Systematic summary and analysis of Chinese HVAC guidelines coping with COVID-19

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Abstract
Heating, Ventilation, and Air-Conditioning (HVAC) system that is almost indispensable service system of modern buildings is recognized as the most important engineering control measure against pandemics. However, the effectiveness of HVAC systems has been questioned on their ability to control airborne transmission. After the outbreak of COVID-19, China has controlled the spread within a relatively short period. Considering the large population, high population density, busy transportation and the overall underdeveloped economy, China’s control measures may have some implications to other countries, especially those with limited resources. This paper intends to provide a systematic summary of Chinese ventilation guidelines issued to cope with COVID-19 transmission. The following three aspects are the main focus of these guidelines: (1) general operation and management schemes of various types of HVAC systems, (2) operation and management schemes of HVAC system in typical types of buildings, and (3) design schemes of HVAC system of makeshift hospitals. In addition, some important differences in HVAC guidelines between China and other countries/institutions are identified and compared, and the possible reasons are discussed. Further discussions are made on the following topics, including the required fresh air supply, the extended operation time, the use of auxiliary equipment, the limited capacity of existing systems, and the use of personalized systems.

Keywords
COVID-19, respiratory infectious diseases, mitigation measures, HVAC operation and management, ventilation

Introduction
Until the end of September 2021, more than 1 year and a half since the outbreak of COVID-19, over 233 million confirmed cases and over 4.7 million deaths worldwide have been reported.¹ According to the Global Economic Prospects issued by the World Bank, the world economy has shrunk by 4.3% in 2020,² and compared with 2019, the number of the unemployed globally in 2020 has risen by 1.098%.³ Obviously, the negative impact of the pandemic will continue to suppress the vitality of the global economy for a long time and bring potential instability risks to human society. In addition to the COVID-19, there have been also several major outbreaks of respiratory infectious diseases, including SARS, H1N1, H7N9 and MERS, in the 21st century. Efforts on developing feasible and effective solutions are therefore always needed.

Most respiratory infectious diseases, including COVID-19, generally have three main transmission routes, namely, contact transmission, droplet transmission and airborne transmission.⁽⁴⁾ Disinfectants can effectively inactivate the virus within a short period of time.⁽⁵⁾–⁽⁷⁾ Regular sterilization and disinfection of solid surfaces and frequent hand washing

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with appropriate disinfectants are therefore believed as effective measures to reduce the risk of contact transmission.\textsuperscript{4,10,11} Wearing a face mask, either N95 or surgical mask, can be effective in preventing virus-laden particles from penetrating into the user’s respiratory mucosa, thus reducing the risk of infection caused by droplet and airborne transmission\textsuperscript{12,13} Administrative control measures, such as monitoring body temperature at the entrances of buildings, controlling the number of occupants and defining a social distance between persons, have played a very important role in preventing the occurrence of cluster infection. Occupants’ aided measures, such as intermittent occupancy, are feasible, economic and effective to reduce the risk of cross-infection.\textsuperscript{14}

Apart from measures described above, engineering control measures are also important and are considered to be more effective sometimes than using personal protective equipment and administrative control measures.\textsuperscript{15} Heating, Ventilating and Air Conditioning (HVAC) system is the most important engineering control measure to cope with the pandemic. The main method is to dilute the concentration of virus-laden particles by supplying sufficient fresh air volume and to keep indoor air flowing from clean areas to polluted areas. When the capacity of the existing ventilation system is limited, air purifiers can be used to increase the equivalent of fresh air.\textsuperscript{16,17} In addition, other measures, for example, applying auxiliary equipment in the ducts, such as filters and ultraviolet (UV) lamps, can effectively reduce the concentration of virus-laden particles in the indoor air.\textsuperscript{18–20} For some infectious diseases, maintaining indoor air temperature and humidity within a certain range can also reduce the infection risk.\textsuperscript{18,21–23} However, improper operation and management of HVAC systems that increase airborne transmission have been widely recognized. For example, insufficient Air Change per Hour (ACH) does not guarantee the necessary dilution, while the change of ACH can modify the designed air distribution that may in turn increase the risk of cross-infection.\textsuperscript{24–26} In addition, inappropriate arrangement of the supply and exhaust vents and incorrect control of the pressure gradient between different areas may result in the reverse flow of polluted air into clean areas.\textsuperscript{27–30} Furthermore, the use of air purifiers may also change the designed air distribution indoors and thus increase the risk of cross-infection.\textsuperscript{31,32}

Natural ventilation is recommended during the pandemic, but it is inherently unstable.\textsuperscript{33} Some studies reported that humidification has a limited effect on the liveability of SARS-CoV-2 in a certain range.\textsuperscript{24,33} More importantly, some routine operation schemes during normal periods may increase the risk of cross-infection during the pandemic, such as using recirculation air, some types of heat exchangers, and Demand-Controlled Ventilation (DCV) systems.

