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Design characteristics on the indoor and outdoor air environments of the COVID-19 emergency hospital

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\textbf{A R T I C L E  I N F O}

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\textbf{A B S T R A C T}

According to the discussion of the design method and operational effect for Wuhan Huoshenshan Hospital, this paper summarized the design control points of indoor and outdoor environment of COVID-19 emergency hospital. Based on the design of Wuhan Huoshenshan Hospital, this paper analyzed and discussed the site design, building layout, three-zones and two-passages, the design scheme of the ventilation and air conditioning system for negative pressure ward and negative pressure isolation ward, air distribution, as well as some other key designs for COVID-19 emergency hospital. The design points were summarized and refined. The design methods and technology requirements of the COVID-19 emergency hospital were provided in this study, such as ventilation and air conditioning system setting, ventilation quantity of wards, pressure gradient control measures among different areas, upper and lower air distribution, filter setting mode and distance of air inlet and outlet, which could benefit to provide references for the design of similar projects in the future.

\section{1. Introduction}

In order to cope with coronavirus disease 2019 (COVID-19), Wuhan Huoshenshan Hospital started to construct on January 23, 2020. After ten days, the hospital was completed and put into operation. On February 3, 2020, 1,400 medical staffs were transferred to undertake the medical treatment task of Wuhan Huoshenshan Hospital. Up to April 3, 2020, the hospital had received a total of 3059 patients, in which 2806 had been cured and left hospital. None of the medical personnels was infected \[1\]. As the first COVID-19 emergency hospital, Wuhan Huoshenshan Hospital plays an important role and is well received since it was put into operation \[2\]. However, there was no domestic and international design standard to the point, and there was also a lack of cited literatures during the design. After the outbreak of the epidemic, global scientific research powers rapidly carried out various researches. According to the search and analysis of the global research status of COVID-19, Longhao Zhang found that the number of papers published had an increasing trend from mid-January 2020, among which 50 papers were published in the same day of February 6. Most of the studies focused on epidemiology, clinical characteristics, diagnosis and treatment, basic research, children and pregnant women, psychological protection, epidemic prevention and management and so on \[3\].

February 2020, Chinese government, local governments and trade associations had successively issued design guidelines and technical requirements for COVID-19 emergency hospitals \[4-6\]. In terms of the research papers, some were about the anti-epidemic design of COVID-19 epidemic situation \[7,8\], some were concerned with the indoor and outdoor air distribution and diffusion, the disinfection, the prevention and control management of ward infection of the emergency hospital.

The COVID-19 patients were clinically classified into four types such as mild, normal, severe and critical. In allusion to different levels of disease, the strategies adopted in Wuhan that patients were treated separately to the treatment of different places. The mild confirmed cases were admitted to the cabin hospital. The normal and severe cases were admitted to the isolated ward of designated hospitals or emergency hospitals. The critical cases were admitted to the ICUs of designated hospitals or emergency hospitals.

For Novel Coronavirus, “Respiratory droplets and close contact transmission are the primary means of transmission. In a relatively closed environment exposed to high concentration of aerosol for a long time there is the possibility of aerosol transmission. Novel Coronavirus can be separated in stool and urine, note that stool and urine may cause aerosol or contact transmission of environmental contamination.” \[9\]. Therefore, for the emergency hospitals admitted the confirmed cases with COVID-19, the
comprehensive prevention and control measures should not only strengthen the personal protection of medical staffs (mask, gloves, protective clothing, goggles and hand hygiene, etc.), disinfection (cleaning and disinfection of the diagnosis and treatment environment, ward air and object surface, etc.), but also should pay attention to the site design and layout of emergency hospitals. The “three-zones and two-passages” (polluted zone, semi-polluted zone, clean zone, medical staff passage, patient passage), negative pressure ward setting, the way of air conditioning and ventilation of the wards, air distribution of the wards and diagnosis area, disposal of pollutants and air discharge, etc. should be considered in designs. How to ensure the working conditions of medical staffs, strengthen the protection of occupational exposure of medical staff and patients, and minimize the risk of infection outbreak via the design and control of the indoor and outdoor environment of hospitals has coming to be a highlighted problem, which must be regarded with great interest and urgently be solved during the design of emergency hospitals.

2. Site design and building layout

As a typical hospital for respiratory infectious diseases, COVID-19 emergency hospital is highly infectious and would be concerned in the public eye. It should have strict requirements for indoor and outdoor environment. The site selection and site design must strictly meet the requirements of the current national standard. The site and general layout designs should be reasonably partitioned by functions. The space distribution and corresponding flow lines for doctor and patient, people and vehicles, pollutant and clean thing and so on, should be distinguished clearly. The physical and psychological space of the hospital area separated from the surrounding buildings should be fully considered. A complete greening plan should be carried out, in which the greening isolation distance of more than 20 m should be set to the health protection zone. Based on the good orientation, the space between the buildings should meet the requirements of sanitation, sunshine, lighting, ventilation and firefighting. The discharge of waste water, waste gas, noise and castoff shall be properly disposed of in accordance with the current relevant national norms and provisions for environmental protection.

