Scientific and Technological Progress and Future Perspectives of the Solar Assisted Heat Pump (SAHP) System

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Abstract

Among all available solar technologies, solar-assisted heat pump (SAHP) is the most popular technology for low- and medium- temperature applications, i.e., drying, space heating, and water heating. This paper presents a critical review of the SAHP, leading to identification of the key technological challenges with the current SAHP technology, including (1) poor energy performance at low ambient temperatures; (2) difficulty in coupling solar thermal panels with heat pumps to achieve increased operational time and reduced electrical energy usage; (3) mismatch between heat demand of the building and heat supply of the SAHP system; and (4) lack of multi-functional modelling tool. A recently developed SAHP technology is introduced, which can effectively tackle the challenges with the current SAHPs, thus achieving enhanced solar efficiency, improved heat pump energy efficiency, and fast responsive time to the heat demand of buildings. The future research directions of the SAHP were identified: (1) multi-source heat pump; (2) heat pump defrosting capacity using waste heat and renewable energy; (3) advanced heat storage and exchange unit (HSEU) technology; and (4) advanced machine learning and multi-objective evolutionary optimisation models for performance prediction and optimisation of the SAHP using big datasets.

Keywords: Solar-assisted heat pump; Solar efficiency, Coefficient of Performance, Heat storage and exchanging unit, Multi-source heat pump; Machine Learning.

1 Introduction

Solar heating systems have been widely used to provide the domestic hot water owing to their simple structure, low cost, stable operation, and effective solar energy collection. However, their application in space heating is largely limited by the mismatch between the energy supply and energy demand, on daily and seasonal basis. On the other hand, a heat pump, by using the grid electricity and a frequently available low-grade heat source, can provide a stable and steady heat supply to buildings and infrastructures. Combining solar thermal panels with heat pumps can overcome the challenges associated with stand-alone solar heating systems (i.e., mismatch between heat supply and demand) and stand-alone heat pump systems (i.e., long operational time, low energy efficiency and high electricity bills), thus enabling an energy efficient, stable, reliable and cost-effective heating for buildings and infrastructures. Such systems, namely SAHP, have gained great attention globally and associated research, developments and applications have been fast progressing over the past decades.

In the UK, the government declared that fossil fuel heating will be banned in all new built homes after 2025. Similarly, EU requires the developers to implement heat pumps or solar heating systems for domestic hot water production from 2027 [1]. China has committed to achieve carbon neutral by 2060; the important measures are to promote the use of renewable energy and reduce the use of fossil fuels, especially coal [2]. In the U.S., federal and state governments have established numerous policies to promote clean energy [3]. In Russia, the Energy Strategy to 2030 stipulates that the share of renewables must remain at least 4.5 per cent in the period from 2020 to 2030, generating 80-100 billion kilowatt-hours per year [4]. In Brazil, The Ten-year energy expansion plans (PDEE) aims for renewable energy to account for 42.5% of the country's total primary energy supply by 2023 up from 42.1% in 2014 which are the basis for ordinary power capacity auctions [5]. Japan aims to cut its greenhouse gas emissions by 26% from 2013 levels by 2030, but its environment ministry warned in July the electricity industry, which accounts for 40% of its CO_2 emissions, will miss its 2030 reduction target [6]. Among all these initiatives, SAHP is identified as a key technology that can help these countries to fulfil their commitments.

The increasing interest in the SAHP and the rising number of research and industrial projects in recent years have created a substantial need to identify best practices for further development of the technology. This paper presents a critical review of the current scientific and technological advances in SAHP, introduces a specific SAHP system that can achieve the enhanced solar efficiency, improved heat pump energy efficiency, and fast responsive time to buildings' heating demand, and discusses the future perspectives in the SAHP development. The results will help accelerate the development of new SAHP technology, and consequently contribute to significant reductions in fossil fuel consumption, fast implementation of solar energy technologies, significant reduction in carbon emissions, and accelerated sustainable developments globally.