Generally, proper operation and management of HVAC systems during the pandemic are of great importance from the perspective of reducing the risk of cross-infection. In this aspect, some guidelines on HVAC operation and management during the pandemic have been issued by the World Health Organization (WHO) and other authoritative institutions worldwide, such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Federation of European Heating, Ventilation, and Air Conditioning Associations (REHVA), The Society of Heating, Air-Conditioning, and Sanitary Engineers of Japan (SHASE), Indian Society of Heating, Refrigerating and Air Conditioning Engineers (ISHRAE) and Architectural Society of China. In addition, some studies\textsuperscript{36,37} have summarized the important operation strategies of HVAC systems against COVID-19. China has a good performance in coping with the pandemic, and considering the large population, high population density, busy transportation and underdeveloped economy, China’s control measures may have some implications to other countries, especially those with limited resources. Therefore, this study systematically and comprehensively summarizes the operation and management schemes of HVAC systems recommended in related guidelines issued by Chinese government, authoritative institutions and professional societies. In addition, some procedures recommended in Chinese guidelines, which differ from those in ASHRAE, REHVA, SHASE, ISHRAE and WHO, are identified and compared, and the possible reasons are analyzed, so as to provide a reference for practitioners to formulate relevant guidelines in the future based on the needs and available resources. Furthermore, this study provides discussions on possibilities for the improvement of future ventilation systems.

**A brief summary of different HVAC systems**\textsuperscript{38–45}

During the pandemic of COVID-19, different HVAC systems have different operation strategies. Some types of HVAC systems are not even suitable to be used during the pandemic. This section briefly analyzes the management and maintenance methods of several typical HVAC systems. A summary of suggestions for different HVAC systems is shown in Figure 1. The purpose of any type of HVAC system during the pandemic is first to ensure the safety of occupants and second to meet comfort requirements. Before a system is put into use, a thorough check should be performed to ensure that all components of the system can work properly and the components that are easy to accumulate dust and breed bacteria have been cleaned, disinfected or even replaced. Fresh air must be ensured to be taken directly from the outdoor, and the surrounding of the intake vent must be kept clean and free from pollution, and away from the exhaust outlet. Avoid short circuits between the intake air and the exhaust air and regularly clean and disinfect key components, such as filters and surface condensers. As for the operation schedule, the air-conditioning system should be switched on 1–2 h in advance. After the building is unoccupied, the
ventilation system should continue to operate for 1 h for general ventilation of the building.

**All-air system**

**General suggestions.** The prerequisite for adopting the all-air system during the pandemic is to close the return air valve and to operate under all-fresh-air conditions. If return air must be used, the maximum ratio of fresh air to return air should be maintained, which should not be smaller than 40%. Since the system is operating under all-fresh-air conditions, the indoor air temperature may not meet the comfort requirements in a period after the system starts to run. Therefore, the system should be switched on in advance to preheat or precool the indoor space. The building should be fully ventilated after being unoccupied. Note that, due to the aforementioned sufficient ventilation and disinfection, the next-day pre-heating and pre-cooling should be performed using all return air. During the pandemic, the level of comfort requirements should be lowered. The temperature in winter should be set to 16°C and in summer 28°C.

The all-air system include a single-fan system and a dual-fan system, which have different operation strategies.

**Single-fan system.** As the single-fan system only has supply fan, the way of exhausting indoor air should be carefully considered. Generally, there could be three different scenarios as follows:

- If an exhaust fan is installed at an appropriate position of the space, the exhaust fan shall be operated.
- If there is no exhaust fan and there are windows, windows should be open for natural ventilation.
- If the above two scenarios are not satisfied but there is a smoke exhaust fan, the exhaust fan should be activated.

**Dual-fan system.** The dual-fan system has both a supply fan and an exhaust fan. In this case, in addition to the general suggestions, the following three recommendations should be followed:

- Valves of both the supply and exhaust air should be adjusted at the maximum opening level to ensure the maximum air exchange rate.
- When the building is unoccupied, if the system is operating under variable air volume (VAV) conditions, two additional suggestions should be followed:
  i. In wintertime, the fresh air valves of the VAV box in the inner and outer zones of the building should be remained at the minimum and maximum opening levels, respectively, and the reheating coil in the outer zone needs to be fully opened.
  ii. In summertime, VAV box can be operated as usual.

**Fan-coil system**

If there is no fresh air system in a space, doors and windows should be open to strengthen ventilation as much as possible. Spaces that are impossible to open windows for ventilation should not be used.

**Fan-coil unit with fresh air system.** During the pandemic, the fan-coil units with fresh air systems can operate as usual, but the following suggestions should be followed:

- If the outdoor air temperature meets the comfort requirement, switch off the fan coil and keep only the...
fresh air system running and ensure the normal and continuous operation of the mechanical exhaust system.

