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Air-source heat pump heating based water vapor compression for localized steam sterilization applications during the COVID-19 pandemic

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ABSTRACT

Sterilization is of great importance to prevent the spread and resurgence of the COVID-19, yet sterilization methods are all energy intensive in general. Steam sterilization is easily maintained and can be applied in various scenarios with less residual pollution. However, the current steam generator (so called boiler) has brought many energy and environmental concerns. With the investigation on steam sterilization’s features, this study proposed a clean and flexible steam generation system with the air source heat pump and water vapor compressor, and the system can be further simplified through the combination with district heating pipeline. The critical design parameters and simulated performance of the system are evaluated and optimized through a MATLAB simulation, and a prototype was built with experimental performance assessing. The results show the system has an average boiler efficiency of over 170% when the ambient temperature varies from 5 °C to 35 °C and the temperature of outlet steam is above 110 °C, and has the best economic performance when the operating period is above 3 years. Furthermore, the air-source heat pump boiler system is proved to effectively respond to the surging sterilization demands during the peaks of the COVID-19 pandemic and is well consistent with the UN Sustainable Development Goals.

1. Introduction

The COVID-19 has brought severe challenges to all aspects of society and global development [1,2], and the second wave of COVID-19 has already occurs in some regions [3] and could be even worse according to some predictions [4]. It has been found that coronavirus could be infectious on inanimate surfaces for up to 9 days [5]. Therefore, daily sterilization in public places is essential to prevent the spread of the virus [6] and the resurgence in contagion [7]. In addition, a large volume of medical waste is produced that poses a significant risk to medical staff, patients and the public [8]. This medical waste must be cleaned and sterilized to prevent further spread of the virus.

The existing sterilization methods can be mainly divided into incineration treatment, chemical treatment and thermal treatment [9]. The detailed advantages and limitations are summarized in Supplementary Note 1. Compared to disinfectant [10] and infrared, high-temperature steam can evenly dissipate heat with lower secondary pollution (over-dose of ozone and other disinfectants are easy to cause secondary pollution) [11]. It was also found that the face mask sterilized by high-temperature steam can achieve similar performance to the new face mask [11]. For textiles sterilization, high-temperature steam circulation is officially specially appointed [13] and will be in high demand for hospitals, apartments, hotels and other public places [14]. Meanwhile, during the outbreak stage of the epidemic, chemical sterilization material is often in short supply while the amount of waste is large. In that case, the easily maintained high-temperature steam sterilization is considered almost the only choice [11].

However, the existing fossil-based steam generators have a negative impact on the local environment [15] and are faced with increasingly severe restrictions [16]. Meanwhile, they are extremely dependent on the supply of fossil fuels, resulting in a weak response to emergency situations.

Utilizing solar heat or electricity to generate steam is more environmentally friendly and convenient [17,18]. Recently, Lin Zhao et al. proposed a passive high-temperature steam generator for medical sterilization with a successful sterilization cycle [19], yet this technology needs further verification. Meanwhile, solar energy is unavailable on cloudy days and nights. Electricity is more stable and flexible for steam generation such as the electric boiler, but electricity is secondary energy and thus makes the operation cost of electric boilers higher than fossil fuel-fired boilers. Heat pump is considered to be a more efficient and
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Nomenclature

Symbols

- $Q$: heating capacity (kW)
- $P$: power consumption (kW)
- $W$: energy consumption (kW)
- $h$: specific enthalpy (kJ kg$^{-1}$)
- $m$: mass flow rate (kg s$^{-1}$)

Abbreviations

- evap: evaporator side
- cond: condenser side
- $L$: low stage of cascade cycle
- $H$: high stage of cascade cycle
- $r$: refrigerant
- DH: district heating
- WVC: water vapor compressor
- $is$: isentropic
- $i$: inlet

2. Description and evaluation of the steam sterilization process

In essence, steam is an excellent heat carrier with a huge latent heat released in the sterilization process and then condenses into water. With the increasing demand for steam sterilization, it is necessary to analyze the application status and potential of steam sterilization.