2. Technological challenges associated with the SAHP and related research actions

The major components of a SAHP system are the solar thermal panel module, the heat pump module, and the heat storage & exchanger module. The different manners of combination among these modules lead to different types of SAHP systems [7]. Generally, the SAHP systems could be broadly classified as the parallel, series and combined types, as shown in Figs.1-4. When coupled in series, the captured heat energy is fed into the evaporator of the heat pump by working fluid. Then, the evaporator receives this energy from the working fluid, and the temperature of the working fluid is reduced as a result of this cycle. Systems in series could be installed in a direct expansion (Fig.2) or indirect expansion (Fig.3) configuration. By integrating the parallel and the series systems together, a dual-source SAHP system (Fig.4) is proposed. The dual-source SAHP system is a combination of the parallel SAHP system and the series SAHP system. The system can be in operation in three modes: 1. solar energy directly supplying mode; 2. heat pump energy directly supplying mode; 3. solar-assisted heat pump energy supplying mode. Although the scientific and technological advances in SAHP have been well progressed [8], a few critical challenges and gaps still remain, which will be introduced as follows.

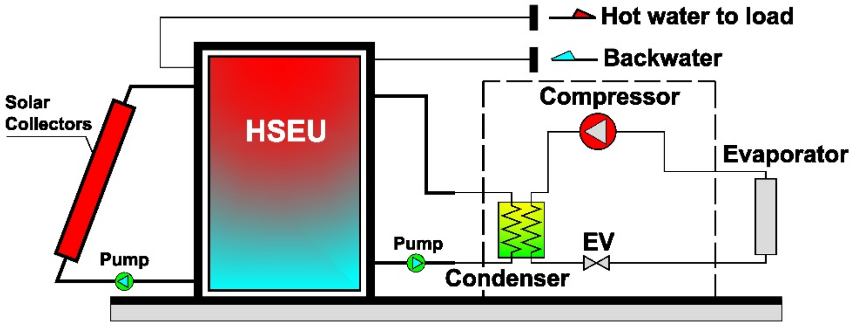


Fig. 1. Schematic of a parallel SAHP system

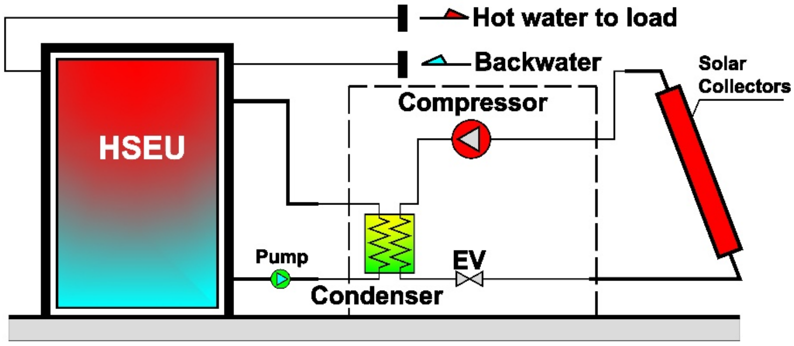


Fig. 2. Schematic of a series direct expansion SAHP system

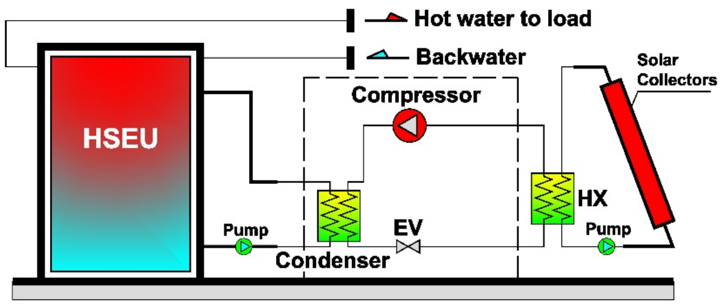


Fig. 3. Schematic of a series indirect expansion SAHP system

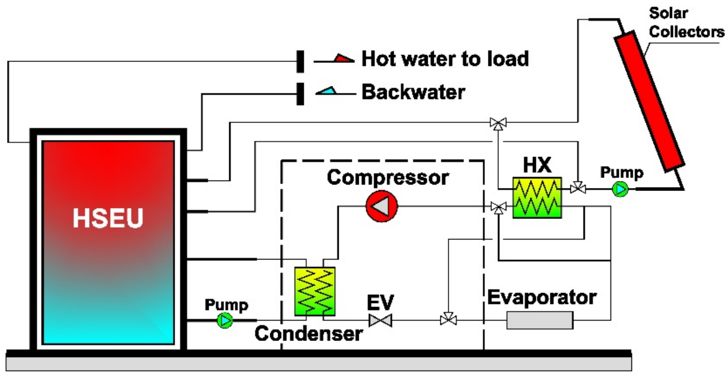


Fig. 4. Schematic of a combined SAHP system

The results of the investigations [9–13] showed that there is a limit of solar irradiation on the collector field, above which is better to work in parallel mode and below which is better to work in series mode. This irradiation limit depends on the characteristic performance curves of the solar collector and of the heat pump, as well as on the temperature conditions of the heat sources and sinks. This can be used as a criterion for switching between parallel and series operation mode [14]. In spite of the solar radiation, the direct expansion SAHP systems cannot be used in large scale system because the increasing area and number of solar evaporators will cause the reduction of the system leakproof, thus leading to the leakage of the refrigerant.

2.1 Poor energy performance at low ambient temperature

When operating at a lower evaporating temperature, a SAHP system cannot perform as well as it does in the moderate climates. Owing to the lower thermal efficiency of the solar thermal panels and lower COP of the heat pump [15] at cold weather conditions, the energy efficiency of the SAHP will be significantly lower [16], accompanied by a number of associated problems including the reduced volumetric efficiency, elevated compressor discharge temperature, increased compression ratio, reduced refrigerant mass flow rate and decreased operational efficiency [17]. Furthermore, the performance of the heat pump will be affected by the frosting of the evaporator which, by blocking the surface of the evaporator, will significantly reduce the heat capacity [18] and COP of the heat pump [19].

