molecules in the outdoor air onto the surface of the solid desiccant material. Among of different configurations, a rotary desiccant wheel is the most commonly employed design for solid desiccant dehumidifiers.

The main components of desiccant include the matrix, clapboard, wheel case, air heater, driven motor, and other elements [69]. The matrix usually contains supporting material and desiccant material. The desiccant wheel is driven by an engine and moves at a given rotary velocity. It consists of a large number of channels, whose walls are constituted by supporting material and coated or impregnated with desiccant material. The cross section of the wheel is divided into the process air side and regeneration air side by the clapboard. Water vapor is adsorbed by the desiccant when moist air is passing through the process air side. When the hot air, which is heated up by the heater, flows through the regeneration side, water is desorbed from the desiccant. The desiccant material is then regenerated. The airflow can be either in a counterflow or concurrent arrangement. The reduction of moisture in the process air occurs at the price of the energy consumed to heat the regeneration air. Notably, the wheel is usually installed with thermal insulation and air-proof material. Thus, the energy and mass exchange between the wheel and environment is neglected in most cases. The main materials used as support are paper, aluminum, synthetic fibers, or plastic, and common absorbents are silica gel and activated alumina [70].

The white-box model applied the partial differential equations to describe the mass transfer and heat transfer process. It is dynamic, considering the change in time and space. The model is often based on water (vapor) or air mass and energy balance for both air flows (i.e., process and regeneration air flows) and the solid desiccant materials in the wheel. Important assumptions should be made, and auxiliary relations should be provided to close the governing equations.

Because of the complexity and nonlinearity of coupled heat and mass transfer models, only a few works obtained analytical solutions using a lot of simplification and specifications [71]. Thus, numerical methods have been applied to solve the partial differential governing equations. The finite difference method [72] and finite volume method [73] were mostly adopted. Those equations in the literature were often solved through discretization of time and space variables using the Euler method [70] (e.g., Euler forward method). An iterative procedure is also required because of the periodic nature of system, as well as the nonlinear and coupled model equations [74], although the explicit scheme (which does not need the iteration process) is often recommended [69].

(b) Grey-box model

Another candidate model is the regression-based model, which could be much simpler and potentially more suitable for control purposes as long as enough historic, measured data are available to train and validate the model(s). In general, the performance depends on process and regeneration air temperature, humidity, and velocity, as well as the revolution speed. Existing performance curves that exist in building simulation tools (like EnergyPlus) were also used in some research works [75–77]. Those performance curves used for the desiccant wheel and direct expansion coil were generated using the manufacturer's publicly available sizing software.

(c) Black-box model

Because of the complexity of the desiccant dehumidification system, the high-fidelity model is usually time-consuming and mathematically driven. One study [78] used multilayer artificial neural network models for desiccant dehumidification. Their results show reasonable R^2 with a value of 0.9251–0.9660.

2.3. Carbon control

Carbon capture for zone CO_2 is an effective technology with two benefits: reducing zone CO_2 concentration and reducing the CO_2 releasing to the atmosphere that causes a global warming effect. Very limited studies focus on carbon capture in indoor environments through

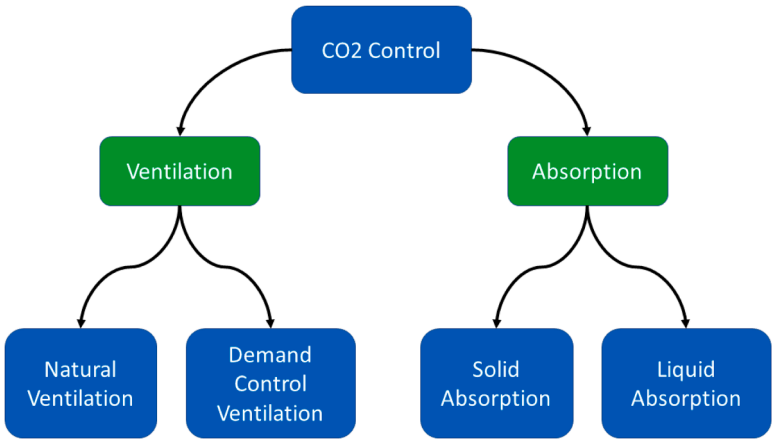

Fig. 6. CO_2 control.

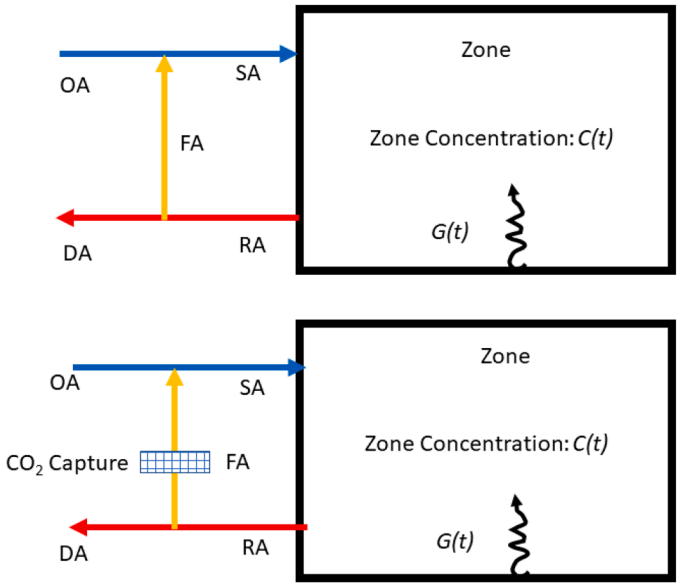

Fig. 7. Carbon control (OA=outdoor air, SA=supply air, RA=return air, DA=discharge air, FA=filtering air).

RTU systems [36–38,79,80]. The controls of CO2 are described with details in those studies [36–38]. The indoor CO_2 concentration is usually higher than that of the outdoors. The major sources of indoor CO_2 include occupant breathing, gas burning from occupant behaviors (e.g. cooking), and chemical release from indoor materials. Extra CO_2 can cause occupants to have headaches or nausea. The major approach of controlling indoor CO_2 is through ventilation or filtering. With carbon capture as emerging research, the optimal CO_2 concentration could also be achieved by using advanced filtering. The CO2 control strategy diagram is shown in Fig. 6. The diagram of a carbon control in building is shown in Fig. 7.

2.3.1. Zone CO2 model without carbon capture

The ordinary differential equation (ODE) for the zone CO_2 concentration is given in Eq. (13):

$$V_{zone}\frac{dC_{zone}}{dt} = Q_{oa}(C_{zone} - C_{oa}) \; - G(t) \tag{13}$$

Solving Eq. (13) results in the CO_2 concentration in Eq. (14):

$$C_{zone} = C_{oa} + \frac{G(t)}{Q_{oa}} + \left[C_{zone}(0) - C_{oa} - \frac{G(t)}{Q_{oa}}\right] e^{\left(\frac{Q_{oa}}{V_{zone}}\right)t} \tag{14}$$

2.3.2. Zone CO2 model with carbon capture

The ODE equation for carbon capture is given in Eq. (15):

$$V_{zone}\frac{dC_{zone}}{dt} = Q_{oa}(C_{zone} - C_{oa}) - \mathrm{G(t)} - Q_{oa}\frac{1-f}{f}A \tag{15}$$

Solving Eq. (15) gives Eq. (16):

$$C_{zone} = (C_{oa} - A) + \frac{G(t)}{Q_{oa}} + \frac{A}{f} + \left[C_{zone}(0) - (C_{oa} - A) - \frac{G(t)}{Q_{oa}} - \frac{A}{f}\right] e^{\left(\frac{Q_{oa}}{V_{zone}}\right)t} \tag{16}$$

2.4. VOC control

VOCs can be chemical compounds released from building materials [81]. VOCs can endanger occupant health through multiple levels, including headache; irritations of the eyes, nose, and throat; dry cough; dizziness and nausea; and tiredness. VOCs can be bad for respiration systems, blood vessel systems, and nerve systems. Similar to CO2 control, the ventilation system and filtering are the major technologies used to control VOCs. A diagram of VOCs is shown in Fig. 8. There are three types of VOCs: volatile organic compounds (VOCs), Semi-Volatile Organic Compounds (SVOCS), and very-volatile organic compounds (VVOCs). The total- Volatile Organic Compounds (TVOCs) are the combination of the three types of VOCs.