2.1. Treatment of steam sterilization

In fact, the COVID-19 will be inactivated after the treatment at 56 °C for 30 min [29]. Therefore, the water vapor above 100 °C will have the indubitable sterilization effect if the interaction time is long enough. However, there is an enormous variation in materials and other requirements, which results in the difference of steam disinfection processes. The following table summarizes the common steam sterilization process (see Table 1).

To summarize, there are a few noteworthy features for the steam sterilization:

(1) For saturated steam, there is a one-to-one relationship between the temperature and pressure value. In general, the processing time can be further shortened with the treated temperature increasing. However, excessive sterilization temperature may also cause damage to the material.

(2) The superheated steam sterilization is suitable for the some specific sterilization process such as the production of traditional Chinese medicine [41]. It is also found that the steam quality has a great influence on the germicidal efficacy [42], and it is

| Usage       | Treatment | Supplementary notes               |
|-------------|-----------|-----------------------------------|
| Medical waste | 134 °C, temperature fluctuation $<$ 3 °C [30] | The treatment for 30min is enough, and even 15–20min is effective. For the most unfavorable situation, treatment time at 134 °C should not be less than 45min [32] |
|             | 120 °C(90min) for hazardous waste [31] | Combined with microwave technique, the steam temperature could be low to 93 °C [9] |
|             | 121 °C(15min) [12] | The mask will deform and become sticky when it is treated at 134 °C [34]. Indirect heat exchange is suggested to avoid the reaction between the fiber and condensate water [33]. |
|             | 65 °C(30min) [34] | For items direct contact with human body, steam has absolute advantages over chemical disinfectant [37]. |
| Mask        | $< 100$ °C (10min) [33] | 8 cycles in push-pull mode (0.2 ± 0.02 m/s) can reach 99% sterilization rate [40]. |
| Textiles    | > 100 °C, circulating steam for 15min [13,36] | For items direct contact with human body, steam has absolute advantages over chemical disinfectant [37]. |
| Tableware   | > 100 °C, circulating steam for 15min [38] | |
| Public area | > 100 °C, steam [39] | |
necessary to control all links of the steam flow, such as steam source [43] and steam transmission pipeline. In order to prevent the steam from condensing in the pipeline, the generated steam should have a certain superheated degree.

Based on the above considerations, the steam generator for sterilization should be of flexible regulation on the output temperature.

2.2. The capacity and potential of steam sterilization

The treatments of steam sterilization vary in different application scenarios. For example, the medical waste sterilization is usually carried out through a sterilization pot, and the steam consumption is closely related to the number, volume, filling in the sterilization pot and the enthalpy difference before and after the sterilization steam. Another problem worthy of discussion is the capacity required by steam sterilization and the corresponding potential value. According to different usages, Table 2 summarizes the corresponding capacity and potential of steam sterilization methods.

Herein, the typical steam demands for different usages are investigated. Based on that, the energy consumption is estimated for different usages. In conclusion, in terms of the potential of steam sterilization, the most noteworthy parts are as follows:

(1) Recovery value of steam sterilization on mask: It takes up to 0.0342 kWh for the production of a mask [49] with 0.06 kg CO₂ emission. More crucially, there is a supply shortage of melt-brown [50], which is the core material of the mask. And the shortage could be mitigated with the recovery of mask, let alone the energy-saving and environmental protection potential.

(2) Emergency plan of steam sterilization in hospital: High temperature steam is used as a heat source for disinfection, cooking, washing, ironing, drying, boiling water, hot water and distilled water, whose supply cannot be interrupted to maintain the medical service. In China, there are more than 2500 tertiary hospitals [51], each of which can accommodate at least 500 people, with a ward area of more than 3000 m² [52].

(3) Steam disinfection in public areas and other items: At present, steam sterilization for such application scenarios is usually carried out by small-sized equipment such as steam mops and steam sterilization cabinets. However, it is more advantageous to use larger capacity boilers for sterilization especially in large public buildings such as airports or hotels.

3. Distributed steam generation

Based on the above analysis, it is apparent that ensuring an efficient and environmental-friendly steam supply during the pandemic is of great significance. Therefore, two electricity-based methods for distributed steam generation are proposed and discussed, which both are through water vapor compressor.