- During operation, ensure the per capita fresh air volume is not less than 30 m$^3$/h.
- For the fan-coil system, if a coil serves only one room, the system can operate normally; if a coil serves multiple rooms or a fan-coil system takes return air directly from the ceiling area shared by different rooms, the fan-coil system should be switched off.

**Multi-split system and split-type air conditioner**

During the pandemic, multi-split systems and split-type air conditioners can operate as usual, but the following issues should be noted:

- If there is a fresh air system, keep it running continuously, otherwise, open windows regularly for ventilation.
- In the wintertime of the severe cold region, the reliability of the antifreeze protection function of a system needs to be checked before running the system.
- Stop using the room where there is no fresh air system and the windows cannot be open for ventilation.

**Fresh air system and fresh air heat recovery system**

From the above descriptions that no matter what kind of HVAC system is used in a building, there is no exception that the fresh air system or openable windows are required. Therefore, in order to ensure a safe indoor environment during pandemics, the following suggestions should be adopted:

- There are no damages and cracks in the negative pressure section of the fresh air ducts indoors.
- Relevant measures should be implemented to the fresh air system with a heat recovery device based on its configuration. A system that is equipped with a rotary heat recovery device should be stopped, and the fresh air system and the exhaust system operate independently. A system that has a plate-type or a plate-fin-type heat exchanger is not recommended for use, and the fresh air system and exhaust system can operate independently by opening the bypass valve. For those without bypass valves, only the fresh air fan should be switched on and the exhaust fan should stop running, and then windows or other exhaust systems should be used to maintain the pressure balance. A system that has a heat exchanger without risk of cross-contamination, such as a heat pipe, can be used as usual.
- During the pandemic, the fresh air unit should be operated at the rated power.
- For the fresh air handling unit with water-pipe heating/cooling, the setting value of the supply air temperature in the wintertime is recommended ≥18°C (if running with 100% fresh air, the temperature setting value should be slightly increased); the setting value of the supply air temperature in the summertime is recommended ≤28°C (if running with 100% fresh air, the temperature setting value should be slightly lowered); the electric water valve for heating/cooling is automatically adjusted through the automatic control system; and if there is no automatic control system, the water valve should be fully open.
- The filter screen of the fresh air handling unit should be cleaned regularly. The cleaning frequency is at least once a month. If the fresh air system is renovated, an air filter with at least medium-efficiency grade 3 should be installed.

**General guidelines for “Office buildings” and “Markets”**

Office buildings and markets are two types of buildings related closely to economic recovery. There are some general guidelines for their re-opening:

- Assign special personnel to strictly manage the entrance of the building. Visitors should have their body temperature checked and shown their health codes. Only those people with normal body temperature are allowed to enter the building.
- Another necessary prerequisite for people entering the building is to wear personal protective equipment, namely, a face mask.
- Occupants are required to maintain a safe social distance, which is generally 1 m.
- Operation and management schemes of different types of systems refer to the section “A brief summary of different HVAC systems”.

**Office buildings**

General guidelines for the use of various HVAC systems during the pandemic have been introduced. In addition, note that for office buildings with all-air systems, the indoor CO$_2$ and PM$_{2.5}$ concentrations should be monitored, and when the CO$_2$ concentration is higher than 600 ppm, the number of occupants should be reduced and the fresh air should be increased. The total air exhaust volume of the centralized exhaust system on a floor shall not be less than 70% of the total air supply volume. Recommendations for specific areas of office buildings are listed as follows:
Building entrances

- Terminate the use of the fingerprint attendance machines.
- During the pandemic, an emergency channel should be set up at the entrances of a building, which has the functions such as non-intrusive body temperature measurement and alert, face recognition and check-in.

Elevators

- During the pandemic, elevator cars and elevator shafts should be kept at a certain negative pressure by increasing the exhaust air volume.
- Elevator cars should be disinfected every 2 h, and elevator buttons should be arranged in non-direct contact.

Office areas

- Office areas with no fresh air system or low fresh air supply should have an extra ventilation plan, such as regular ventilation by open windows (each ventilation time should be no less than 20 min).

Meeting rooms

- The use priority should be given to meeting rooms with windows, independent air-conditioning systems, and a sufficient ventilation capacity. In addition, the number of attendees and their distance must be controlled.
- If there are openable windows, the window should be open for ventilation before and after use, and the ventilation time is not less than 30 min. If there is an air purifying device, it should be switched on during the meeting. Air purification devices should be cleaned and disinfected regularly, at least once a month.
- An air cleaning device should be installed with a high-efficiency air filter, which should be, again, cleaned and disinfected regularly, not less than once a month.

Toilets

The exhaust system in toilets should be switched on and remain on continuously throughout the day. There should be a consideration to decide the location of exhaust vents to eliminate the potential risk of the exhaust air flowing into other indoor areas and fresh air intake vents. Temporary disinfection facilities such as UV lamps should be installed to disinfect toilets during the unoccupied time.