Limited models were found for VOCs under the impacts of outdoor airflow and supply airflow within an indoor environment [25,26]. Thus, the VOCs models integrated with filter control are developed in the following equations. The VOCs are assumed to be uniformly distributed inside the zone. VOCs include a variety of chemicals, some of which may have short- and long-term adverse health effects. Concentrations of many VOCs are consistently higher indoors (up to 10 times higher) than outdoors. VOCs are emitted by a wide array of products, numbering in the thousands. Examples include paints and lacquers, paint strippers, cleaning supplies, pesticides, building materials and furnishings, office equipment such as copiers and printers, correction fluids and carbonless copy paper, graphics and craft materials such as glues and adhesives, permanent markers, and photographic solutions.

Organic chemicals are widely used as ingredients in household products. Paints, varnishes, and wax all contain organic solvents, as do many cleaning, disinfecting, cosmetic, degreasing, and hobby products. Fuels are made up of organic chemicals. All of these products can release organic compounds while being used and, to some degree, when they

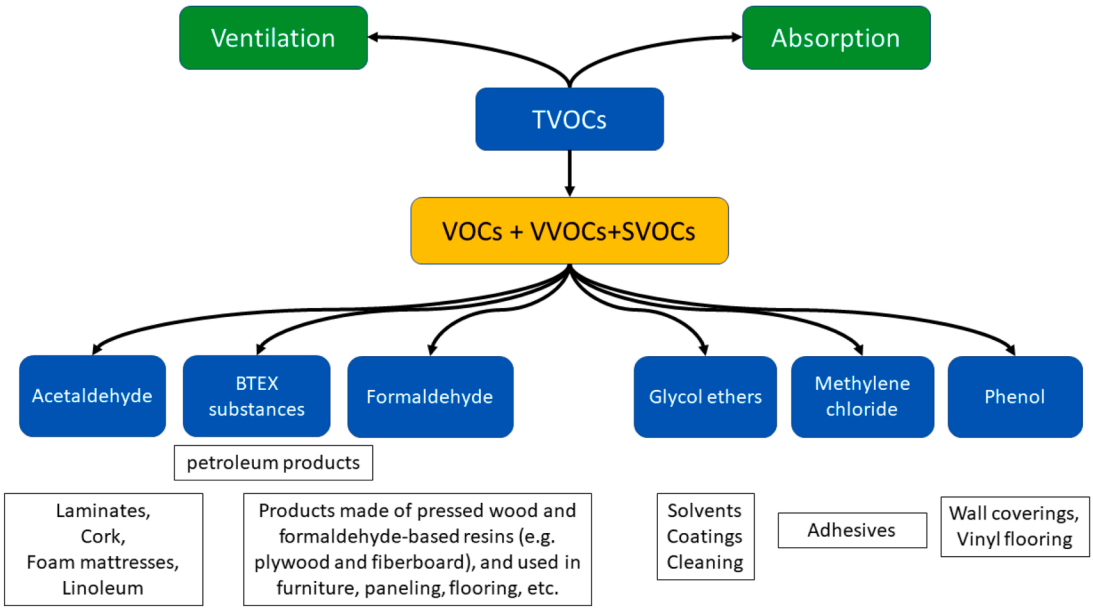

Fig. 8. TVOC sources in buildings.

are stored.

One study proposed an analytical control model for the mass transfer of VOCs within indoor environment [25]. A latest study [82] is using adsorption-based air filter to remove VOCs from room air system using experiments and a model was developed to predict the service life of filters. Another study developed an analytical model for the building materials [27]. The majority studies focus on VOC absorption, which is a material perspective [28,29].

2.4.1. *VOCs model with outdoor air*

The ODE equation for the zone VOCs concentration is given by Eq. (17):

$$V_z\frac{dC_z}{dt} = Q_{oa}(C_z - C_{oa}) - G(t) \tag{17}$$

The analytical solution is given as Eq. (18):

$$C_z = C_{oa} + \frac{G(t)}{Q_{oa}} + \left[C_z(0) - C_{oa} - \frac{G(t)}{Q_{oa}}\right] e^{\left(\frac{Q_{oa}}{V_z}\right)t} \tag{18}$$

2.4.2. *VOCs model with filtering*

The ODE equation for VOC capture is given by Eq. (19):

$$V_z\frac{dC_z}{dt} = Q_{oa}(C_z - C_{oa}) - \mathrm{G(t)} - Q_{oa}\frac{1-f}{f}A \tag{19}$$

The analytical solution is given as Eq. (20):

$$C_z = (C_{oa} - A) + \frac{G(t)}{Q_{oa}} + \frac{A}{f} + \left[C_z(0) - (C_{oa} - A) - \frac{G(t)}{Q_{oa}} - \frac{A}{f}\right] e^{\left(\frac{Q_{oa}}{V_z}\right)t} \tag{20}$$

3. Multi-target controls

3.1. *Temperature + Humidity control*

Temperature and humidity control are usually coupled together to control the indoor air temperature and relative humidity. The coupling depends on the system characteristics. One study proposed a comprehensive air-conditioning system including fresh water generation, dehumidification, humidification, and cooling [83]. Their modeling results and experimental measurements agree well. One of the conclusions was that the power savings increase with increasing supply air temperature and decreasing outdoor air wet bulb temperature, as well as increasing fresh air ratio. Traditionally, the mechanical dehumidification is used for dehumidification purposes for air-conditioned zones. However, it is not energy-efficient when compared with desiccant dehumidification systems. A majority of the literature studies have focused on desiccant dehumidification systems.

3.1.1. *Temperature control with desiccant dehumidification*

A field study [84] concluded that desiccant dehumidification is superior to conventional condensing or mechanical dehumidification in Hong Kong through a retrofit analysis. The reasons are that (1) desiccant dehumidification can run independently with an HVAC system, which can handle part of the sensible and latent heat loads; and (2) desiccant dehumidification can achieve up to 4.9 % and 7.7 % of annual energy savings for an office and a hotel, respectively, compared with conventional condensing/mechanical dehumidification, which usually requires over-cooling and reheating. Because of the energy waste from traditional dehumidification, another study decoupled the traditional cooling and dehumidification through a combination of dry-cooling and a dedicated outdoor air ventilation system. Results show energy savings of 54 % compared with a traditional constant volume air system accompanied by reheat. A recent review study [85] pointed out that both the solid desiccant and liquid desiccant can integrate with evaporative cooling systems to form a hybrid cooling system. This hybrid system has very good potential to replace the conventional vapor compression cycle cooling system. The hybrid system has many benefits: it is quiet and consumes much less energy. The evaporative cooling could be direct evaporative cooling or indirect evaporative cooling. An earlier study reviewed the liquid desiccant system [86] integrated with evaporative cooling. Liquid desiccant has a benefit in that it has extremely high effectiveness for dehumidification and has highly efficient utilization of low-grade heat. The study also mentioned that the hybrid system is superior to conventional air-conditioning systems. Other earlier studies [87,88] show that the hybrid cooling system could save energy by 20 %–30 % by comparing the hybrid system with the traditional vapor cycle–based cooling system in actual building operations.

Integrating with air source heat pumps, a desiccant system can be also used for space heating [89]. A hybrid heating system was proposed to integrate heat pumps and liquid desiccant dehumidification [90]. Some of the greatest benefits were that (a) part of the heat pump

condenser heating will be used for regeneration for the dehumidification and (b) the heat pump evaporator cooling is used for cooling the liquid desiccant entering the dehumidifier.