3.1. Air source heat pump boiler for steam generation

Fig. 1 sketches the air-source heat pump boiler (ASHPB) that can extract heat from the ambient air and generate high-temperature water vapor for various sterilization demands. The boiler system is mainly composed of an air source heat pump and a water vapor compressor, which are connected by a flash tank [28]. The operating parameters of a specified model of air-source heat pump boiler, with detailed introduction in Supplementary Note 2 (see Table 3).

3.1.1. Air-source heat pump boiler system prototype and its experimental performance

Through theoretical simulation and data sorting, the ambient temperature, intermediate temperature and flash temperature can affect the performance of ASHPB. Fig. 2 illustrates the synthetically impact of those interfering factors on ASHPB. As is shown in Fig. 2, the ambient temperature has the most remarkable influence on the boiler efficiency of ASHPB. Distinct planes stratification has been formed in the boiler efficiency according to the difference of ambient temperature. Under conditions with constant intermediate and flash temperatures, boiler efficiency increases as the ambient temperature increases. When the flash and intermediate temperatures increase, the boiler efficiency increases up to a certain point, after which it decreases. Consequently, an optimum temperature zone exists for each ambient temperature.

For an ambient temperature of 15 °C, as is shown in Fig. 3, the flash temperature and intermediate temperature have made the boiler efficiency into a convex plane and there exists an optimal region where boiler efficiency is above 1.7.

From Fig. 4 we could see that with a flash temperature above 90 °C, the boiler efficiency hardly exceeds 1.74, which indicates the flash temperature should not be too high, otherwise it will bring a decrease in the COP value of the cascade heat pump.

The intermediate temperature, which reflects the internal conditions of the cascade heat pump, also has a significant impact on the overall efficiency of the system and should be well controlled. In a particular region as is shown in Fig. 4, the boiler efficiency is always above 1.74. Therefore, the design parameters of the air-source heat pump boiler should be carefully combined with the local ambient temperature conditions to optimize the performance of the equipment. Fig. 5 further shows the annual temperature distribution in some typical cities of China, and it can be seen that the heat source condition above 15 °C occupies the majority in these cities, which further implies the ASHPB.

### Table 2

| Usage                | Capacity | Potential |
|----------------------|----------|-----------|
| Medical waste        | For a typical 4.46 m³ double-layer sterilization pot, a 0.5 t h⁻¹ boiler can well satisfy its steam demand in the light of feedback based on practical application [46]. In that case, according to the density of medical waste about 100 kg m⁻³ [46], the 0.5 t h⁻¹ steam generator can sterilize 446 kg medical waste at each turn. | There are adequate disinfection centers to deal with the daily medical waste load. However, at the beginning of the outbreak, the medical waste tends to multiply in amount. Even in mega-cities such as Wuhan, medical waste increased from the normal level of 40 t/d to 240 t/d [2] and thus continuous operating 10 t/h boiler is needed to make up the difference. |
| Mask                 | The sterilization effect of steam disinfection on masks has been verified [33,35]. However, most of the current tests are carried out in the laboratory and the specific amount of steam and the number of disinfection cycles need to be further determined. | WHO and UNICEF recommend that adolescents aged 12 and above wear masks [46]. As a result, the demand and energy consumption of masks will be greatly increased, as shown below: Mask demand 129 G/ month, Energy 4.6 PJ/consumption month |
| Textiles Tableware   | The disinfection of textiles or tableware is commonly carried out in steam disinfection cabinets as follows: 8 kWh – 900L – 500Sets (1 bowl, 1 cup, 1 spoon, 1 chopsticks) [47] | |
| Public area          | For the ground, desktop and other surface disinfection, the relationship between the small steam sterilization mop and the sterilization area is estimated as follows: 1850W/100m² [48]. Based on this energy consumption, a 0.5 t/h boiler could be used for the disinfection of about 190 households (0.5 t/h boiler: 350kW – 1.9 × 10⁴ m²) and public area, e.g. supermarkets, schools and public transportation. | |
has wide regional adaptability.