Staff canteens

- During the occupied period, the air supply and exhaust systems should be running as designed. In addition, it continues to be operated for 1 h after use to achieve a full replacement of indoor air.
- For canteens that use multiple vertical cabinet split air conditioners or multi-line air conditioners, which have no fresh air system and no exhaust system, the air conditioner should be switched off and, if possible, natural ventilation should be used; if the air conditioner system must be used, the air vent must be cleaned and disinfected regularly and windows (if any) should be open; in addition, natural ventilation is required before and after the serving period, and the ventilation every time is not less than 30 min per time.
- For canteens that are not equipped with a mechanical ventilation system or have no openable windows for natural ventilation, and if they cannot be renovated, they should not be used.

Underground garages

- The ventilation system of an underground garage should be switched on 1.0–2.0 h before employees start to work, which should always be on during working periods.
- During the commuting periods, the density of personnel is relatively high. In this circumstance, the use of a smoke exhaust system should be considered to increase the exhaust air volume without neglecting the anti-freezing of equipment and pipelines.
- The smoke exhaust system should be inspected regularly to prevent polluted air from entering the office area through the smoke exhaust system.

Management requirements

- The air-conditioning and ventilation systems shall be switched off under the following situations:
  i. A suspected or confirmed case of COVID-19 was found.
  ii. The type of central air-conditioning ventilation system and the range of air supply volume are unclear.
- Cleaning and disinfection of the air-conditioning and ventilation systems should meet the following requirements:
  i. The routine cleaning and disinfection of the air-conditioning and ventilation systems shall comply with requirements of the Code for Cleaning and Disinfection of Centralized Air-Conditioning and Ventilation Systems in Public Places (WS/T 396-2012). 250–500 mg/L chlorine (bromine) or chlorine dioxide disinfectant can be used for spraying, soaking or wiping the targeted components for 10–30 min.
  ii. Quaternary ammonium salt disinfectants are recommended for disinfecting metal parts.
iii. When confirmed and suspected cases of COVID-19 are found, the air conditioning and ventilation systems should be switched off, disinfected and cleaned, which can be restarted only after passing the hygiene evaluation.

Markets\(^{38,40,42–44,46}\)

Shopping malls and supermarkets are places with a high risk of cross infection. Following suggestions should be taken during the pandemic:

- The number of customers in shopping malls and supermarkets should be limited.
- Employees should strengthen personal protection, including wearing masks, gloves and working clothes.
- Switch on the fresh air system and exhaust system, open windows to maximize the natural ventilation and to increase ventilation rate.
- Increase the cleaning and disinfection or replacement frequency of air handling equipment in the air-conditioning and ventilation systems. Places that occupants contact frequently such as banisters and elevator buttons should be disinfected regularly.

Schools\(^{48,49}\)

It must be stated that most indoor spaces in most schools and universities in China do not have mechanical ventilation systems and thus natural ventilation through open windows and/or doors is the way to have outdoor air. Schools and universities have different methods to deal with the transmission of the COVID-19. In middle and primary schools, students stay in classrooms for almost all days, and the irrelevant personnel is generally not allowed to enter the campus. However, most universities cannot be strictly closed to the general public. In addition, college students are active in the library, classrooms, dormitories and so on. Therefore, preventing and mitigating transmission in universities is a more difficult task than in schools. For schools, an important method is to reduce the number of students at entrances through personnel diversion and to prohibit parents from gathering at the entrance after school (note: It is common in China that parents wait at entrances of schools to pick up their children). For universities, the following suggestions should be followed:

- Irrelevant persons should not be allowed to enter the campus.
- Students and teachers need to have their body temperature checked and wear masks before they enter public places such as the library, canteens, classrooms and dormitories.
- All persons must report their health information every day. Abnormal persons must be identified and sent to the hospital immediately.
- The serving time of canteen should be extended. Diners are arranged to have meals at different times, who should be guided to different canteens when necessary.
- Classrooms, offices, laboratories and canteens must be ventilated every day. The ventilation should not be less than 3 times per day, and each time should not be less than 30 min.
- UV lamps should be used in canteens and restaurants, which should be switched on for environmental disinfection in every morning, noon and evening, with 30 min for each time.
- Places where occupants contact frequently, such as desks, chairs, and floors, should be disinfected every day.

Hotels\(^{50}\)

An urgent problem to be solved during a pandemic is the shortage of isolation places. Hotel buildings are equipped with independent rooms with necessary living conditions and can be used as temporary isolation places in emergency times to centrally isolate suspected persons and confirmed cases with mild symptoms.