Meanwhile, the building design should meet the medical procedures of infectious disease hospitals. The layout of the building should be divided into the polluted area, the semi-polluted area and the clean area combined with the flow line design. The passage of pollutant and clean thing, stream of people and logistics should also be considered. All of the temporary storage room of medical waste, general refuse transfer station as well as sewage treatment station and incinerator were likely to produce secondary pollution, the unified planning and construction should be carried out. The aims of these planning and design requirements were to effectively prevent the occurrence of hospital infection and protect the indoor and outdoor environment of the hospital.

For Wuhan Huoshenshan Hospital, the effective designs and controls of site design and building layout were carried out in strict accordance with relevant regulations [10]. The hospital was a total construction area of 34,571 m², about 1,000 beds (including 30 beds in ICU). It was composed of Inpatient Building No.1 and Inpatient Building No.2. Building No.1 was a single-storey building with the layout of a Chinese character "艹"-shaped. It consisted of 9 single-storey nursing units, medical technology building and ICU center, in which each nursing unit was formed by 23 wards. Some containers formed the nursing units. The central area was a protective zone which was divided into a clean corridor (clean zone) and a nurse corridor (potentially contaminated zone). The finger corridor area was the ward area, which was divided into three zones: the medical corridor (semi-contaminated zone), the ward (contaminated zone) and the patient corridor (contaminated zone). A standard of Grade III surgery, negative pressure checkout room and three CT rooms were set in the medical technology building. The ICU center is located between Inpatient Building No.1 and Inpatient Building No.2. Both the medical buildings and ICU center were steel structure board house. For Inpatient Building No.2 was a two-storey building with an “E” shaped layout. It was divided into four clusters which consists of 8 nursing units with 23 wards singly. The configuration mode of the clean corridor, the nurse corridor and the nursing units in Building No.2 were the same as that of Inpatient Building No.1, except that the clean corridor and the nurse corridor is one-side configuration.

The layout of the hospital is shown in Fig. 1.

Huoshenshan Hospital was a temporary emergency hospital that was specially built in response to the epidemic situation in the end of 2019. Thus it was different from other infectious disease hospitals. The clinical manifestation and received way of the epidemic patients should be clarified firstly, and then the construction scale of each part of the hospital would be determined reasonably according to the target of beds. The treatment objects of the hospital were definitively all the ordinary, severe and critical patients who had been admitted and diagnosed with COVID-19. The received way was transfer treatment. Therefore, in terms of functional settings, the primary consideration was to maximize the number of beds and then the diagnostic function would be weaken. Considering the characteristics of the site, and a certain distance from the eastern water system on the basis of satisfying the bed demand as many as possible, the overall plane layout was L-shaped. According to the predominant wind direction of Wuhan in winter, the outdoor oxygen station, negative pressure aspiration station, garbage temporary storage room, mortuary and incinerator were placed in the southeast corner of the site, minimizing the impact on the environment of the hospital. The existing facilities of Wuhan worker’s sanatorium was used as the logistics support area of the hospital, strictly distinguishing the cleaning support area and medical isolation area (Fig. 1). In the design, the corresponding measures were taken to minimize the impact on the surrounding environment. For example, the distances of isolation and protection from the adjacent urban roads and residential areas on the west side were increased as far as possible, such as effective 40 m away from Zhiyinhua Avenue; not less than 120 m from the nearest residence on the west side, and the isolation barrier along Zhiyinhua Avenue. In order to ensure the Zhiyin lake to avoid being affected by the use of the hospital, the surface water was fully collected and disinfected [11]. Referring to waste harmless treatment and other environmental protection engineering practices, all the ground surface were covered with anti-seepage film [12], to ensure that no water could enter the lake and no water could seep down. After All of rainwater and sewage were collected and treated intensively to reach the standard, they could be discharged into the municipal pipe network.

Based on the experience of Xiaotangshan SARS Hospital in 2003, the building was arranged in a fishbone shape. A central axis was set to the continuous passage which connected the clean area with medical staffs. Ward units were arranged in the two sides of the central axis, in which the wards belonged to the polluted areas. Compared with Xiaotangshan Hospital, there were many differences, such as the way of patients in or out of the ward, the internal division of the nursing unit and the flow line of medical staffs [13].

A semi-contaminated zone was arranged between the clean area and the ward unit, which was namely the transition section between the medical staff and the ward. Most of the work for medical staffs can done in the semi-contaminated zone. Outside each nursing unit, there was a patient passage separated from the medical staff passage, to ensure that the workers would not be infected. Before medical staffs entered a contaminated zone from the clean area, they should pass through a labyrinthine buffer zones named sanitary passage. The sanitary passage was taken as the Buffer barrier between potentially contaminated and clean zones, which can ensure medical staffs to pass in safety. Only if the sanitary passage was properly configured, it can play its role of protection and isolation [14]. Therefore, the design of Huoshenshan Hospital adopt a more safer design idea of “three-zones and four-corridors” according to local conditions. The three-zones were clean zone (working zone), semi-polluted zone (medical office zone) and polluted zone (ward
zone). The four-corridors were clean corridors, nurse corridors, medical corridors and patient corridors. All of them formed the basic nursing units in hospital. The design layout was demonstrated in Fig. 2.