It was found that the defrost penalty results in a reduction of heat pump energy efficiency by approximately 40%, leading to a degradation in heating capacity reduction by 43% [20]. Zhang et al investigated a heat pump for the space heating of buildings in Harbin, the coldest provincial capital city in China. The results showed that the coefficient of performance (COP) was only 1.04 to 1.89 under the conditions of −20.9 to −16.6°C outdoor temperature and 19.8 to 22.5°C indoor temperature [21]. Several studies were carried out to mitigate the impact of defrosting to the performance of the heat pump, including using CO_2 cycle [22], auxiliary boiler[23], finned-tube solar collector/evaporator [24], micro-channel heat transfer technology [25], PCM [26], and vapour injection cycle [27,28].

The heat pump performance at low ambient temperature may be also improved by suitable modifications in the exiting compression cycles. The single stage compression systems become less efficient with loss of capacity under extreme conditions [29]. To overcome these limitations, multi-stage or hybrid compression cycles were proposed by many researchers; these include multi-stage compression cycles [30], cascade cycles [31], ejector assisted compression cycles [32], auto-cascade cycles [33], trans-critical cycles [34], and organic Rankine cycles [35]. Beside, comparison between the heat pumps with variable and constant speed (VS & CS) compressors was undertaken [36], showing that the system using VS compressor is not always cost-effective [37], but is more profitable for a colder climate application.

To summarise, although the performance of SAHP has been improved through dedicated research and industrial developments, there are many challenges in existence under cold weather operational conditions. As a result, the solution to improve the performance of the SAHP at lower temperature condition should be extensively investigated.

2.2 Difficulty in coupling solar collectors with a heat pump to achieve increased solar system operational time and reduced electrical energy usage

The series connection between the solar thermal panels array and a heat pump keeps the heat pump in constant operation, leading to large carbon footprint, significant electrical energy use and an energy inefficient operation [38]. However, owing to the fluctuation of solar radiation throughout a day and its unavailability during the evening and night, the SAHP may have a low efficiency without proper control strategy.

To enhance the stability and performance of a SAHP system, substantial research works have been proposed; these include: (1) optimisation of the structure of the solar thermal panels and evaporator [39–41]; (2) determination of the geometrical sizes and capacity of the SAHP system [42]; (3) selection of adequate refrigerant [43,44]; (4) development of the control strategy for inverter compressor and electronic expansion valve [45–47]; (5) adoption of the cascade structure for the high temperature requirement [30]; and (6) enhancement of the utilisation rate of air source energy. In particular, multi-source SAHP systems have been proposed as a new development that can further improve the stability and performance of the SAHP system [48]. It was concluded that the multi-source SAHP can improve the performance considerably by utilising a composite evaporator [49].