### 3.1.2. Air-source heat pump boiler system prototype and its experimental performance

Through theoretical analysis, the ASHPB has shown wide regional adaptability with high efficiency. Therefore, an ASHPB prototype was further built and tested for the brewing industry. As is shown in Fig. 6, the prototype is mainly equipped with three cascade heat pump water heaters, a flash tank, a water vapor compressor and a water purified system. The three cascade heat pump water heaters are in parallel connection for water heating, each with heating capacity of 58.5 kW under the rated working condition (Ambient temperature: 12 °C; Outlet water temperature: 85 °C), and the cascade heat pump adopted R404A and R245fa mixture as refrigerants for LTC and HTC. And the measurement method is provided in Supplementary Note 1.

Furthermore, a twin-screw compressor is adopted with variable speed for flexible output, which can supply steam up to 0.5 t/h. For brewing industry, the outlet steam temperature is around 110 °C, while the pressure is about 0.12 MPa and the mass flow rate is about 0.2 t/h. Under these boundary conditions, Fig. 7 further illustrates the theoretical and experimental boiler efficiency of the ASHPB. The solid line is the theoretical boiler obtained by the simulation model, while the two dotted lines are 105% and 95% of the theoretical boiler efficiency. The red-cross scatters show the experimental data selected from the average value with stable output over 30 min according to the official standard of boiler efficiency [53]. It can be seen that the experimental results are in good agreement with the theoretical calculation with a deviation of less than 5%. The average boiler efficiency of the ASHPB is more than 180% at ambient air temperature 15 °C and it can reach over 165% when ambient air is at 7 °C.

![Schematic diagram of the air-source heat pump boiler for steam sterilization.](image1)

**Fig. 1.** Schematic diagram of the air-source heat pump boiler for steam sterilization.

![Boiler efficiency of air-source heat pump boiler under different ambient temperature, intermediate temperature and flash temperature.](image2)

**Fig. 2.** Boiler efficiency of air-source heat pump boiler under different ambient temperature, intermediate temperature and flash temperature.

### Table 3

| The operating parameters of the air-source heat pump boiler. | Descriptions and Corresponding value |
| --- | --- |
| **Operating parameters** | **Descriptions and Corresponding value** |
| Cascade heat pump water heater | LTC: Refrigerant: R404A | HTC: Refrigerant: R245fa |
| Superheated degree: | 5 °C | 5 °C |
| Sub-cooling degree: | 5 °C | 5 °C |
| Flash tank | The vessel pressure is set as saturation vapor pressure (mainly 0.0578 Mpa, correspondingly the saturated temperature is 85 °C). | The flash temperature difference is set as 5 °C. |
| Water vapor compressor | Twin-screw compressor; variable speed |
| The ambient temperature | The ambient temperature varies from 5 °C to 35 °C |
| Temperature difference in the heat transfer process | Air side to the evaporator: 15 °C; water side to the condenser: 5 °C |
| In Cascade heat exchanger: 5 °C |
| The temperature of outlet steam | Saturated water vapor; Temperature: 120 °C; Pressure: 0.198 MPa |
| The steam generation rate | Set as 0.5 t h⁻¹ (500 kg h⁻¹) for efficiency evaluation |
Temperature can be seamlessly adjusted from 120°C to over 160°C to satisfy various temperature demands.

3.2. Water vapor compressor combined with the existing heating network

The hot water pipe network can transport heat to distributed urban area for long distance, which is so called district heating (DH) and has already become one of domestic heating way in many countries [54]. The heat source of district heating is usually large-scale and even with the recovery of waste heat, which makes its cost relatively lower. Previous research has studied industrial heat pump for steam generation with district heating as a heat source [55]. In fact, the system could be further simplified and the high-temperature steam can be generated through the combination of the existing hot water network and water vapor compressor as Fig. 8 shows.

According to the investigation, the inlet temperature of district heating can reach 80–100°C [56,57], which could be directly used for flash evaporation. Therefore, with a flash tank and a water vapor temperature can be seamlessly adjusted from 120°C to over 160°C to satisfy various temperature demands.