3. Design for ventilation and air conditioning system in wards

3.1. Design keys and principles

The most important characteristic of medical buildings, especially hospital buildings for infectious diseases, was isolation and protection different from other buildings. Therefore, the priority of the designs of ventilation and air conditioning system was to ensure the normal pressure among functional areas and prevent the cross-infection. The potential cross infection in infectious diseases hospital was divided into two categories, namely, the infection between medical staffs and patients, and the infection among patients. In consideration of the same diagnosed patients of COVID-19 for the emergency hospitals, the prevention of “medical staff-patient” infections should be given the first place while the prevention of “patient-patient” infections would be achieved through segmentation. Firstly, it was a high-priority to ensure that the relationship between flow direction and pressure gradient from the clean zone to the semi-polluted zone then to the polluted area should be completely correct. Secondly, the pressure differences of rooms with different pollution levels should meet the requirements of the standards and be not less than 5Pa [15]. Fig. 3 showed the pressure controls in different zones in designs.

In order to eliminate the possibility of polluted air to the clean zone through the ventilation system, the mechanical supply and exhaust...
system in the clean zone, semi-polluted zone and polluted zone should be set up independently according to the area. The mechanical supply and exhaust system should reduce the air pressure from the clean zone to the semi-polluted zone then to the polluted zone successively. The clean zone should be the positive pressure zone and the polluted zone should be the negative pressure zone. The air supply volumes in the clean zone should be greater than that of air exhaust, while the air exhaust in the polluted area should be greater than that of the air supply.

According to the current standards, the design of the infection prevention and control, ventilation and air conditioning system for the negative pressure wards and negative pressure isolation wards in hospitals were different. However, in the Code for Design of Infectious Disease Hospital (GB 50849-2014) and Requirements of Environmental Control for Hospital Negative Pressure Isolation Ward (GB/T 35428-2017), there was no explicit provisions that how to define the negative pressure wards and the negative pressure isolation ward, and what kind of ventilation and air conditioning measures [16,17]. Therefore, it was difficult for designers to make decisions.

In contrast, the Novel Coronavirus Infectious Disease Emergency Medical Facility Design Criteria (T/CECS 661G-2020) (hereinafter referred to as “COVID-19 Emergency Design Criteria”) clearly defined the negative pressure ward and negative pressure isolation ward for the first time. That is, the negative pressure wards refer to “a ward separated by space and equipped with a ventilation system to control airflow direction, so as to ensure that the indoor air static pressure is lower than that of the surrounding area”. The negative pressure isolation wards refer to “a ward separated by space and equipped with all-fresh air direct current air conditioning system to control the flow direction, so as to ensure the indoor air static pressure is lower than the surrounding area air static pressure, and take effective health and safety measures to prevent cross infection and infection.”.

Studies had shown that severe COVID-19 patients with high viral load may be more infectious than those with mild illness in theory. Especially in the later stage, the virus load of severe patients would be even greater, while patients with mild illness were also infectious. Therefore, it was necessary to establish a hierarchical diagnosis and treatment system based on patients at different stages [18].

For a designated admission hospital of COVID-19, such as Wuhan Huoshenshan Hospital, the admitted persons mainly included normal type, severe and critical type patients. For a general hospital, patient treatment needs, medical resources, operation economy and other factors should be considered integrally, in which the negative pressure isolation ward and ICU should admit critical patients and other separate treatment patients, the negative pressure ward should admit ordinary patients and severe patients. This is consistent with the COVID-19 Emergency Design Standard.

During the design of Wuhan Huoshenshan Hospital, the proportion of beds in the negative pressure isolation ward and the ICU in practice was firstly identified based on the proportion of different types of COVID-19 patients at that time (mild, normal accounted for more than 80%). As a result, two of the seventeen nursing units were set up as negative pressure isolation wards (12%), and others were all negative pressure wards. ICU beds number was up to 30 (3%). The actual survey had proved that the above types of ward settings met the medical treatment needs of COVID-19.

3.2. Ventilation and air conditioning system design

Based on the design of Wuhan Huoshenshan Hospital, several main problems that should be paid attention to analyze and discuss as follow in allusion to the ventilation and air conditioning system of the wards.

3.2.1. Selection of ventilation and air conditioning type

Heating, ventilation and air conditioning systems in COVID-19 emergency hospitals should be rationally partitioned according to the requirements of indoor design parameters, medical equipment, hygiene, use time and air conditioning load. Each functional area or medical nursing unit should have an independent ventilation and air conditioning system. The control object of the negative pressure isolation ward was the deadly pathogen in the air. Considering that returning air handing of the kind of wards cannot guarantee a 100% cut off or kill bacteria in negative pressure isolation wards, the air conditioning system of all fresh air direct flow should be adopted with the minimum ventilation rates of 12. All of them can guarantee the room air environment and achieve a comfortable temperature and humidity requirement. In the negative pressure ward, fan-coil or multi-split air conditioning system can be used in combination with the mechanical air supply and exhaust system. The fresh air conditioning system was used as the air supply system, and the air supply volume should not be less than 6 air ventilation rates per hour. The return air inlet of air conditioning system and fan coil unit should be equipped with filtration equipment with initial resistance of less than 50Pa, primary pass rate of microorganism less than 10% and primary pass rate of particulate matter less than 5%, such as air inlets and outlets of ultra-low resistance. The setup requirements mentioned above were in agreement with the Code for design of infectious disease hospital (GB 50849-2014) and Code for design of general hospital (GB 51039-2014) [19].