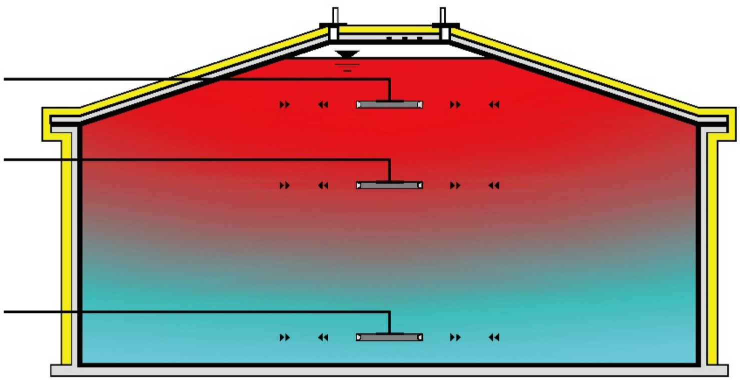
Phase change materials (PCM) could enable creating a balance between the heat supply from the solar thermal panels and heat demand, thus extending the service time of solar system and shortening the operational time of the heat pump [50]. By embedded inside the collectors, PCMs provided a higher operating temperature than the ambient for the solar system and can ease the problem of freezing in cold winter [51]. Recently, several studies were undertaken to investigate the potential contribution of submerging PCMs within hot water storage tanks for various applications, such as individual/collective hot water production [52,53]. However, PCMs have an inherent disadvantage of low thermal conductivity. To overcome this difficulty, several approaches for enhancing the performance of the PCMs were tried. These include: (1) inclusion of the metal fins to increase the heat transfer rate of the PCMs within the heat storage and exchange unit (HSEU) [54], (2) development and implementation of the better performing PCMs e.g. carbon cloths [55], shape stabilised PCMs with graphite [56], microencapsulated-PCM slurries [57] and direct contact latent heat storage systems [58], (3) mixing the porous aluminium gradients with the PCM [59], (4) integrating the compressed expanding natural graphite (CENG) with PCM [60], (5) creating the rectangular cavities that are filled with paraffin [61], and (6) adding fins into the PCM block [62]. Apart from the PCM application, implementation of porous blocks can also increase the heat transfer capacity of the solar collectors due to the improved thermal mix [63].

2.3 Mismatch between heat demand of the building and heat supply of the SAHP

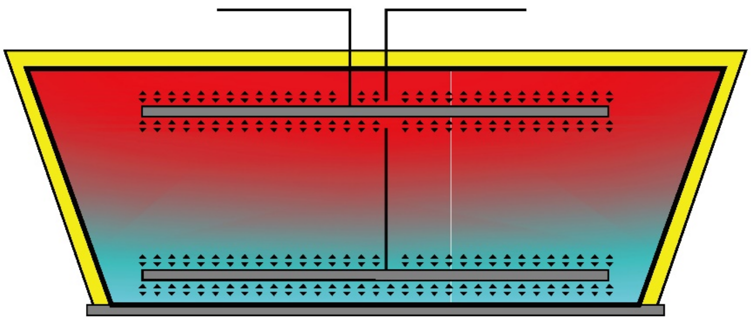
It is known that solar radiation is higher during the summer and low during the winter, and its level is in fluctuation on the daily, weekly, and seasonally basis [64]. In respect to the daily solar radiation variations, the solar energy may be in surplus during the daytime but become unavailable and insufficient during the afternoon, evening and night. On the other hand, a heat pump presents a better performance at a higher temperature operational condition. At a lower temperature (e.g. during the night) operational condition, the heat pump not only presents a reduced energy efficiency but also incurs the defrosting operation which consumes significant amount of electrical energy. In contrast with the poor performance of the solar thermal panels and heat pump during lower temperature operational period (e.g. winter nights), heat demand of the building at this period is significantly high. This creates a mismatch between the heat demand of the buildings and heat supply of the SAHP. Furthermore, the solar energy might be useless during the summer, leading to significant solar energy loss and reduced solar fraction. For a building at Beijing with average heating load of 12.44 kW, the solar fraction for space heating in December is only 0.27 despite of a large collector area of 45 m^2 [65].

Many studies have been conducted to handle the mismatch problem between the heat demand and heat supply. Introducing geothermal source into a SAHP system to form the solar assisted ground source heat pump (SAGSH) is a popular measure of dealing with the challenge [66]. The SAGSH, by feeding solar energy into the ground, can remove the thermal environment deterioration of soil and the temperature reduction of the ground, thus leading to the enhanced system efficiency and more stable system operational condition. A SAGSH system coupled with flat plate solar thermal panels was investigated through both the experimental and theoretical methods. The result shows that the SAGSH system has achieved a much higher COP compared to conventional GSHPs [67].