A study investigated the effects of dehumidification on the radiant floor cooling system in residential buildings through a simulation analysis [91]. Four different dehumidification systems were investigated: isothermal dehumidifier, integrated dehumidifier with air-conditioner, cooling coil by using low-temperature water, and a mechanical ventilation system with air-cooling and dehumidification. Results show that dehumidification could handle part of the cooling load to the conditioned zone, which can reduce the energy consumption of a radiant floor cooling system.

An earlier study investigated the humidifier effects on thermal comfort using a proportional control, which controls the relative humidity in the range of 40 %–50 %, in Brittany or southern England [92]. A mass balance model was proposed for the simulation study (TRNSYS), which was validated by experiments. Their findings were that percentage of mean vote (PMV) is not significantly affected by the humidifier.

A recent study developed a fan coil unit with a humidifier integrated in cold climate regions [93]. Traditionally, a humidifier could decrease the zone air temperature. Their experimental results showed that the humidifier could be heated to maintain the zone air temperature.

Another study [94] showed that a modified liquid desiccant indirect/direct evaporative cooling outdoor air system could consume 42 % less primary energy during heating operation, based on the simulation in TRNSYS.

One study showed that the two-stage hybrid cooling system [95] that integrates desiccant dehumidification with cascade evaporative cooling could achieve 16.15 % energy savings compared with a single-stage evaporative cooling system.

3.1.2. Temperature control with membrane dehumidification

As an emerging technology, membrane dehumidification has attracted attention. A study [96] proposed an integrated frost-free air source heat pump, which integrates the membrane-based desiccant humidifier, dehumidifier, and regenerators. This method leads to an increase in coefficient of performance (COP) and is frost-free, compared with traditional air source heat pumps. A recent study [97] proposed a model for the vacuum membrane–based dehumidification integrated into variable air volume (VAV) systems through a discretized manner. Compared with traditional VAV system, the results show 8.2 % lower primary energy consumption, 7.7 % more energy on dehumidification and cooling, and 2.5 times more fan energy owing to the pressure drop of the membrane component. Another study [98] proposed a thermodynamic analysis for membrane-based liquid desiccant dehumidification integrated with evaporative cooling.

3.2. VOC and CO2 control

VOCs and CO_2 are both chemical gases that can endanger occupants. The major control approach is through ventilation or using air filters. Ventilation can take away VOCs and CO_2 to the outside environment. Typical HVAC systems include a dedicated outdoor air system [99], displacement ventilation system, personalized ventilation system, and under-floor air distribution system. Air filters can absorb or adsorb the VOCs and CO_2 and lock them into the filter materials. A study [100] conclude that humans need around 10,000 L of air through the lungs every day to get 420 L of oxygen to survive and maintain basic functions. The study showed that the filter was the most effective solution in helping to increase IAQ.

The control models for VOC and CO_2 are limited. One study investigated various indoor air pollutant emission models [101]. However, the control-oriented models were not thoroughly developed.

3.3. Ventilation

An earlier study demonstrated that natural ventilation could be used to control zone CO_2 concentration [37]. This study proposed a simple demand control ventilation strategy [36] to control the zone CO_2 concentration to be within a given set point. Simulation results showed that this demand control can help save 34 % of energy related to ventilation air. Furthermore, it can save 26 % of energy for a fully occupied building. Similarly, another study demonstrated the effectiveness of the demand control ventilation for zone CO_2 concentration control [38].

Later, improved demand control ventilation algorithms were proposed [31,32] for multizone HVAC systems. However, they were not robust enough to be implemented into the real HVAC controller. The most recent study [33] aims to make the demand control ventilation (DCV) algorithm suitable in a real controller, in which the memory is usually small because of hardware cost constraints. In real buildings, especially the multi-zone buildings, the ventilation is complicated because different zones require different amounts of ventilation air. The is the biggest challenge for demand control ventilation in practical building operations.

3.3.1. Air filtering

A thorough study of removing VOCs through photocatalytic methods was conducted, which the models of the VOC removals proposed [102,103]. Their model and experimental results show good agreement.

3.3.2. Other

One study showed that ionization can help remove VOCs [104]. A review study [105] showed that liquid desiccant [106–111] and solid desiccant [112,113] can help remove VOCs.

3.4. Humidity, VOC, and CO2 control

One study investigated the transient pattern of VOC removal under the effect of a humidifier and outdoor air ventilation by using a FLUENT simulation [114]. Results show that (1) lower humidity can improve air cleaner performance, and higher humidity leads to degraded air cleaner performance; and (2) ventilation can reduce the VOC quickly. A study [115] proposed that a system composed of a dedicated outdoor air system and membrane dehumidifier could achieve 57 %–89 % energy savings compared with a conventional dedicated outdoor air system. Another study systematically reviewed the liquid desiccant dehumidification on the IAQ [105].

3.5. Temperature, humidity and VOC control

Studies show the effects of temperature, humidity, and VOCs. A recent study [116] shows that humidification has strong effects on temperature and VOC concentrations within buildings through an experiment approach in an enclosed chamber. Humidification was implemented through an ultrasonic humidifier, which has two effects: (1) increasing humidity and reducing the zone temperature simultaneously and (2) removing TVOCs.

A combined system with desiccant dehumidification, chilled ceiling, and displacement ventilation was modelled for the overall performance in a hot and humid climate [117]. The study aimed to find the best IAQ and thermal comfort with minimum energy consumption for the system. The results showed that such a system could use 8.2 % less energy compared with traditional HVAC.

3.6. Temperature, humidity, VOC and CO2 control

Based on literature research, no published research was found for multitarget control for temperature + humidity + VOC + CO_2. No literature was found for temperature + VOC + CO_2, either. This research gap leads to concurrent optimization of indoor air quality and energy

Table 1
Summary for multitarget building control.