According to the above requirements and the nursing unit sets, six negative pressure isolation wards were combined into a ventilation system, while the negative pressure wards were combined into a ventilation system with 6-12 units depending on the conditions in Wuhan Huoshenshan Hospital. Fixed air flow valves, electric air flow valves and other valves were generally adopted to achieve air flow balance in traditional air conditionings. However, there were a large number of fixed air flow valves in Wuhan Huoshenshan Hospital, so that it was difficult to guarantee the inventory and delivery period. As well, it was impossible to reserve time to debug. Therefore, the most reliable air...
volume balance strategy was adopted. Firstly, the ventilation duct loop system adopted reversed return system to reduce the tuyere number of single system and improve the self-balance ability of the system. Then, the power distributed system was used to exhaust in the ward, and independent first-level exhaust fans were equipped based on rooms, which can not only conduct to the control of the exhaust volume, but also effectively avoid the pollution between the rooms. Finally, the wind speeds of the ventilation main pipe were appropriately reduced to reduce the pressure difference caused by the transportation distance.

At the beginning of the operation of Wuhan Huoshenshan Hospital, the minimum outdoor temperature was below 0 °C, and it was necessary to start the air-conditioning heating system. Therefore, both the ward buildings and the protective area for doctors were equipped with air source heat pump based on rooms. The outdoor units were installed on the roof or the ground. The indoor units were wall-mounted and located above the wall near aisle in the ward to minimize the impact on the indoor air flow. All the air supply systems of the ward were equipped with electric heating device with three-grade adjustment, and the air supply temperature can be appropriately decreased with the rise of air temperature in the later period, to reduce the energy consumption of air source heat pumps. All sanitary hot water in the ward was produced by distributed electric water heaters, which were installed in the ward toilet. In the operating room and ICU center in the medical technology building, air source heat pump systems with direct expansion purification were set strictly in accordance with relevant national regulations. The onsite demonstration of the wards in hospital was shown in Fig. 4.

After the actual operation test for more than two months, the ventilation and air conditioning system have been proved to be reasonable and reliable. For the convenience of system regulation and management, it was suggested that each nursing unit should be divided into at least two systems, and the number of connected wards should be the same as far as possible to achieve mutual standby.

3.2.2. Determination of ventilation rate

According to the Code for Design of Infectious Disease Hospital (GB 50849-2014), there were definite requirements for the air supply and exhaust rate of negative pressure ward and negative pressure isolation ward. The minimum ventilation rate (fresh air volume) of the outpatient department, the medical technology room and the ward, and the fever clinic for respiratory infectious disease should be 6 times/h. The negative pressure isolation ward shall adopt all fresh air direct flow air conditioning system. The minimum ventilation rate should be 12 times/h. The air supply rate of each room in the clean area should be 150 m³/h greater than air exhaust. The air exhaust rate of each room in the polluted area should be 150 m³/h greater than air supply."

Considering the architectural characteristics of the container room which had an enclosure structure of poor airtightness, the ventilation rate of Wuhan Huoshenshan Hospital were higher than the standard requirements. According to the consultation with the hospital receiver, the final air supply and exhaust volumes were finally determined to fully ensure the ventilation rate and pressure gradient of the ward as follows: 8 times/h air supply and 12 times/h air exhaust for negative pressure ward, 12 times/h air supply and 16 times/h air exhaust for the negative pressure isolation ward, 12 times/h air supply and 16 times/h air exhaust for ICU room, the 300 m³/h difference between air supply and exhaust.

When the project was put into operation, the air pressure difference between the patient corridor and the ward in actual tests remained 6Pa, higher than the required 5Pa by the specification. The air pressure difference between the medical corridor and the ward was from 12Pa to 15Pa, higher than the standard requirement of 10Pa, which can verify the rationality of air volume values. A sketch map was presented in Fig. 5. With the increase of filter resistance in later operation, the air supply and exhaust rate of the system would slightly decrease, and the corresponding pressure difference fluctuated within a reasonable range.

In view of the above situations, there were no problems caused by poor airtightness of the enclosure structure in the conventional infectious disease hospital, so the ventilation rate required by the Code of Design of Infectious Disease Hospital was effective and reliable, which was consistent with the Requirements of Environmental Control for Hospital Negative Pressure Isolation Ward (GB/T 35428-2017). However, it should be noted that the ventilation system in the negative pressure isolation ward should be able to ensure the pressure gradient requirements of each partition at the end resistance of filters.