For the seasonal heat mismatch that leads to significant solar energy waste during summer [56], the seasonal heat storage is a solution. Overall, there are four types of seasonal heat storage technologies, i.e., the aquifer thermal energy storage (ATES), the borehole thermal energy storage (BTES), the tank thermal energy storage (TTES), and the pit thermal energy storage (PTES) [68]. These are shown schematically in Fig. 5. However, the high cost of the seasonal storage is a barrier that has prevented its wide application in engineering practice. The more affordable and effective seasonal storage technologies should be closely investigated.



(a)



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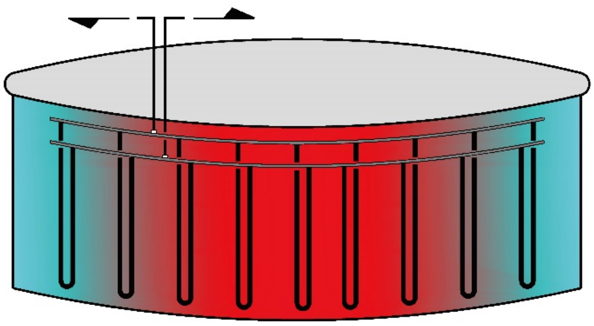

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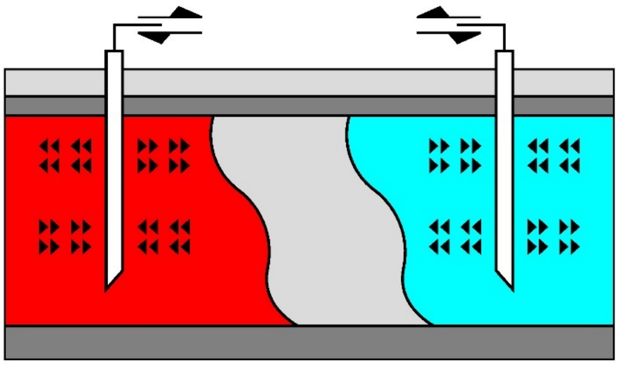

(d)

Fig. 5. Schematics of the long-term thermal storage: (a) TTES; (b) PTES; (c) BTES; (d) ATES;

2.4 Lack of the specialist multi-functional models for simulation, optimisation and performance prediction of the SAHP system

The SAHP system simulation and optimisation is an important research subject. The optimisation process of a SAHP system always use a dedicated simulation model. Many investigations have been conducted on the performance enhancement of SAHP systems by optimising the control strategy. The optimisation and design methods for different SAHP systems are not always same owing to the multiple impacting factors engaged. To tackle the challenge for optimisation and design of the various SAHP systems, a comprehensive and fully-inclusive design and optimisation tool for the SAHP systems is critically required.

Development of the numerical and analytical models to simulate the heat transfer process within each part of the system is the core task of the SAHP optimisation [69,70]. TRNSYS is currently applied to the SAHP simulation which can achieve the reasonable accuracy [71]. CFD is also a useful tool to simulate the performance of the SAHP and optimise its geometrical parameters and determine its operational conditions [72]. However, a multi-functional specialist simulation program able to simulate both the individual parts and integrated SAHP system, optimise their structural configuration and predict the future operational performance is still unavailable which requires immediate actions.

3. Latest development of the SAHP technologies

Some special function buildings can provide exhaust air with spare heat, such as some residential and office buildings with good air tightness, inner hot spring resorts and some industry buildings. The spare heat in the exhaust air of these kinds of buildings has full potential to improve the performance of air source heat pump systems. In order to tackle the challenges remaining with current SAHPs, i.e., low solar energy utilisation rate, poor energy performance at cold weather, high electrical energy use for defrosting, and mismatch between the heat demand and supply, a novel ventilation heat recovery SAHP system has recently been developed by the author as show in Fig. 6.

It comprises three major innovative parts: (1) a ventilation heat recovery heat pump employing double-stage evaporators and vapour injection compressor. It uses exhaust air from buildings and outdoor air as the heat sources and can minimise the ventilation heat loss and provide a unique defrosting approach by using the exhaust waste heat without additional power consumption. (2) a multiple-throughout-flow micro-channel solar thermal panels array. It has a lower pressure drop and heat loss than a conventional one-to-one-flow solar thermal panels array. (3) a fast-responsive heat storage & exchanger unit (HSEU). It is divided into two chambers and can quickly react to residents' demand on heating.