Control target	Model method	Control algorithm	Optimization	HVAC unit	Experiment or simulation (control benefits)	Reference
Temperature and humidity	Physical	Proportional	No	Cooling and heating	Both (644 hours of comfort improvement)	[92]
Temperature and humidity	Grey-box	Rule-based	No	Cooling and heating	Both (4.9 % and 7.7 % energy savings from desiccant dehumidification)	[84]
Temperature and humidity	Physical	Rule-based	No	Cooling	Simulation (upto 70 % of power savings)	[83]
Temperature and humidity	Physical	Rule-based	No	Cooling	Both (cooling capacity increased by 30 % in [87] and 44.5 % in [88])	[87,88]
Temperature and humidity	Physical	Rule-based	No	Heat pump	Both (COP increased by 18 % for air-system, and 35 % for water system)	[90]
Temperature and humidity	Physical	On/off	No	Radiant floor	Simulation (quantitative comparison not given)	[91]
Temperature and Humidity	Physical	On/off	No	Humidifier and cooling and heating	Both (quantitative comparison not given)	[92]
Heating and humidification	n/a	On/off	No	Humidifier and heating coil	Experiment (average humidity ratio was increased by 5.7 g/kg)	[93]
Heating and humidification	Physical	On/off	No	Humidifier and heating coil	Simulation (42 % less energy consumption identified)	[94]
Temperature and humidity	Physical	Rule-based	No	Dehumidification and cooling	Simulation (16.15 % energy reduction and 26.93 % water reduction)	[95]
Temperature and humidity	Physical	Rule-based	No	Heat pump, membrane humidification and dehumidification system	Simulation (64.3 % higher COP)	[96]
Humidity	Physical	n/a	no	Membrane dehumidification	Simulation (8.2 % less energy consumption)	[97]
Temperature and humidity	Physical	n/a	no	Membrane liquid desiccant dehumidification, and evaporator cooling	Simulation (not available)	[98]
Temperature and humidity	Physical (CFD)	n/a	no	Dehumidification, and evaporator cooling	Simulation (not available)	[62]
Humidity	n/a	n/a	no	Humidifier	Experiment (COP=5.85)	[19]
Temperature and humidity	Physical	Rule-based	yes	Humidifier	Both (27.1 % humidity increase)	[20]
Humidity	Physical (CFD)	n/a	no	Membrane humidifier	Both (quantitative metrics not provided)	[21]
Humidity	Physical	n/a	no	Mechanical dehumidification	Simulation (33 % energy savings)	[22]
Humidity	Grey-box	Rule-based	yes	Liquid desiccant dehumidification	Simulation (quantitative metrics not provided)	[18]
Temperature and humidity	Physical	no	no	Solar desiccant and air-conditioning	Simulation (higher COP)	[64,65]
Temperature and humidity	n/a	n/a	n/a	Solar desiccant and air-conditioning	Experiment (over 2 % efficiency improvement)	[66]
Humidity	Physical	n/a	n/a	Liquid desiccant dehumidification	Simulation (power saving 55.65 %)	[67]
Humidity	Physical	n/a	n/a	Liquid desiccant dehumidification	Simulation(quantitative metrics not provided)	[68]
Humidity	Black-box	n/a	n/a	Solid desiccant dehumidification	Simulation(quantitative metrics not provided)	[118]
Humidity	Physical	n/a	n/a	Solid desiccant dehumidification	Simulation (reducing the latent heat load by 58.2 %–69.3 %.)	[119]
Humidity	Physical	n/a	n/a	Solid desiccant dehumidification	Simulation (30 % energy savings)	[120]
Humidity	Physical	n/a	n/a	Liquid desiccant dehumidification	Simulation(quantitative metrics not provided)	[121]
Humidity	Physical	n/a	n/a	Liquid desiccant dehumidification	Simulation (3.19 %-10.57 % of energy efficiency)	[122]
Temperature and humidity	Physical	n/a	n/a	Liquid desiccant dehumidification and Air-conditioning	Simulation(quantitative metrics not provided)	[123]
Humidity	Physical	n/a	n/a	Liquid desiccant dehumidification	Simulation(quantitative metrics not provided)	[124]
Humidity	Physical	n/a	n/a	Liquid desiccant dehumidification	Simulation (12 % efficiency increase)	[125]
Temperature and humidity	Physical	n/a	n/a	Liquid desiccant dehumidification and air-conditioning	Simulation (17.4 % energy reductions and 41 % of COP increase)	[126]
Humidity	n/a	n/a	n/a	Liquid desiccant dehumidification	Experiment (desiccant reduction reached upto 73.94 %)	[127]
Humidity	Physical	n/a	n/a	Liquid desiccant dehumidification	Simulation (simulation agrees well with experimental data)	[128]
Humidity	Grey-box	n/a	n/a	Liquid desiccant dehumidification	Simulation (model verified by measurement data)	[129]
Humidity	physical	Rule-based	yes	Liquid desiccant dehumidification	Simulation (12.49 % energy savings)	[130]
Humidity	Physical	n/a	n/a	Membrane dehumidification	Simulation (COP increase by 30.23 %)	[131]
Humidity	Physical (CFD)	n/a	n/a	Membrane humidification	Simulation (model verified by measurement data)	[132]
VOC/CO_2	Physical	n/a	n/a	Air filter	Simulation (filtering efficiency increased by 8.1 %)	[100]
VOC	Physical	n/a	n/a	Cleaner	Simulation(model verified by measurement data)	[102, 103]

(*continued on next page*)

Table 1 (*continued*)

Control target	Model method	Control algorithm	Optimization	HVAC unit	Experiment or simulation (control benefits)	Reference
VOC	n/a	n/a	n/a	Ionizer	Experiment (just experiment)	[104]
VOC	Physical	n/a	n/a	Humidifier, ventilation	Simulation(quantitative metrics not provided)	[114]
Humidity	Physical	n/a	n/a	Membrane dehumidifier	Simulation(model verified by measurement data)	[115]
Temperature, humidity, and VOC	Physical	n/a	n/a	Humidifier	Simulation(model verified by measurement data)	[116]
Temperature, humidity, and VOC	Physical	n/a	n/a	Desiccant dehumidification and ventilation	Simulation(model verified by measurement data)	[117]
Virus	n/a	n/a	n/a	Humidifier	Experiment(just experiment)	[55]

CFD: computational fluid dynamics

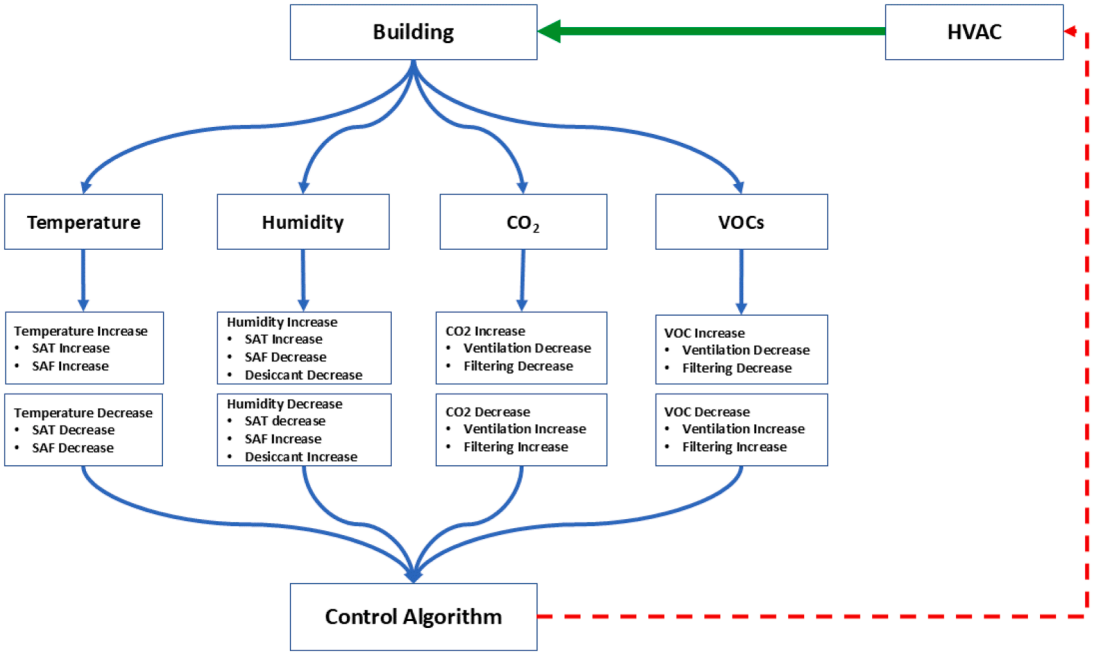

Fig. 9. Proposed simulation framework.

efficiency in buildings. More research efforts are expected in the cross-section of indoor air quality and energy efficiency.

3.7. Summary of control studies

Based on the literature review of building controls, an intermediate summary is organized in Table 1. Physical and grey-box models were the dominant modeling approach for temperature and humidity controls. Rule-based controls were being used mostly to evaluate the hardware performance. Optimizations are seldom used in these controls. Both simulations and experiments were being conducted for the control benefits. However, simulations cases are more than experimental cases. This might because experiments need more resources.

A simulation framework handling indoor air quality and energy efficiency is shown in Fig. 9.

4. Conclusions

This study reviewed the multitarget controls for building thermal comfort and indoor air quality. Four targets are investigated for buildings: temperature, humidity, CO_2, and VOCs. Published literatures exist for each of the four categories respectively. For a combination of multiple targets, especially the decarbonization (CO_2) integration, more research efforts are still needed.

The major findings are summarized in the following list:

(1) For temperature and dehumidification control, a large body of research publications have used modeling (white-box, grey-box, and black-box) and experimental approaches. For humidification control, numerous investigations used white-box and grey-box models, except black-box models. However, for VOC and CO_2 control, experiments are the dominant approach while the models used a white-box approach, except grey-box or black-box.
(2) The desiccant dehumidification is still going on with innovative and energy-efficient materials. The research on mechanical dehumidification is relatively established.
   a. Desiccant dehumidification is usually independent with main cooling/heating systems. More research studies were conducted on solid desiccant dehumidification systems in the past 10 years. Liquid desiccant dehumidification is still under active research. It is more complicated than solid desiccant dehumidification. Solid desiccant dehumidification is simpler than a liquid desiccant dehumidification system. A liquid desiccant dehumidification system is more promising and received more attention compared with solid desiccant dehumidification.
   b. Desiccant dehumidification is more energy-efficient than a conventional mechanical dehumidification system.