For hotel buildings that are used for temporary isolation, the following guidelines should be followed:

- The hotel shall be divided into the clean area and the quarantine area (including semi-polluted area and polluted area), and the check-in and check-out areas should be arranged separately.
- Take occupants’ body temperature two to three times a day and minimize the transfer of personnel. Gathering places should be closed, such as banquet halls, restaurants, gyms, indoor and outdoor swimming pools and other functional spaces. All persons should stay in their rooms as much as possible to avoid cross-infection.
- Hotel rooms should give the priority to the use of inverter-driven split-type air conditioners. Each room shall have an independent fresh air supply (exhaust) and filtration system, and the exhaust system should be installed with a high-efficiency air filter.
- For areas used to receive suspected and confirmed patients, ACH should not be less than 6 h\(^{-1}\).
- Some areas which use an all-air system or a fan-coil unit with a fresh air system refer to “A brief summary of different HVAC systems” for operation suggestions.
- Ensure the exhaust air volume is greater than the fresh air volume to maintain a slightly negative pressure in isolation rooms, and avoid the airflow passing between different rooms.
• Places that occupants contact frequently such as banisters and elevator buttons should be disinfected regularly.

**Hospitals**

Hospitals have characteristics of gathering (including most infected persons) and frequent interpersonal contacts, which are high-risk places during the pandemic. The National Health Commission, many professional institutions, and some hospitals have formulated regulations and suggestions to reduce the risk of cross-infection. At the beginning of the pandemic, the Chinese government built some makeshift hospitals to cope with the severe situation. Ensuring a zero or low risk of cross-infection in these places is an important mission for designers.

**Ordinary hospitals**

Ordinary hospitals can be roughly divided into two areas, namely, outpatient department and inpatient department, which need to meet different requirements.

**Outpatient departments**

The outpatient service area is the first place that people enter the hospital. If effective measures are adopted, the spread risk of infectious diseases can be drastically reduced. The main measures used in outpatient departments are summarized as follows:

- Take visitors’ body temperature before they enter the hospital. Send people with abnormal body temperature into the fever clinic for a further examination.
- Visitors must wear a face mask and medical staff should wear additional personal protective equipment depending on where they are.
- Control the number of people in the outpatient departments.
- In the registration hall, waiting rooms and infusion rooms, fan-coil units, split-type air conditioners, indoor parts of multi-split systems and all-air systems that do not supply 100% outdoor air should be switched off. The independent fresh air system and exhaust system and open windows should be switched on. The fresh air system should be switched on 2 h before opening for service, and the exhaust system should be closed 2 h after being closed for service.
- In consultation offices and examination rooms, the fresh air system and exhaust system should run continuously for 24 h. Open windows as much as possible if the indoor air temperature does not deviate much from the comfort zone. A movable air cleaner with a high-efficiency filter should be used.
- The air-conditioning system should be cleaned and disinfected in time. Places that occupants contact frequently such as banisters, floors and elevator buttons should be disinfected regularly.
- Control the direction of indoor airflow to ensure air flows from the clean area to the polluted area.

**Inpatient departments**

Compared with outpatient departments, inpatient departments involve more contacts between people but less movement of people. In inpatient departments, the following measures should be implemented:

- The number of visitors and their contact with patients should be reduced. All people must wear a mask and have their body temperature checked before entering the inpatient departments. Medical staff should wear appropriate personal protective equipment based on the required protection level.
- In general wards, the fresh air system and exhaust system should run all the time. Open windows as much as possible if the indoor air temperature is acceptable. If possible, an additional movable air cleaner with a high-efficiency filter should be used or a low-resistance medium-efficiency filter should be installed in return air ducts.
- Take patients’ body temperature every day, and patients with abnormal body temperature must be sent to isolation wards.
- Condensed water of air conditioners in polluted areas should be collected centrally and discharged into the sewage drainage system for further treatment.
- Use disposable equipment whenever possible and disinfect the medical waste in time.
- The air-conditioning system should be cleaned and disinfected in time. Places that occupants contact frequently such as banisters, floor and elevator buttons should be disinfected regularly.

**Makeshift hospitals and infectious hospitals**

Makeshift hospitals are transformed from existing buildings, which are temporary places for accommodating suspected people and confirmed patients with light symptoms. Infectious hospitals are specially used to treat people with infectious diseases. It is a big challenge to prevent concentrated outbreaks and to mitigate the risk of cross-infection in such places. The following measures are recommended to be implemented:

- The space should be divided into a clean area, a restricted area (semi-clean area) and a quarantine
Adopt an all-fresh air system in negative pressure for each area should be equipped with an independent ventilation system. Pressure gradients should be created in such spaces, in order to control the airflow direction successively from the clean area, semi-polluted area to polluted area.