The prototype of the SAHP system is shown in Fig. 7, which is installed at the University of Hull. The heat pump has a heating capacity of 5-10 kW. There are 8 solar panels connected in a multiple-throughout-flow loop and each panel has an aperture area of about 2 m^2. The thermal storage tank has a volume of around 1,600 litres with two chambers.

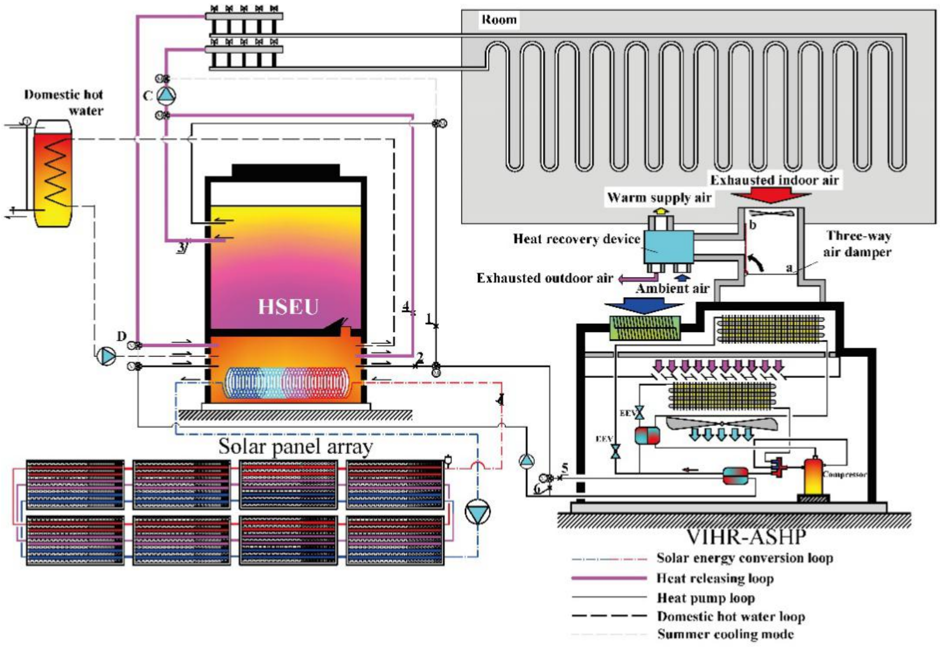

Fig. 6. Schematic of the novel SAHP system

Fig. 7. Prototype demonstration of the novel SAHP system

The heat pump is structurally renovated, as shown schematically in Fig. 8. It has a higher COP than convectional vapour injection heat pump (VIHP) and ASHP at given ambient temperatures, as shown in Fig. 9. Under the fixed parameters: (1) the exhaust air flow rate (1.0 kg/s), (2) the air flow rate of ambient air (6 kg/s), and (3) vapor injection temperature (5°C), the COP of the VIHR-HP ranges from 3.72 to 4.16 when the ambient temperature increases from -10°C to 0°C, and it is 3.34 to 3.88 for the VIHP and 3.02 to 3.61 for the ASHP. It is obvious that the innovative heat pump has a higher COP and the advantage is more remarkable at a lower ambient temperature.

The quick and efficient defrosting process is another prominent advantage of the proposed VIHR-HP. Frost on the evaporator surface can be removed quickly by using exhaust air from the building, during which the heat pump can be turned off and thus reduce the energy consumption of the compressor. A defrosting process carried out on the 16th of November 2019 is presented in this paper. The power capacity variation of the heat pump during the defrosting processes is shown in Fig. 10. The power capacity dropped to 0W during the defrosting process as the exhaust air extracted from the building was used to defrost the ice. The exhaust air is extracted by a ventilation system with high temperature and then sent to the heat pump evaporators directly to defrost the ice. After 4 mins of the defrosting process, the heat pump commenced operation and took 7 mins to get the working performance back to normal.