Researchers question what the technoeconomic benefit is for the desiccant dehumidification (e.g., payback) compared with traditional dehumidification. No studies are available to quantify how much energy is saved by comparing desiccant dehumidification system and mechanical dehumidification. The lack of research is a remaining gap for desiccant dehumidification system performance under different climate zones and building characteristics (e.g., school, office). Desiccant system can be integrated into the main cooling and heating system. It still a challenge to integrate systems for different air-conditioning and heating systems.

c. Liquid desiccant dehumidification integrated with evaporating cooling as a hybrid cooling system has become a new trend for research and development.

(3) Limited studies for VOC and CO_2 control are available through air filtering and ventilation. There are more studies needed for advanced controls in this thread.

(4) No study has investigated the simultaneous control of three targets (temperature+VOC+CO_2), or four targets (temperature+humidity+VOC+CO_2).

Above studies reveal the simulation frameworks incorporating the indoor air quality and energy efficiency are still missing. Current technologies are focusing either on indoor air quality, or energy efficiency respectively. Integrating them together is a new field neglected. From the perspective of practical implementation of multi-target controls, it seems there is a need to develop such control products, including control panels and control algorithms. Furthermore, the field tests before deployments are also worth investing.

CRediT authorship contribution statement

Yanfei Li: Writing – original draft, Methodology, Investigation, Conceptualization. **Jian Sun:** Writing – review & editing, Supervision, Conceptualization. **Borui Cui:** Writing – original draft, Investigation. **Kai Li:** Writing – review & editing, Conceptualization. **Jin Dong:** Writing – review & editing, Conceptualization. **Jamie Lian:** Writing – review & editing, Supervision, Conceptualization. **Xianhui Zhao:** Writing – original draft, Conceptualization. **Kashif Nawaz:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors of this manuscript declare no interest of conflict.

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Data availability

No data was used for the research described in the article.

References

[1] M Sofos, J Langevin, M Deru, E Gupta, KS Benne, D Blum, et al., Innovations in Sensors and Controls For Building Energy management: Research and Development Opportunities Report For Emerging Technologies, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2020.
[2] S Wang, Z. Ma, Supervisory and optimal control of building HVAC systems: a review, HVACR Res. 14 (2008) 3–32.
[3] ASHRAE. ASHRAE Handbook: Fundamentals n.d.
[4] ANSI/ASHRAE Addendum d to ANSI/ASHRAE Standard 55–2017 n.d.
[5] Pfeiffer CF, Skeie N-O, Perera DWU. Control of temperature and energy consumption in buildings-a review. 2014.
[6] WW Shein, Y Tan, AO. Lim, PID controller for temperature control with multiple actuators in cyber-physical home system. 2012 15th Int, Conf. Netw.-Based Inf. Syst. (2012) 423–428.
[7] MR Kulkarni, F. Hong, Energy optimal control of a residential space-conditioning system based on sensible heat transfer modeling, Build. Environ. 39 (2004) 31–38.
[8] H Mirinejad, SH Sadati, M Ghasemian, H. Torab, Control techniques in heating, ventilating and air conditioning systems, J. Comput. Sci. 4 (2008) 777.
[9] J Cigler, P Tomáško, J. Širokỳ, BuildingLAB: A tool to analyze performance of model predictive controllers for buildings, Energy Build. 57 (2013) 34–41.
[10] OM Brastein, DWU Perera, C Pfeifer, N-O. Skeie, Parameter estimation for grey-box models of building thermal behaviour, Energy Build. 169 (2018) 58–68, https://doi.org/10.1016/j.enbuild.2018.03.057.
[11] S Privara, J Širokỳ, L Ferkl, J. Cigler, Model predictive control of a building heating system: The first experience, Energy Build. 43 (2011) 564–572.
[12] G Lymperopoulos, P. Ioannou, Building temperature regulation in a multi-zone HVAC system using distributed adaptive control, Energy Build. 215 (2020) 109825.
[13] A-H Attia, SF Rezeka, AM. Saleh, Fuzzy logic control of air-conditioning system in residential buildings, Alex. Eng. J. 54 (2015) 395–403.
[14] G Fraisse, J Virgone, JJ. Roux, Thermal control of a discontinuously occupied building using a classical and a fuzzy logic approach, Energy Build. 26 (1997) 303–316.
[15] Y Chen, LK Norford, HW Samuelson, A. Malkawi, Optimal control of HVAC and window systems for natural ventilation through reinforcement learning, Energy Build. 169 (2018) 195–205, https://doi.org/10.1016/j.enbuild.2018.03.051.
[16] L Zhang, J Wen, Y Li, J Chen, Y Ye, Y Fu, et al., A review of machine learning in building load prediction, Appl. Energy 285 (2021) 116452.
[17] M. Shehadi, Review of humidity control technologies in buildings, J. Build. Eng. 19 (2018) 539–551.
[18] M Bhowmik, P Muthukumar, R. Anandalakshmi, Experimental based multi-objective optimisation for structured packed bed liquid desiccant dehumidification systems, J. Build. Eng. 32 (2020) 101813, https://doi.org/10.1016/j.jobe.2020.101813.
[19] SS Salins, PS Nair, SK Reddy, S. Kumar, Experimental investigations of humidification parameters and transient analysis in a rotating centrifugal humidifier, J. Build. Eng. 41 (2021) 102770.
[20] L Chen, X Zhang, C Wang, C. Yang, A novel environmental control system facilitating humidification for commercial aircraft, Build. Environ. 126 (2017) 34–41.
[21] P Shamsizadeh, E Afshari, M. Mosharaf-Dehkordi, Design of membrane humidifier using obstacles in the flow channels for ventilator, Appl. Therm. Eng. 196 (2021) 117265.
[22] LZ Zhang, DS Zhu, XH Deng, B. Hua, Thermodynamic modeling of a novel air dehumidification system, Energy Build. 37 (2005) 279–286, https://doi.org/10.1016/j.enbuild.2004.06.019.
[23] BF Yu, ZB Hu, M Liu, HL Yang, QX Kong, YH. Liu, Review of research on air-conditioning systems and indoor air quality control for human health, Int. J. Refrig. 32 (2009) 3–20, https://doi.org/10.1016/j.ijrefrig.2008.05.004.
[24] IG Kavouras, EG. Stephanou, Gas/particle partitioning and size distribution of primary and secondary carbonaceous aerosols in public buildings, Indoor. Air. 12 (2002) 17–32.
[25] F Li, J. Niu, Control of volatile organic compounds indoors—development of an integrated mass-transfer-based model and its application, Atmos. Environ. 41 (2007) 2344–2354.
[26] MK Kim, L Baldini, H Leibundgut, JA. Wurzbacher, Evaluation of the humidity performance of a carbon dioxide (CO2) capture device as a novel ventilation strategy in buildings, Appl. Energy 259 (2020) 112869.
[27] J Xiong, C Liu, Y. Zhang, A general analytical model for formaldehyde and VOC emission/sorption in single-layer building materials and its application in determining the characteristic parameters, Atmos. Environ. 47 (2012) 288–294.
[28] E Gallego, FJ Roca, JF Perales, X. Guardino, Experimental evaluation of VOC removal efficiency of a coconut shell activated carbon filter for indoor air quality enhancement, Build. Environ. 67 (2013) 14–25.
[29] L Zeng, G Liu, J Gao, B Du, L Lv, C Cao, et al., A circulating ventilation system to concentrate pollutants and reduce exhaust volumes: case studies with experiments and numerical simulation for the rubber refining process, J. Build. Eng. 35 (2021) 101984.
[30] FM Baena-Moreno, M Rodríguez-Galán, F Vega, B Alonso-Fariñas, LF Vilches Arenas, B Navarrete, Carbon capture and utilization technologies: a literature review and recent advances, Energy Sources Part Recov. Util. Environ. Eff. 41 (2019) 1403–1433.
[31] X Lin, J. Lau, Demand controlled ventilation for multiple zone HVAC systems: CO2-based dynamic reset (RP 1547), HvacR Res. 20 (2014) 875–888.
[32] X Lin, J. Lau, Demand-controlled ventilation for multiple-zone hvac systems—part 2: Co2-based dynamic reset with zone primary airflow minimum set-point reset (rp-1547), Sci. Technol. Built. Environ. 21 (2015) 1100–1108.
[33] ZD O'Neill, Y Li, HC Cheng, X Zhou, ST Taylor, Energy savings and ventilation performance from CO2-based demand controlled ventilation: simulation results from ASHRAE RP-1747 (ASHRAE RP-1747), Sci. Technol. Built. Environ. 0 (2019) 1–25, https://doi.org/10.1080/23744731.2019.1620575.
[34] T Lu, X Lü, M. Viljanen, A novel and dynamic demand-controlled ventilation strategy for CO2 control and energy saving in buildings, Energy Build. 43 (2011) 2499–2508.