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4. Perspective of the localized steam generation methods

4.1. The economic analysis the ASHPB and WVC combined with DH for steam generation

Compared to the experimental performance, the economic performance of steam generator has a greater impact on customers’ willingness and thus its application potential [58]. Therefore, a comparison work on the two proposed steam generation methods and other two typical boilers (the electric boiler and the gas-fired boiler) is carried out. Table 4 shows the working and operating conditions on ASHPB, DH combined with WVC the electric boiler and the gas-fired boiler. In terms of efficiency and the corresponding operation cost, the steam generation methods based on air-source heat pump and water vapor compressor have obvious advantages. Using 0.5 t h⁻¹ as design capacity and 6000 h as annual operating time, due to relatively higher boiler efficiency, the ASHPB has the lowest operation cost.

Fig. 9 shows the change of total operating expenses of those steam generation methods with the increase of the operating period. The ASHPB has the highest initial expense followed by DH with WVC. With the lowest operating cost per year, in the 1st year, the total operating expenses of electric boiler exceeds that of ASHPB. In the 4nd year, the total operating expenses of the gas-fired boiler exceeds that of ASHPB. In the following operating period, ASHPB has the lowest total operating expenses and shows significant economic benefit, which can save CNY5, 750,000 compared to the electric boiler and CNY 1,145,000 compared to the gas-fired boiler. Additionally, the total operating expenses of DH combined with WVC is the lowest in the 3rd year and exceed that of ASHPB in the 7th year, but is still lower than that of gas-fired boiler and electric boiler. Therefore, for users with access to hot water pipeline and less budget, this method is a more suitable one for steam generation.

4.2. The application outlook of the ASHPB for steam sterilization

Except the advantages in economy (e.g. lower 10-year total operating cost), the air-source heat pump boiler is also a suitable technology for surging sterilization demands and other steam demands. During the outbreak stage of COVID-19, the daily output of medical waste in Wuhan sharply from about 40 tons to 247 tons and far exceeded the original medical waste disposal capacity of about 50 tons per day [61]. In addition, the prices of disinfectants and masks have increased to more than 10 times the prices before the pandemic but were still un-available [62,63]. Material shortages and inadequate sterilization capacity will not only bring great risks to the medical staff but also endanger the health and safety of the community. In such cases, ramping up of steam sterilization capacity through heat pump could make a significant difference, because of its quick uptake speed, high flexibility and the relatively stable supply of water and electricity, which are the only two elements that are needed for ASHPB operation.

There is also a concern that the sterilization facilities may lie idle after the pandemic due to a surplus in treatment capacity [2]. In addition, the heat pump sterilization facilities that are adopted during COVID-19 can play a continuous role during the post-COVID green recovery and long-term net-zero energy transition. On one side, high-temperature steam (water vapor) is a widely used heat vector that will play a continuous role in industrial production shown as Fig. 11. Such concept of combining the ambient heat and electricity for high-temperature steam generation in ASHPB is well consistent with the UN Sustainable Development Goals [64] which is more important during the post-COVID green recovery and long-term net-zero energy transition as described in Supplementary Note 4.
5. Conclusions

In this paper, the features and potential of steam sterilization are investigated and evaluated. Based on that, a clean and flexible steam generation system with the air source heat pump and water vapor compressor is proposed for steam sterilization, and the system can be further simplified through the combination with district heating pipeline. The air-source heat pump boiler has been studied by theoretical and experimental analysis. Through the analysis in the paper, the following conclusions can be concluded.

i. Steam sterilization has specific advantages and more extensive application possibilities.
ii. In terms of application performance, the ASHPB has a higher boiler efficiency (174% at 15 °C ambient temperature for 110 °C steam generation), and can meet most sterilization demand.
iii. In terms of economic performance, yet the ASHPB has a relatively higher initial expense, it will has the best economic performance when the operating period is above 3 years.
iv. For public health emergencies like COVID-19, the ASHPB can quickly respond to the surging sterilization demands due to its quick uptake speed, high flexibility and the relatively stable supply of water and electricity.

Credit author statement

Ruzhu Wang: Supervision, Conceptualization, Writing-Reviewing and Editing. Hongzhi Yan: Software, Validation Data curation, Writing- Original draft preparation. Bin Hu: Visualization, Investigation. Validation.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2021.111026.

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