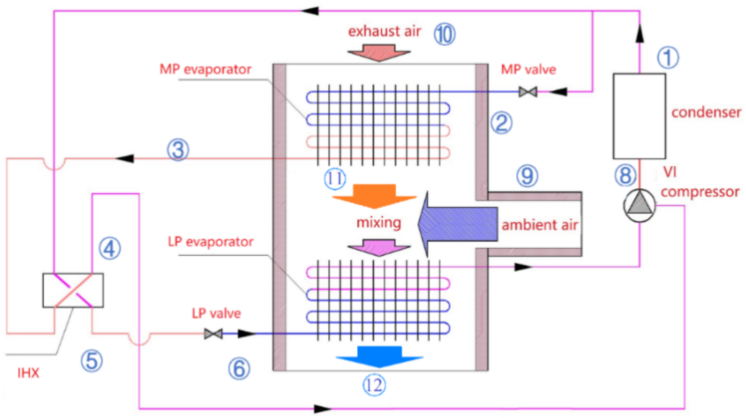

Fig. 8. Schematic of the novel vapour injection heat recovery heat pump (VIHR-HP)

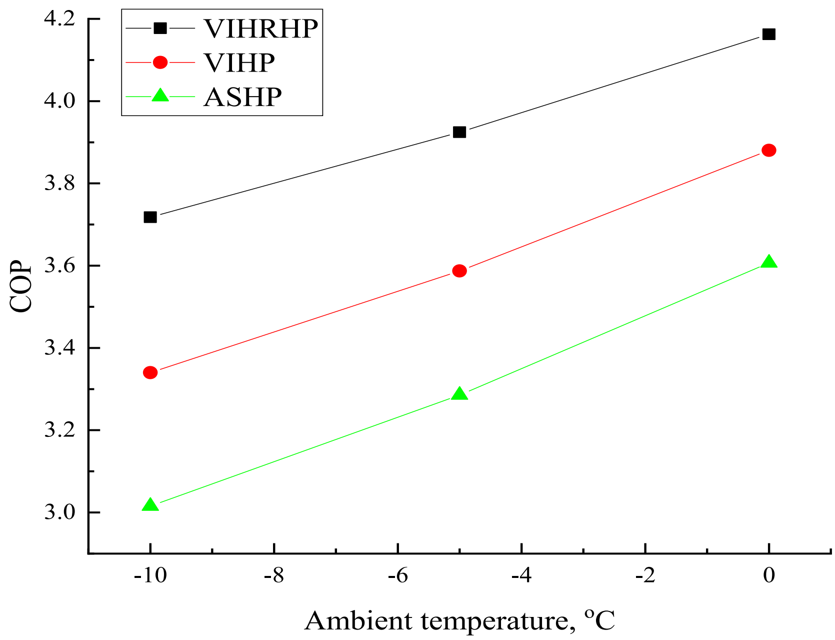

Fig. 9. COP variations with the ambient temperature for the VIHR-HP, conventional VIHP and ASHP [73]