[35] JD Figueroa, T Fout, S Plasynski, H McIlvried, RD. Srivastava, Advances in CO2 capture technology—the US Department of energy's carbon sequestration program, Int. J. Greenhouse Gas Control 2 (2008) 9–20.
[36] T Lu, X Lü, M. Viljanen, A novel and dynamic demand-controlled ventilation strategy for CO2 control and energy saving in buildings, Energy Build. 43 (2011) 2499–2508, https://doi.org/10.1016/j.enbuild.2011.06.005.
[37] M Griffiths, M. Eftekhari, Control of CO2 in a naturally ventilated classroom, Energy Build. 40 (2008) 556–560.
[38] J Li, J Wall, G. Platt, Indoor air quality control of HVAC system, in: Proc. 2010 Int. Conf. Model. Identif. Control, IEEE, 2010, pp. 756–761.
[39] A Yüksel, M Arıcı, M Krajčík, M Civan, H. Karabay, A review on thermal comfort, indoor air quality and energy consumption in temples, J. Build. Eng. 35 (2021) 102013, https://doi.org/10.1016/j.jobe.2020.102013.
[40] L-R Jia, J Han, X Chen, Q-Y Li, C-C Lee, Y-H. Fung, Interaction between thermal comfort, indoor air quality and ventilation energy consumption of educational buildings: a comprehensive review, Buildings 11 (2021) 591, https://doi.org/10.3390/buildings11120591.
[41] PG Ellis, PA Torcellini, D. Crawley, Simulation of Energy Management Systems in EnergyPlus, National Renewable Energy Lab. (NREL), Golden, CO (United States), 2008.
[42] X Lu, Y Fu, Z O'Neill, Benchmarking high performance HVAC Rule-Based controls with advanced intelligent Controllers: a case study in a multi-zone system in Modelica, Energy Build. 284 (2023) 112854.
[43] A Andriamamonjy, R Klein, D. Saelens, Automated grey box model implementation using BIM and Modelica, Energy Build. (2019).
[44] I Hazyuk, C Ghiaus, D. Penhouet, Optimal temperature control of intermittently heated buildings using model predictive control: part I–building modeling, Build. Environ. 51 (2012) 379–387.
[45] Z Liao, AL. Dexter, A simplified physical model for estimating the average air temperature in multi-zone heating systems, Build. Environ. 39 (2004) 1013–1022.
[46] S Wu, J-Q. Sun, A physics-based linear parametric model of room temperature in office buildings, Build. Environ. 50 (2012) 1–9.
[47] Z Wang, T. Hong, Reinforcement learning for building controls: The opportunities and challenges, Appl. Energy 269 (2020) 115036.
[48] B Delcroix, JL Ny, M Bernier, M Azam, B Qu, J-S. Venne, Autoregressive neural networks with exogenous variables for indoor temperature prediction in buildings, Build. Simul. 14 (2021) 165–178, https://doi.org/10.1007/s12273-019-0597-2.
[49] T Hong, Z Wang, X Luo, W. Zhang, State-of-the-art on research and applications of machine learning in the building life cycle, Energy Build. 212 (2020) 109831.
[50] Y Li, Z O'Neill, L Zhang, J Chen, P Im, J DeGraw, Grey-box modeling and application for building energy simulations-a critical review, Renew. Sustain. Energy Rev. 146 (2021) 111174.
[51] Y Li, J Sun, B Fricke, P Im, T. Kuruganti, Grey-box fault models and applications for low carbon emission CO2 refrigeration system, Int. J. Refrig. (2022).
[52] Y Li, Z O'Neill, L Zhang, J Chen, P Im, J DeGraw, Grey-box modeling and application for building energy simulations-a critical review, Renew. Sustain. Energy Rev. 146 (2021) 111174.
[53] B Cui, C Fan, J Munk, N Mao, F Xiao, J Dong, et al., A hybrid building thermal modeling approach for predicting temperatures in typical, detached, two-story houses, Appl. Energy 236 (2019) 101–116.
[54] MR Starke, RK Jackson, JD Munk, DL Fugate, B. Cui, Building Thermal Model Development of Typical House in U.S. For Virtual Storage Control of Aggregated Building Loads Based On Limited Available Information, Oak Ridge National Lab. (ORNL), Oak Ridge, TNUnited States, 2017.
[55] TA Myatt, MH Kaufman, JG Allen, DL MacIntosh, MP Fabian, JJ. McDevitt, Modeling the airborne survival of influenza virus in a residential setting: the impacts of home humidification, Environ. Health 9 (2010) 55, https://doi.org/10.1186/1476-069X-9-55.
[56] M Kasahara, Y Kuzuu, T Matsuba, Y. Hashimoto, Physical model of an air-conditioned space for control analysis, ASHRAe Trans. 106 (2000) 304.
[57] S De Antonellis, M Intini, CM Joppolo, L Molinaroli, F. Romano, Desiccant wheels for air humidification: an experimental and numerical analysis, Energy Convers. Manage. 106 (2015) 355–364, https://doi.org/10.1016/j.enconman.2015.09.034.
[58] D Kadylak, P Cave, W. Mérida, Effectiveness correlations for heat and mass transfer in membrane humidifiers, Int. J. Heat. Mass Transf. 52 (2009) 1504–1509, https://doi.org/10.1016/j.ijheatmasstransfer.2008.09.002.
[59] D Kadylak, W. Mérida, Experimental verification of a membrane humidifier model based on the effectiveness method, J. Power Sources 195 (2010) 3166–3175, https://doi.org/10.1016/j.jpowsour.2009.12.005.
[60] D Chen, W Li, H. Peng, An experimental study and model validation of a membrane humidifier for PEM fuel cell humidification control, J. Power Sources 180 (2008) 461–467, https://doi.org/10.1016/j.jpowsour.2008.02.055.
[61] M. Shehadi, Review of humidity control technologies in buildings, J. Build. Eng. 19 (2018) 539–551.
[62] W Shi, Y Min, Y Chen, H Yang, Development of a three-dimensional numerical model of indirect evaporative cooler incorporating with air dehumidification, Int. J. Heat. Mass Transf. 185 (2022) 122316, https://doi.org/10.1016/j.ijheatmasstransfer.2021.122316.
[63] AA Pesaran, TR Penney, AW. Czanderna, Desiccant cooling: State-Of-The-Art Assessment, National Renewable Energy Lab.(NREL), Golden, CO (United States), 1992.