- Each area should be equipped with an independent mechanical ventilation system. Pressure gradients should be maintained at 5 Pa.
- The return air dampers of the ventilation system must be closed and the return air inlets should be blocked. The outdoor air damper should be fully opened. The ventilation system should be working continuously for 24 h a day.
- Air supply systems in restricted areas should include at least two-level filtrations with coarse and medium-efficiency, and in quarantine areas should include at least three-level filtrations with coarse, medium and high-efficiency. The exhaust system should have a high-efficiency filtration. Filters at all levels should be equipped with differential pressure detection and alarm devices.
- Exhaust fans in quarantine areas should be installed at the outdoor side, and air outlets should be kept away from air inlets and other occupied areas. The exhaust air should be discharged at a high altitude, with the horizontal distance from any air inlets not being less than 20 m or the vertical distance not being less than 6 m.
- In negative pressure wards, several air purifiers with sterilization and disinfection functions should be placed. The minimum fresh air volume should be set to be the larger one of 6 h\(^{-1}\) and 60 L/s/person. The pressure difference between a negative pressure ward and its adjacent rooms should be maintained at at least 5 Pa.
- If small single rooms (such as dormitories and hotels) are used as isolation wards, the ACH of each room should not be less than 6 h\(^{-1}\). If large spaces, such as exhibition centers, gyms and factories are used as isolation wards, the per capita fresh air volume should not be less than 40 L/s.
- Adopt an all-fresh air system in negative pressure for isolation wards. The minimum fresh air volume should be set to be the larger one of 12 h\(^{-1}\) and 160 L/s/person. The pressure difference between a negative pressure isolation ward and its adjacent rooms should be maintained at 5–15 Pa. Ensure that the air in a ward would not leak to other areas.
- The supply air should be treated by a three-level filtration system that includes simultaneously primary-, medium- and high-efficiency filters, and the exhaust air should be treated by a high-efficiency filter. The exhaust air filter should be installed at the room side.
- The air supply vents should be installed in the ceiling area that is over the position of medical staff, and exhaust vents should be installed on the wall close to the beds. Ensure the airflow distribution could cover all the ward areas to facilitate the rapid discharge of polluted air.
- Isolation wards should be equipped with toilets and restrooms, where the exhaust system should provide an ACH of not less than 12 h\(^{-1}\). The exhaust air should be discharged after passing a high-efficiency filter.
- The signal of air supply fans and exhaust fans should be monitored all the time to ensure their normal operation, to monitor the pressure difference of air filters all the time, and to replace the blocked air filter in time.

**HVAC systems of Huoshenshan makeshift hospital**

**Construction profiles.** Huoshenshan hospital is one of the most important makeshift hospitals constructed in early 2020 in Wuhan, Hubei province of China to cope with the rapid increase in the number of suspected and confirmed cases. Huoshenshan hospital has a construction area of around 33,900 m\(^2\). The main divisions of the building are consulting rooms and wards, etc.

**Air-conditioning systems**

All functional areas without a special cleanness requirement are installed with split-type air conditioners with auxiliary electric heating devices. The condensed water of the split-type conditioner should be drained to the floor drain of the ward bathroom and be discharged after centralized treatment with sewage and wastewater.

**Ventilation systems**

1. Carry out organizational ventilation to ensure the orderly flow of air and reduce air cross-contamination in different areas.
2. Equipped with mechanical air supply and exhaust systems for wards, examination rooms, medical offices and other rooms that produce odorous and harmful gases, water vapour and wet operations. Set electric auxiliary heating device for the fresh air fan, and the fresh air should be directly sent to the clean corridor of the ward area. Install exhaust fans in the lower part of the ward and on top of the toilet, and the exhaust air should be discharged centrally by the exhaust fan.
Table 1. Recommended pressure values for areas.

| Negative pressure wards, Pa | Buffer rooms, Pa | Clean medical corridors, Pa | Office areas/locker rooms, Pa |
|-----------------------------|------------------|-----------------------------|-----------------------------|
| -15                         | 0                | 5                           | 10                          |

(3) Install a separate system in places with serious pollution such as laboratories, disposal rooms and dressing rooms.

(4) Maintain a negative pressure in the testing room and infectious ward and a positive pressure in the medical office area.

(5) Install centralized air supply system and exhaust system in corridors and rooms of medical staff. The difference between the supply air and exhaust air can maintain a positive pressure in aforementioned areas to prevent the air in the polluted area from flowing to these areas. The pressure difference between the negative pressure isolation wards and their adjacent buffer rooms and clean corridors should be maintained at least 5 Pa. The recommended pressure values for different areas are shown in Table 1.

(6) All air supply systems should be equipped with primary-, medium- and high-efficiency filters.

(7) All exhaust systems should be equipped with primary-, medium- and high-efficiency filters.

(8) Outdoor air of the air supply system should be taken from a high altitude, and the air inlets should be at least 6.0 m above the roof. The distance between inlets and exhaust outlets is as far away as possible, and the horizontal distance should be at least 20 m.

(9) All wards and medical staff’s offices should be installed with wall-mounted or movable air purifiers to improve the indoor air quality.

(10) The switches of exhaust fans in wards must be controlled by specialized personnel, and patients should not be allowed to adjust the switches.