3.2.3. Air distribution of air supply and exhaust

The current domestic relevant standards for the air inlet and outlet settings of wards were put forward with upper air supply and lower air exhaust as well as directional airflow, which could be attributed to the following reasons. Firstly, the directional airflow with the air outlet in the upper room and air outlet near the head of a bed should be adopted to remove out of dead zone, stagnation and short circuit which can prevent the accumulation of bacteria and viruses. Secondly, most of the medical staff in the ward mostly stood up to work, while patients breathed in bed for a long time with high low pollution concentration. The air distribution can reduce the chance of the medical staff to be infected by the way of avoiding the medical staffs between the infectious source and the air outlet. Thirdly, the air outlet was installed near the floor to make clean air flow downward from the breathing area and work area to the polluted floor area, which can benefit to discharge the polluted air as soon as possible.

In terms of the air distribution mode in the ward, the domestic and foreign researchers had conducted a series of explorations and studies. Cheong et al. conducted on-site testing and CFD numerical simulation under three ventilation strategies, which showed that the air distribution with the best pollutant removal effect was upper and lower air distribution on both sides of the bed [20]. Liu Yanxiang et al. used the simulation software COMSOL to simulate four different air distribution

![Fig. 4. Negative pressure ward and ICU ward.](image-url)
in the ward to find that the upper and lower air distribution could reduce the probability of mutual infection of patients based on the influence of bacteria distribution on indoor air quality [21]. Ying Zhang et al. proposed the application of adaptive wall-mounted ventilation and made a comprehensive evaluation from the aspects of pollutant diffusion, removal efficiency, thermal comfort and operating cost [22]. Li Angui et al. proposed that the air distribution of single slit type outlet attached the vertical wall with deflector as the recommended for the negative pressure isolation ward. Fresh air from the slit air outlet with up-down direction airflow was directly sent to the respiratory zone of the medical staff (standing height) through the deflector, and then to the respiratory zone of the patient (downward direction), and finally was exhausted from the lower part of both sides of the contralateral bed. The air distribution can make the working area to have better thermal environment, the higher ventilation efficiency, the better orientation of air supply and exhaust flow. The fresh air was directly sent to the breathing area of medical staff, and polluted air could be exhausted as soon as possible in an organized manner [23].

Lv Zhongyi et al. adopted the simulation software XFlow to simulate the pollutant concentration of the wards according to the air distribution of upper supply and lower return in negative pressure isolation wards. The results indicated that the pollutant concentration was relatively higher from the patient’s face upper to the air outlet and lower at other positions, which showed that the air distribution could form the directional airflow towards the air outlet to effectively eliminate the ward pollution [24].

Therefore, it can be considered theoretically that the best airflow direction was that the clean fresh air was sent directly to the breathing area of medical staffs, and then to the patient’s breathing area, and finally to quickly exhaust the exhaled contaminant of patients from the lower outlets on both sides of the bed, which could reduce the backflow of polluted air in the ward. In view of the above requirements and simulations, the air inlets were set up at the end of the bed and near the door of the ward, and the air outlet were set up at the bottom of the bed in Wuhan Huoshenshan Hospital according to the actual situation, which could achieve better air supply and exhaust.

3.2.4. Filter setting mode

There were clear requirements for setting the filter of the ventilation system in the domestic standards. The air supply in the negative pressure isolation ward shall be treated with rough efficiency, medium efficiency and sub-high efficiency filters. The exhaust air shall be filtered by a high efficiency filter to exhaust. The high efficiency filter for the exhaust air of the negative pressure isolation ward shall be installed in the air outlet of the wards. Negative pressure isolation ward admitted severe and critical patients, in which the virus might be carried by the patient and escaped during the treatment. The exhaust high efficiency filters were installed in the air outlet of the room to cut off and filter the virus at the source for avoiding the pollution of the air duct and spread through the exhaust system, which was convenient for the replacement and disinfection of the filter in situ. The Schematic diagram of air distribution in ward is shown in Fig. 6.

The air supply inlet in the negative pressure isolation ward and negative pressure ward in Wuhan Huoshenshan Hospital was equipped with three-stage filters including coarse, medium and high efficiency at the entrance of the blower, which can not only prevent the introduction of other pathogenic bacteria affecting the patient, but also prevent dust from entering to bring the parasitic virus or carrier.

The exhaust high efficiency filter of the negative pressure isolation ward was located at the air outlet of the room, while the exhaust high efficiency filter of the negative pressure ward was located at the entrance of the exhaust fan. On the one hand, Huoshenshan Hospital admitted the same kind of patients with no cross-infection problem. On the other hand, a large number of high efficiency filters were set up in the negative pressure ward, which would bring a lot of problems in equipment procurement, installation, maintenance, replacement and disinfection. The filter was centrally set up at the entrance of the outdoor exhaust fan, which can avoid the elimination and replacement of the filter in the ward, greatly reducing the risk of infection of maintainers. The exhaust high efficiency filters should be replaced regularly according to the pressure difference detection. The removed exhaust high efficiency filters should be put into a safe container for disinfection and sterilization after disinfection in situ, and should be treated as medical wastes.
4. Outdoor designs for the ventilation and air conditioning system

4.1. Setting of pressure and exhaust fans

The exhaust fans in the semi-polluted zone of the ward and the polluted zone should be set at the end of the exhaust pipes to ensure that the whole exhaust pipes were under negative pressure, to prevent the pollutants in the exhaust pipes leakage to the air pipe to pollute the outdoor environment or other rooms. In order to ensure safe operation and convenient maintenance, the exhaust fan should be set in an open area outside. The blower could be set according to the specific situation of the site if the safe distance between the supply and the exhaust fan was met.