[64] BS Davanagere, SA Sherif, DY. Goswami, A feasibility study of a solar desiccant air-conditioning system—Part I: psychrometrics and analysis of the conditioned zone, Int. J. Energy Res. 23 (1999) 7–21.
[65] BS Davanagere, SA Sherif, DY. Goswami, A feasibility study of a solar desiccant air-conditioning system—Part II: transient simulation and economics, Int. J. Energy Res. 23 (1999) 103–116.
[66] W Yang, W Wang, Z Ding, Z Wang, X Zhao, S. He, Performance study of a novel solar solid dehumidification/regeneration bed for use in buildings air conditioning systems, Energies 10 (2017) 1335, https://doi.org/10.3390/en10091335.
[67] B Su, W Qu, W Han, H Jin, Feasibility of a hybrid photovoltaic/thermal and liquid desiccant system for deep dehumidification, Energy Convers. Manage 163 (2018) 457–467, https://doi.org/10.1016/j.enconman.2018.02.018.
[68] A Ali, K Ishaque, A Lashin, N Al Arifi, Modeling of a liquid desiccant dehumidification system for close type greenhouse cultivation, Energy 118 (2017) 578–589, https://doi.org/10.1016/j.energy.2016.10.069.
[69] TS Ge, Y Li, RZ Wang, YJ. Dai, A review of the mathematical models for predicting rotary desiccant wheel, Renew. Sustain. Energy Rev. 12 (2008) 1485–1528.
[70] S De Antonellis, CM Joppolo, L. Molinaroli, Simulation, performance analysis and optimization of desiccant wheels, Energy Build. 42 (2010) 1386–1393.
[71] D-Y Lee, D-S. Kim, Analytical modeling of a desiccant wheel, Int. J. Refrig. 42 (2014) 97–111.
[72] CEL Nóbrega, NCL. Brum, An analysis of the heat and mass transfer roles in air dehumidification by solid desiccants, Energy Build. 50 (2012) 251–258.
[73] L-Z Zhang, H-X Fu, Q-R Yang, J-C. Xu, Performance comparisons of honeycomb-type adsorbent beds (wheels) for air dehumidification with various desiccant wall materials, Energy 65 (2014) 430–440.
[74] AS Norazam, HM Kamar, N Kamsah, MI. Alhamid, Simulation of adsorption process in a rotary solid desiccant wheel, in: AIP Conf. Proc. 2062, AIP Publishing LLC, 2019 020012.
[75] X Fang, J Winkler, D. Christensen, Advanced Dehumidification Analysis On Building America Homes Using EnergyPlus, 2010.
[76] S Liu, C-H Jeong, M-S. Yeo, Effect of evaporator position on heat pump assisted solid desiccant cooling systems, Energies 13 (2020) 5918.
[77] Y Khan, G Singh, J Mathur, M Bhandari, P. Srivastava, Performance assessment of radiant cooling system integrated with desiccant assisted DOAS with solar regeneration, Appl. Therm. Eng. 124 (2017) 1075–1082.
[78] P Gandhidasan, MA. Mohandes, Artificial neural network analysis of liquid desiccant dehumidification system, Energy 36 (2011) 1180–1186, https://doi.org/10.1016/j.energy.2010.11.030.
[79] A Parisio, L Fabietti, M Molinari, D Varagnolo, KH. Johansson, Control of HVAC systems via scenario-based explicit MPC, in: 53rd IEEE Conf. Decis. Control, IEEE, 2014, pp. 5201–5207.
[80] F Scotton, L Huang, SA Ahmadi, B. Wahlberg, Physics-based modeling and identification for HVAC systems?, in: 2013 Eur. Control Conf. ECC IEEE, 2013, pp. 1404–1409.
[81] SS Cox, JC Little, AT. Hodgson, Predicting the emission rate of volatile organic compounds from vinyl flooring, Environ. Sci. Technol. 36 (2002) 709–714.
[82] MG Khararoodi, F Haghighat, C-S. Lee, Develop and validate a mathematical model to estimate the removal of indoor VOCs by carbon filters, Build. Environ. 233 (2023) 110082, https://doi.org/10.1016/j.buildenv.2023.110082.
[83] SA Nada, HF Elattar, A. Fouda, Performance analysis of proposed hybrid air conditioning and humidification–dehumidification systems for energy saving and water production in hot and dry climatic regions, Energy Convers. Manage. 96 (2015) 208–227.
[84] Z Ding, X Yu, Z Ma, W Wu, L Zhang, DYW Yu, et al., On-site measurement and simulation investigation on condensation dehumidification and desiccant dehumidification in Hong Kong, Energy Build. 254 (2022) 111560, https://doi.org/10.1016/j.enbuild.2021.111560.
[85] S Abdullah, MNBM Zubir, MRB Muhamad, KMS Newaz, HF Öztop, MS Alam, et al., Technological development of evaporative cooling systems and its integration with air dehumidification processes: a review, Energy Build. 283 (2023) 112805, https://doi.org/10.1016/j.enbuild.2023.112805.
[86] Y Yin, J Qian, X. Zhang, Recent advancements in liquid desiccant dehumidification technology, Renew. Sustain. Energy Rev. 31 (2014) 38–52, https://doi.org/10.1016/j.rser.2013.11.021.
[87] YJ Dai, RZ Wang, HF Zhang, JD. Yu, Use of liquid desiccant cooling to improve the performance of vapor compression air conditioning, Appl. Therm. Eng. 21 (2001) 1185–1202.
[88] Q Ma, RZ Wang, YJ Dai, XQ. Zhai, Performance analysis on a hybrid air-conditioning system of a green building, Energy Build. 38 (2006) 447–453.
[89] S Tian, X Su, Y. Geng, Review on heat pump coupled desiccant wheel dehumidification and air conditioning systems in buildings, J. Build. Eng. 54 (2022) 104655, https://doi.org/10.1016/j.jobe.2022.104655.
[90] T Zhang, X Liu, Y. Jiang, Performance optimization of heat pump driven liquid desiccant dehumidification systems, Energy Build. 52 (2012) 132–144, https://doi.org/10.1016/j.enbuild.2012.06.002.
[91] A Zarrella, M De Carli, C. Peretti, Radiant floor cooling coupled with dehumidification systems in residential buildings: A simulation-based analysis, Energy Convers. Manage 85 (2014) 254–263, https://doi.org/10.1016/j.enconman.2014.05.097.
[92] F Fermanel, J. Miriel, Air heating system: influence of a humidifier on thermal comfort, Appl. Therm. Eng. 19 (1999) 1107–1127, https://doi.org/10.1016/S1359-4311(98)00110-0.