(11) Air supply vents should be equipped with regulating valves. The opening level of the valve that is nearest to the fan should be 50%, and the farthest should be 100%, while the opening level of other valves should be adjusted according to this linear law.

**HVAC systems of Leishenshan makeshift hospital**

**Construction profiles.** Leishenshan hospital is another important makeshift hospital after Huoshenshan hospital, which has a construction area of around 79,700 m². The building is mainly divided as follows: inpatient area, medical area, rest area, examination room, operating room, Intensive Care Unit (ICU), Computed Tomography (CT), Magnetic Resonance Imaging (MRI), B-scan ultrasonography and electrocardiogram (ECG).

**Cooling and heating sources and systems.** All functional areas without a special cleanliness requirement should be installed with split-type air conditioners with auxiliary electric heating. The MRI rooms and the equipment rooms that have a strict requirement on air temperature and relative humidity should be mounted with an independent, special, air-conditioning system that can provide the required constant indoor air temperature and relative humidity. Operating rooms and ICUs should be equipped with purified air-conditioning units with air-source heat pumps. Low-noise centrifugal fan boxes should be adopted in fresh air systems in all areas, and an auxiliary electric heating system should be installed at the outlet of fans to ensure that the outlet air temperature is not lower than 18°C.

**Ventilation systems**

1. In order to form a reasonable pressure gradient, ensure the orderly flow of air, and thus avoid cross-infection, the design of the ventilation system follows the Regulation for Architectural Design of Infectious Diseases Hospital (GB50849-2014).

2. Wards and toilets should be installed with mechanical air supply and exhaust systems. The supply air of each ward should be 500 m³/h, and the exhaust air should be 700 m³/h. Maintain wards with a negative pressure to effectively control the spread of viruses and other pollutants. For each ward, the supply air inlet should be installed at a sidewall and an exhaust air outlet at a relatively low position, with the bottom at least 100 mm above the floor. An exhaust air outlet should be installed at the sidewalk of the toilet of each ward, and each outlet should be equipped with a high-efficiency filter. The air supply and exhaust branch pipes should be installed with electric airtight air valves, which can be closed separately during room disinfection.

3. A mechanical exhaust system should be installed in polluted walkways of these wards, and the exhaust outlet should be located on the sidewall. The exhaust system should provide an ACH of not less than 6 h⁻¹ to ensure negative pressure is maintained in this area.
Discussion

A brief comparison of guidelines during normal and pandemic periods

The core difference between guidelines during the normal and pandemic periods is that the former considers the balance of thermal comfort, indoor air quality and energy saving, while the latter focuses on the indoor air quality, more specifically the transmission risk of infectious diseases. When compared to the guidelines during normal periods, the following major changes have been introduced by the guidelines during pandemic periods, such as increasing the required fresh air volume, extending the operation time (as shown in Figure 2), upgrading the level of filter, strengthening the cleaning and disinfection of devices and increasing the application of auxiliary equipment, and so on. Table 2 summarizes the fresh air volumes recommended during the normal and pandemic periods.

A consensus in almost all guidelines is to maximize the supply of fresh air and to limit or even avoid the use of return air. However, the maximum supply of fresh air may come with a huge amount of energy consumption, which should only be a short-term solution in a very limited scale of application. In addition, there may be a lack of scientific and practical evidence on the suggestion of the use of return air, and further investigation is required. For the fresh air supply, Chinese guideline suggests that it should be not less than 30 m$^3$/h/person; ASHRAE, a minimum ACH of 3 h;62 REHVA, the CO$_2$ concentration should be less than 800 ppm (warning);34 SHASE, a minimum supply of 30 m$^3$/h/person and a minimum ACH of 2 h;63 ISHRAE, 8.5 m$^3$/h/person;64; and WHO, 36 m$^3$/h/person.65 These different numbers suggested by different countries are more or less close to each other, except for the ISHRAE from India. The required fresh air supplied to maintain a certain level of risk of cross-infection is influenced by the infectivity of the virus and the assumed percentage of an infected person in a space, which is therefore difficult to determine.

As for the control of indoor temperature and relative humidity, occupants should reduce the requirements for thermal comfort during the pandemic. In most guidelines, the recommendation is to reduce the viability of SARS-CoV-2 by humidification, but REHVA suggests that there is no practical effect related to humidification.34 Chinese guidelines suggest deactivating the humidification function of a system, as it may bring other negative effects to occupants’ health.