A quick built of the Wuhan Huoshenshan Hospital in ten days was attributed to the container houses. However, container houses roof structure was not strong enough to sustain the weight of the heavy equipment and duct. If the supply and exhaust fans were set on the roof, reinforced and anti-vibration treatments were necessary. A large number of people would cross operation on the roof, which was bound to increase the workload and impact the whole project schedule and cause construction risk. The roof should be made into slope roof eventually. Excessive occupancy of roof was not conducive to construction, equipment maintenance and filter replacement. It was cloudy and rainy in the winter in Wuhan, so that pierced pipes and holes made on the roof of containers were a great risk of water leakage and seepage. Subsequent construction link also verified our ideas [25]. After comparing and weighing, the design chooses to arrange the fan on the ground in an orderly way. In order to ensure the safety of the ward supply and exhaust system, the specifications and models of the pressure and exhaust fans were unified as far as possible, and each type of fan is reserved in the warehouse. In addition, consideration should be given to the influence of increasing filter final resistance on system air supply and exhaust after running for a period of time.

4.2. Setting of fresh air inlet and exhaust outlet

In the Code of Design of Infectious Disease Hospital (GB50849-2014), there were incomplete setting requirements for fresh air outlets and exhaust vents. It was only required that the exhaust outlet of the exhaust system should be far away from the air supply system and should not be near the personnel activity area,. While, there was no clear requirement on the distance between the fresh air inlet and the exhaust outlet and the sewage ventilation pipe. The design of Wuhan Huoshenshan Hospital referred to the requirements of emergency ventilation in the Code for Heating and Air conditioning of Civil Building (GB50736-2012) [26], the horizontal spacing was no less than 20 m when the horizontal distance is less than 20 m, air outlet should be higher than the inlet, the vertical elevation difference was no less than 6 m. As for the requirements of the height of the air outlet, it refers to Requirements of Environmental Control for Hospital Negative Pressure Isolation Ward (GBT35428-2017), in which the air outlet was 3 m above the roof (within the range of 15 m). Further analysis and demonstration were made on this basis.

From the perspective of pollutant diffusion, under the same outdoor parameters, the higher the height of exhaust outlet was, the more helpful it was for pollutant diffusion and dilution, and the less the impact of pollutants was on the ground. According to the relevant research, the exhaust outlet should be set at a height necessary for diluting the...
pollutants to a safe concentration. For SARS virus, the polluted air concentration below $100 \times 10^{-9}$ after diluting 10,000 times was no longer infectious [27]. At the beginning of the design of Wuhan Huoshenshan Hospital, an overall arrangement of the plane positions of the admission and exhaust outlet was made, and the horizontal distance between the admission and exhaust outlet was kept above 20 m, as shown in Fig. 7. The design process was strongly supported by the research team of Tsinghua University. Through the numerical simulation of outdoor pollutant diffusion [28,29], it was found that when the exhaust outlet height was 6.5 m, the pollutant concentration near the fresh air outlet was $49 \times 10^{-6}$ under the majority of unfavorable wind conditions (westerly wind, 1.9 m/s). However, when the height of the exhaust outlet was raised to 9 m under the unfavorable wind conditions (west wind, 1.9 m/s), the pollutant concentration near the fresh air outlet was decreased to $25 \times 10^{-6}$. Considering that during the design period of the project, the understanding of the COVID-19 transmission mechanism was not sufficient, the possibility of filter attenuation or even failure should be considered for safety reasons. Finally, under the premise of implementation, the height of the exhaust outlet was determined as 9 m. Under the condition of the exhaust high efficient filter being set and used, the environmental safety could be further improved.

5. Purification and disinfection and ventilation system control

5.1. Purification and disinfection

COVID-19 could be transmitted either directly by respiratory droplets or indirectly by dust mites, and relevant studies had shown that COVID-19 had been detected in various environmental surfaces, air samples and sewage in hospitals and communities [30–32]. The diameter of novel coronavirus was very small, about 60–110 nm, and the virus in the air was mainly attached to the suspended particulate matter (particulate diameter: above 0.1 μm), so the high efficiency filter above H13 (filtration efficiency: above 99.9%) can effectively filter the suspended particulate matter containing virus. Ehsan et al. conducted a literature search to verify the evidence of the safety of air filtration and recirculation. In spite of the lack of supporting documents, appropriate filtration measures were an important way to keep hospital air clean [33]. The air supply system and the exhaust system of the polluted area (semi-polluted area) of Wuhan Huoshenshan Hospital were all equipped with high efficiency filters, and the air inlet and outlet positions were reasonably set, so as to ensure the safety of the ventilation system.