[93] J Ye, X Liu, L Xu, L. Ni, Experimental study on the heating and humidifying performance of fan coil units with humidification modules in severe cold regions, Energy Build. 276 (2022) 112500, https://doi.org/10.1016/j.enbuild.2022.112500.
[94] S-J Lee, H Lim, J-W. Jeong, Energy benefit of liquid desiccant-assisted humidification in buildings during winter operation, Energies 14 (2021) 1360.
[95] M El Hourani, K Ghali, N Ghaddar, Effective desiccant dehumidification system with two-stage evaporative cooling for hot and humid climates, Energy Build. 68 (2014) 329–338, https://doi.org/10.1016/j.enbuild.2013.09.040.
[96] W Su, X. Zhang, Performance analysis of a novel frost-free air-source heat pump with integrated membrane-based liquid desiccant dehumidification and humidification, Energy Build. 145 (2017) 293–303, https://doi.org/10.1016/j.enbuild.2017.04.024.
[97] H-J Cho, S-Y Cheon, J-W. Jeong, Energy impact of vacuum-based membrane dehumidification in building air-conditioning applications, Appl. Therm. Eng. 182 (2021) 116094, https://doi.org/10.1016/j.applthermaleng.2020.116094.
[98] J Lin, S-M Huang, R Wang, KJ. Chua, Thermodynamic analysis of a hybrid membrane liquid desiccant dehumidification and dew point evaporative cooling system, Energy Convers. Manage 156 (2018) 440–458, https://doi.org/10.1016/j.enconman.2017.11.057.
[99] P Yin, SA. Mumma, Study of the dedicated outdoor air system (1): a review, HVAC 33 (2003) 44–46.
[100] VK Vijayan, H Paramesh, SS Salvi, AAK. Dalal, Enhancing indoor air quality –The air filter advantage, Lung India Off Organ Indian Chest Soc. 32 (2015) 473–479, https://doi.org/10.4103/0970-2113.164174.
[101] Z. Guo, Review of indoor emission source models. Part 1. overview, Environ. Pollut. 120 (2002) 533–549, https://doi.org/10.1016/S0269-7491(02)00187-2.
[102] Y Zhang, R Yang, R. Zhao, A model for analyzing the performance of photocatalytic air cleaner in removing volatile organic compounds, Atmos. Environ. 37 (2003) 3395–3399.
[103] R Yang, Y-P Zhang, R-Y. Zhao, An improved model for analyzing the performance of photocatalytic oxidation reactors in removing volatile organic compounds and its application, J. Air. Waste Manage Assoc. 54 (2004) 1516–1524.
[104] SL. Daniels, On the ionization of air for removal of noxious effluvia"(Air ionization of indoor environments for control of volatile and particulate contaminants with nonthermal plasmas generated by dielectric-barrier discharge), IEEE Trans. Plasma Sci. 30 (2002) 1471–1481.
[105] H-X Fu, X-H. Liu, Review of the impact of liquid desiccant dehumidification on indoor air quality, Build. Environ. 116 (2017) 158–172, https://doi.org/10.1016/j.buildenv.2017.02.014.
[106] H. Wu, Discussions of mass transfer behaviors between VOCs and TEG solutions by surface tension and equilibrium process, Sep. Sci. Technol. 50 (2015) 1294–1301.
[107] H Wu, T-C Feng, T-W. Chung, Studies of VOCs removed from packed-bed absorber by experimental design methodology and analysis of variance, Chem. Eng. J. 157 (2010) 1–17.
[108] CK Chau, WM. Worek, Cosorption processes of triethylene glycol in a packed-bed liquid desiccant dehumidifier, HVACR Res. 15 (2009) 189–210.
[109] T-W Chung, TK Ghosh, AL Hines, D. Novosel, Dehumidification of moist air with simultaneous removal of selected indoor pollutants by triethylene glycol solutions in a packed-bed absorber, Sep. Sci. Technol. 30 (1995) 1807–1832.
[110] Z Weirong, Q Kaiyang, LIU Xiaohua, C. Xiaomin, Pilot study of the impact of liquid desiccant dehumidification on IAQ, Hv Ac 11 (2004) 28.
[111] YW Zheng, R Cheng, R Tu, XH Liu, YP. Zhang, Performance analysis of liquid desiccant dehumidifier used to absorb formaldehyde. 11th REHVA World Congr. 8th Int, in: Conf. IAQVEC Clima 2013, Prague, 2013.
[112] J Nie, L Fang, G Zhang, Y Sheng, X Kong, Y Zhang, et al., Theoretical study on volatile organic compound removal and energy performance of a novel heat pump assisted solid desiccant cooling system, Build. Environ. 85 (2015) 233–242.
[113] G Zhang, YF Zhang, L. Fang, Theoretical study of simultaneous water and VOCs adsorption and desorption in a silica gel rotor, Indoor. Air. 18 (2007) 37–43.
[114] Y Wang, B Deng, CN. Kim, Transient Characteristics of VOCs Removal by an Air Cleaner in Association with a Humidifier Combined with Different Ventilation Strategies in an Office, Indoor. Built. Environ. 21 (2012) 71–78, https://doi.org/10.1177/1420326X11419928.
[115] S-Y Cheon, H-J Cho, J-W. Jeong, Energy saving potential of a vacuum-based membrane dehumidifier in a dedicated outdoor air system, Energy Convers. Manage 227 (2021) 113618, https://doi.org/10.1016/j.enconman.2020.113618.
[116] Z Feng, X Zhou, S Xu, J Ding, S-J. Cao, Impacts of humidification process on indoor thermal comfort and air quality using portable ultrasonic humidifier, Build. Environ. 133 (2018) 62–72, https://doi.org/10.1016/j.buildenv.2018.02.011.
[117] X Hao, G Zhang, Y Chen, S Zou, Moschandreas DemetriosJ, A combined system of chilled ceiling, displacement ventilation and desiccant dehumidification, Build. Environ. 42 (2007) 3298–3308, https://doi.org/10.1016/j.buildenv.2006.08.020.
[118] DB Jani, M Mishra, PK. Sahoo, Performance prediction of rotary solid desiccant dehumidifier in hybrid air-conditioning system using artificial neural network, Appl. Therm. Eng. 98 (2016) 1091–1103, https://doi.org/10.1016/j.applthermaleng.2015.12.112.
[119] Y Chen, A Ozaki, H. Lee, Energy saving potential of passive dehumidification system combined with energy recovery ventilation using renewable energy, Energy Build. 268 (2022) 112170, https://doi.org/10.1016/j.enbuild.2022.112170.
[120] Y Zeng, J Woods, S. Cui, The energy saving potential of thermo-responsive desiccants for air dehumidification, Energy Convers. Manage 244 (2021) 114520, https://doi.org/10.1016/j.enconman.2021.114520.
[121] Z Li, X-H Liu, Z Lun, Y. Jiang, Analysis on the ideal energy efficiency of dehumidification process from buildings, Energy Build. 42 (2010) 2014–2020, https://doi.org/10.1016/j.enbuild.2010.06.008.
[122] W Li, Y Yin, Y. Wang, Performance evaluation of a heat pump-driven liquid desiccant dehumidification system integrated with fresh air supply, Energy Build. 275 (2022) 112473, https://doi.org/10.1016/j.enbuild.2022.112473.
[123] L Wang, F Xiao, X Niu, D. Gao, A dynamic dehumidifier model for simulations and control of liquid desiccant hybrid air conditioning systems, Energy Build. 140 (2017) 418–429, https://doi.org/10.1016/j.enbuild.2017.01.073.
[124] X Ou, W Cai, X He, D Zhai, X. Wang, Dynamic modeling and validation of a liquid desiccant cooling and dehumidification system, Energy Build. 163 (2018) 44–57, https://doi.org/10.1016/j.enbuild.2017.12.041.
[125] J Liu, T Zhang, X. Liu, Model-based investigation of a heat pump driven, internally cooled liquid desiccant dehumidification system, Build. Environ. 143 (2018) 431–442, https://doi.org/10.1016/j.buildenv.2018.07.027.
[126] J-Y Park, H-W Dong, H-J Cho, J-W. Jeong, Energy benefit of a cascade liquid desiccant dehumidification in a desiccant and evaporative cooling-assisted building air-conditioning system, Appl. Therm. Eng. 147 (2019) 291–301, https://doi.org/10.1016/j.applthermaleng.2018.10.101.
[127] Z Yang, B Lin, K Zhang, Z. Lian, Experimental study on mass transfer performances of the ultrasonic atomization liquid desiccant dehumidification system, Energy Build. 93 (2015) 126–136, https://doi.org/10.1016/j.enbuild.2015.02.035.
[128] R Qi, L Lu, H. Yang, Development of simplified prediction model for internally cooled/heated liquid desiccant dehumidification system, Energy Build. 59 (2013) 133–142, https://doi.org/10.1016/j.enbuild.2012.12.028.
[129] J-Y Park, D-S Yoon, S-J Lee, J-W. Jeong, Empirical model for predicting the dehumidification effectiveness of a liquid desiccant system, Energy Build. 126 (2016) 447–454, https://doi.org/10.1016/j.enbuild.2016.05.050.
[130] X Ou, W Cai, X. He, Model-based optimization strategy for a liquid desiccant cooling and dehumidification system, Energy Build. 194 (2019) 21–32, https://doi.org/10.1016/j.enbuild.2019.04.019.
[131] H Bai, J Zhu, J Chu, X Chen, Y Cui, Y. Yan, Influences of the mixed LiCl-CaCl2 liquid desiccant solution on a membrane-based dehumidification system: Parametric analysis and mixing ratio selection, Energy Build. 183 (2019) 592–606.
[132] P Shamsizadeh, E. Afshari, Numerical modeling of a membrane humidifier for mechanical ventilation, Int. Commun. Heat Mass Transf. 132 (2022) 105931.