Adjusting the operation schedule is one of the most common recommendations during the pandemic. Unlike the normal period, the ventilation system should be switched on earlier and switched off later. The main purpose is to fully remove indoor viruses before occupants enter the room the next day. However, the Chinese guidelines specifically recommend that if the building has been fully ventilated after the occupation, the ventilation system should be operated in the mode of all return air circulation in the next day before occupancy for pre-heating or pre-cooling. In addition, in medical buildings, the fresh air system and exhaust systems should be operated for 24 h, except for the registration hall, waiting rooms and infusion rooms of general hospitals, which require only an extra 2 h of operation. The general operation schedules suggested by different guidelines are shown in Figure 2. The REHVA guidelines recommend that, in commercial buildings, if the building can be ventilated with 3 ACH during business hours, an extension of operation for 1 extra hour both before and after the business hours is sufficient.
With regard to the application of auxiliary equipment, all guidelines agree that the application of higher-efficiency air filters has practical effects. Air cleaners with HEPA are recommended to be placed close to occupants when the ventilation system is unable to supply the needed amount of fresh air. Chinese guidelines do not recommend the use of UVGI in HVAC systems without consulting relevant medical experts, because of its potential radiation hazards.

**Improvement schemes for the future ventilation system**

It is evident from the pandemic that existing ventilation systems are not designed for coping with the transmission of respiratory infectious diseases like SARS-CoV-2. Though guidelines suggest increasing as much as possible the fresh air supply, existing systems do not have the ability to greatly increase the supply. Conventional total volume ventilation systems are designed for diluting pollutants in a whole space, which are ineffective to mitigate the risk for a short-range exposure, especially in short-term exposure events, though such exposure events occur quite commonly in practice.

ASHRAE guideline mentioned the use of personalized ventilation (PV) and personalized exhaust (PE) on some appropriate occasions. PV and PE may be a good supplement to total volume ventilation systems to increase the flexibility of ventilation systems in balancing the energy saving and thermal comfort in normal period and the virus removal in a pandemic. In addition, PV and PE are effective and economical in dealing with short-range exposure. Actually, past studies have demonstrated the ability of PV...
and PE systems in reducing the risk of cross-infection in rooms with mixing ventilation and displacement ventilation, underfloor ventilation and chilled ceiling. The flexibility in system type and setting has a great potential for energy saving. Figures 3–5 show the desk-mounted PV system, chair-integrated PV system, chair-integrated PV and PE system, cabin chair-integrated PV and PE system, bed-integrated local ventilation system and wearable PV system. Table 3 briefly summarizes and analyzes the applicable scenarios of these systems.

**Summary**

This paper reviews the guidelines of the operation and management of HVAC systems issued by Chinese governmental departments and professional institutions during the pandemic of COVID-19. The paper is expected to be a useful reference to other countries, especially those with limited resources. The major points are summarized as follows:

For non-medical buildings, the prerequisite for the normal use of a room is that it can be supplied with sufficient fresh air through mechanical ventilation and/or natural ventilation. It should try to avoid the use of return air as much as possible when a building is occupied. Formulate a reasonable natural ventilation scheme, even if the room is equipped with a mechanical ventilation system. For naturally ventilated office buildings, regular ventilation must be performed with each ventilation period not less than 20 min. For naturally ventilated staff canteens, natural ventilation should always be performed during serving periods. For office buildings with all-air systems, the indoor CO₂ concentration should not be higher than 600 ppm. The minimum per capita fresh air volume is 30 m³/h. If existing ventilation measures do not supply sufficient fresh air, air purifiers with HEPA can be applied. If the minimum fresh air is still not reached, the number of occupants should be reduced. Lengthening the operation time of the ventilation system, especially after occupation, is necessary. Return air may be used in the morning to pre-heat or pre-cool the building. Disable the humidification function. Upgrade the level of air filters and disinfect them regularly. Evaluate the heat recovery section of the HVAC system, and disable it if there is a risk of cross-pollution. Disable systems that can cause the air cross-flow between different rooms/areas, such as a VAV system with the return air being taken from a...
shared ceiling area by different rooms. If confirmed or suspected cases of COVID-19 are identified in a building, the HVAC system of affected areas must be switched off, disinfected and cleaned completely. The building can be put into use only after passing the hygiene evaluation.

For medical buildings, in the registration hall, waiting rooms and infusion rooms, systems that do not supply 100% outdoor air should be switched off. Independent fresh air systems and exhaust systems should be used. Systems should be operated for 2 h before and after occupation. In consultation of the checking rooms and general wards, all-air systems that do not supply 100% outdoor air should not be used. The air supply and exhaust systems should be always on. In all these areas, windows should be open as much as possible. In consultation offices, checking rooms and general wards, an additional movable air cleaner with a high-efficiency filter should be used. In negative pressure isolation wards, all-fresh air systems should be used. For negative pressure (including isolation) wards, both the supply air and the exhaust air should be treated by at least a high-efficiency filter. Airflow distribution should be able to ensure a rapid discharge of polluted air from clean areas (medical staff) to polluted areas (patients). Note that the application of additional air-conditioners and air purifiers may cause undesired air distribution. Several air cleaners with sterilization functions should be used in each isolation ward. The exhaust air in toilets should be discharged after high-efficiency filtration. The condensed water of air conditioners in contaminated areas should be collected centrally and discharged into the hospital’s sewage drainage system.

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