Viruses on the surface of the environment might be more present in some parts of the contaminated or semi-polluted areas. H.Wang et al. conducted viral nucleic acid detection on the isolation ward of a domestic hospital receiving COVID-19, which showed positive results in most places [34]. Therefore, routine disinfection management in the hospital was very important. C, Jie Wang et al. monitored the health data of a domestic hospital receiving Covid-19 during the epidemic, and the data showed that strict disinfection and hand washing could reduce the risk of infection of the staff in the isolation ward [35]. The study of GE Tianxiang et al. showed that the routine disinfection procedures of isolation ward disinfection of 3 times a day and ICU ward disinfection of 6 times a day in the receiving hospital of COVID-19 were effective in reducing the risk of infection [36]. During the epidemic period, Wuhan Huoshenshan Hospital formulated strict infection control and management measures, such as from rational department layout to waste disposal, from strengthening personnel training to taking measures to reduce occupational exposure and infection risk of medical staff, and from strengthening infection prevention and control management to implementing strict disinfection and isolation measures throughout the whole cycle of admission, hospitalization and discharge [37].

5.2. Ventilation system control

The normal operation of ventilation system is the premise to ensure the airflow isolation effect. Park J Y et al. conducted a tracer gas experimental study, and the results showed that the failure or abnormal operation of ventilation equipment in the isolation ward would lead to the spread of infectious bacteria to the human body and the risk of infection [38]. Therefore, the ventilation system should be equipped with an alarm system and a reasonable control program. The main control contents of the ventilation and air conditioning system of Wuhan Huoshenshan Hospital were as follows:

1) The switching sequence should be: exhaust fan in polluted zone (ward) - pressure fan in semi-polluted zone (medical corridor)
- pressure fan in clean area - pressure fan in ward. The shutdown sequence is the reverse of the switching sequence.

2) The ward exhaust fan can be activated only after the ward pressure fan was started (circuit interlocking). The sound and light alarm device would be triggered when the exhaust fan in the ward stops, and pressure fan would be interlocked.

3) The exhaust fan in the ward should be set up for online pressure difference detection of the filter, and the acousto-optic alarm device should be started up in case of overpressure. Pressure difference detection and alarm devices should be set for all levels of air filters in the air supply and exhaust systems.

4) Control of pressure difference gradient in each medical nurse unit (negative absolute pressure difference value) should be mediated by: the ward and the corresponding toilet < buffer room < medical aisle (starting point of airflow pressure difference infiltration). Mechanical micro-pressure gauges with overpressure alarm function or interface were provided at the separation places of different pressure environments (high pressure side).

5) No exhaust systems were set up in the “front line” area where doctors and patients contact (e.g., the medical corridor). Prevent reverse pressure accidents caused by mis-operation(The current testing results showed that the relation of pressure difference between the medical corridor and the ward was more explicit).

6. Discussion

6.1. Control points of design for COVID-19 emergency hospital

All of the actual results proved that design methods and key technology for Wuhan Huoshenshan Hospital are practical and effective. To meet the requirements of the medical treatment and hospital control requirements, the design for COVID-19 emergency temporary hospitals should be in strict accordance with the infectious disease hospital medical process and the relevant specification. The negative pressure ward, the negative pressure isolation ward and the ICU should be rationally allocated according to the characteristics of infectious diseases and the severity conditions of patients. Appropriate ventilation and air conditioning system, air distribution form, and effectively control the pressure gradient relationship between various regions should be adopted. The outdoor environment of the hospital should be fully considered and planned, and the discharged waste water, waste gas, noise and waste should be properly treated in accordance with regulations, to ensure a clean and comfortable environment for medical treatment.

6.2. Limitations of the design for Wuhan Huoshenshan Hospital

Wuhan Huoshenshan Hospital was an emergency medical project in a special period. Its design was subject to the actual conditions at that time, so it has some certain limitations:

Conventional medical projects mostly use constant air volume valve, multi working condition air valve and other equipment, and cooperate with complex differential pressure detection and control system to realize the air volume balance in each area, so as to maintain the air pressure gradient requirements between each area. Due to the short construction time of the project, it was difficult to ensure the equipment inventory and supply cycle, and it was impossible to set aside sufficient commissioning time; Therefore, the coverage of a single ventilation system should be reduced as far as possible in the design, the length of each branch pipe of the system should be kept the same, and the inherent balance of the pipeline system shall be used as far as possible to reduce the setting of valves. Although a relatively ideal balance effect had been achieved, for subsequent projects, especially medical projects that need to take into account the epidemic situation and the conversion of various working conditions at ordinary times, conventional design methods still need to be adopted to realize the accurate control of air volume and differential pressure.

In addition, the heating mode of split air conditioning and wind power heating device was simple and effective, which was suitable for the actual situation at that time, but the energy consumption is huge, so it is not recommended to promote it in subsequent projects.

6.3. Discussion on the construction of permanent infectious disease hospitals combined with epidemic prevention

In the face of the rapid development of the epidemic, emergency temporary hospitals needed to address the most basic needs of medical functions. On the basis, the first was time-limited that the design and construction cycle should be as short as possible. Considering the normalization of the epidemic situation and the successful experience of emergency temporary hospitals, there were many problems that need to be discussed and further studied in the construction of permanent infectious disease hospitals combined with epidemic prevention.

(1) Hospitals, especially infectious disease hospitals, were special public buildings with high hygiene and comfort requirements, which were directly related to the health of medical staff and patients. Therefore, the planning, scheme creativity and architectural design should be carefully considered and planned according to the climatic conditions, the characteristics of the hospital and the medical procedures. With the concept of green building and sustainable development priority, it was recommended to use passive energy-efficient technologies, such as increasing natural ventilation and natural lighting through inner courtyard building layout, introducing air movement under the suitable climatic conditions, strengthening fresh air dilution effect in clean zone and so on. If the passive technology could not meet the requirements of comfort or medical treatment, heating and ventilation, air conditioning and purification air conditioning should be implemented for the whole or part of the hospital, and comparison of multiple schemes should be conducted, to reduce the energy consumption of the hospital building, especially in normal operation.

(2) Negative pressure ward and negative pressure isolation ward had large ventilation rates and strict airflow distribution forms. What should be noted was that the ventilation rate and airflow distribution of the ward mentioned above were basically based on relevant research and data, such as the data of ASHRAE and the CDC in the United States. Apart from the adaptability and effectiveness of novel Coronavirus, the effects of working time, working status and protective modes on the above data should be brought into the research field. Medical staff and care patients were nearly at zero distance in many cases; they must be protected at the three protective levels after entering the ward, and wear electric filter air supply hoods when possible, which should be considered in the study. In addition, many simulations based on CFD methods undoubtedly provided valuable analyses means for the engineering design and reference. In future, the simulation method and the corresponding experiments with the actual operation condition test were expected to be combined efficiently, to improve the understanding of all kinds of infectious diseases caused by bacteria and viruses and control level, and greatly improve the pertinence and accuracy of design technical measures.

(3) The larger number of air change rates in the negative pressure ward and the negative pressure isolation ward could lower the concentration of bacteria and viruses. However, in buildings equipped with heating and air conditioning, a larger number of air changes and ventilation rates would inevitably increase operating energy consumption. Moreover, for COVID-19, how many air changes were needed for effective air dilution control and how much air flow could be added to reduce the risk of...
infection were still under discussed, lacking accurate data and consistent conclusions. In the area with warmer winter and cooler summer, when the ward didn’t need heating and air conditioning to meet the thermal comfort, the above ventilation rate could be appropriately increased. For the negative pressure wards that needed to satisfy the thermal comfort through heating and air conditioning, fan-coil or multi-on-line air conditioning system could be adopted in combination with the mechanical air supply and exhaust systems. The fresh air of the air conditioner could be used with the air supply volume being not less than 6 times/h. The air return outlets of air conditioning systems and fan coil units must be equipped with filtration equipment with initial resistance of less than 50Pa, primary pass rate of microorganism less than 10% and primary pass rate of particulate matter less than 5%, such as air supply and return port with ultra-low resistance. Meanwhile consideration should be given to the needs of hospitals in case of non-epidemic situations. The air conditioning system should be designed with the function of return air heat recovery under the premise of ensuring safety, quickly carried out the conversion from normal time to emergency according to the needs of the epidemic situation, and achieved energy saving and sustainable operation under the condition of meeting the use needs of the epidemic situation and epidemic situation of the hospital.

7. Conclusion

COVID-19 emergency hospital was different from conventional general hospital, its indoor and outdoor environment needed to be designed and controlled around the following points: site design and building layout, indoor and external design of ventilation system, and purification, disinfection and ventilation system control. The ground and general layout design, building layout and planning zoning, ward air conditioning system design, supply and exhaust air distribution, supply and exhaust fan setting, outdoor fresh air outlet and exhaust outlet layout are all related to the design, which are the key contents to be considered in the design; Purification and disinfection, hospital infection control and management measures, operation control of ventilation system, which are related to practical operation, belonging to the scope of operation management and control.

Based on the design of the Wuhan Huoshenshan Hospital, combined with the current standards, specifications, and comparing the related research results at home and abroad, it summarized the following main design methods and main technical points: ventilation and air conditioning system settings, ventilation rate of ward and different regional pressure gradient control measures, air distribution of upper and lower returns, outlet filter set mode, inlet and outlet setting distance, etc. In addition, the proportions of different types of wards determined in the design process have been proved to be able to meet the medical treatment needs of COVID-19. The above results could be used as reference for similar engineering design.

Author contributions

Yan-Hua Chen: Conceptualization, Methodology, Project administration, Resources, Writing-review and editing.
Jianping Lei: Methodology, Resources, Validation.
Jun Li: Methodology, Writing-review and editing.
Zaipeng Zhang: Data curation and Verification.
Zhongyi Yu: Investigation, Writing-review and editing.
Chenqiu Du: Writing-review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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