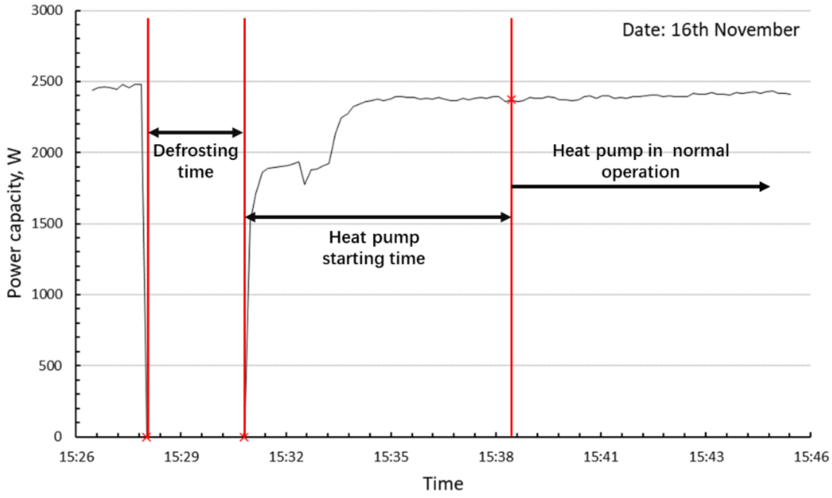

Fig. 10. Heat pump power capacity for the defrosting process

The solar thermal panels within the loop are constructed with several horizontal flow channels and multiple inlets and outlets, as shown in Fig. 11. This can reduce flow resistance owing to the significant reduction in the number of the fluid flow direction change. Besides, the natural convective heat transfer from absorber to glass cover is weakened because of the improved temperature distribution on the absorber. The performance of the multiple-throughout-flow solar array is displayed in Figs. 12 and 13. For an array with 8 panels, the multiple-throughout-flow mode can achieve 10.4% higher solar thermal efficiency compared to the one-to-one-connection mode (74% against 67%). The temperature of the panels at the rear of the array will be reduced from 33.4°C to 32.2°C, leading to the increase of its thermal efficiency by 14.5% (i.e., from 64.3% to 73.6%). Furthermore, the temperature difference between the head and rear panels of the array will be reduced by 84%, leading to the increased overall solar thermal efficiency by 10.4% (i.e., from 67% to 74%).

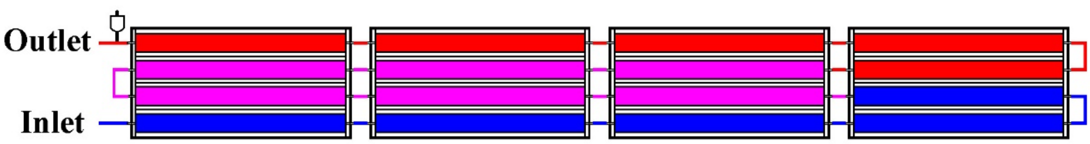

Fig. 11. Schematic of the multiple-throughout-flow solar panels array

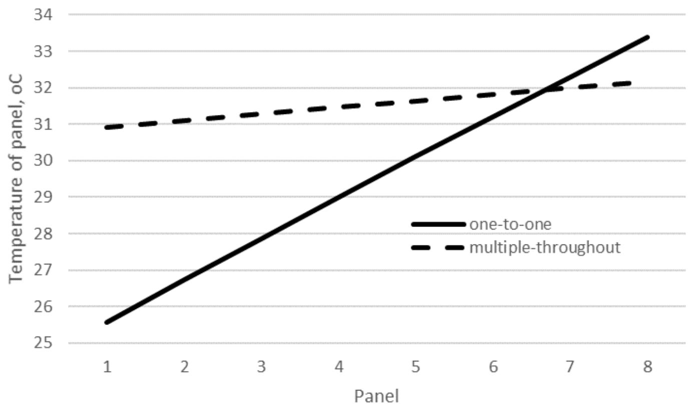

Fig. 12. Temperature variation of the fluid through the panels [74]

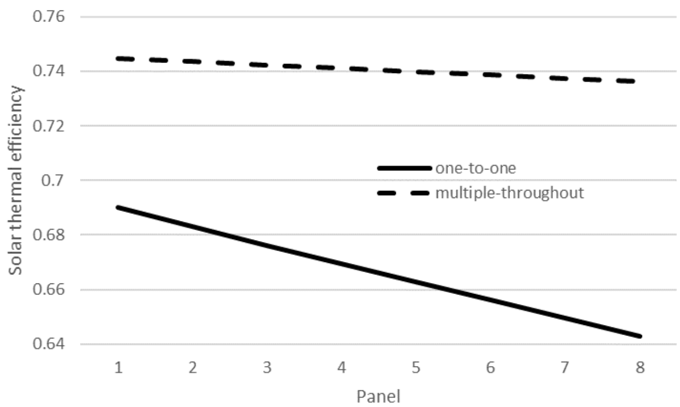

Fig. 13. Solar thermal efficiency variation through the panels [74]

Heat generated from the solar panels array will be first transported to a dedicate-designed fast-responsive heat storage & exchanger unit (HSEU). This HSEU, as shown schematically in Fig. 14, comprises a smaller-sized heat exchange tank (lower part of the unit) and a larger-sized heat storage tank (upper part of the unit). The heat exchanger tank, enabling heat transfer between the solar loop fluid and tank fluid connected to the heating loop, can quickly provide heat to a service building. It performs better than the conventional single storage tank, as shown in Fig. 15. A rapid water temperature escalation in the novel HSEU is achieved, giving a 35-minute time span for the temperature rise while the conventional HSEU has a time span of 175 minutes for a similar temperature rise. Such a fast response will mitigate the possible thermal discomfort of occupants and increase the marketability of the heat pump system.

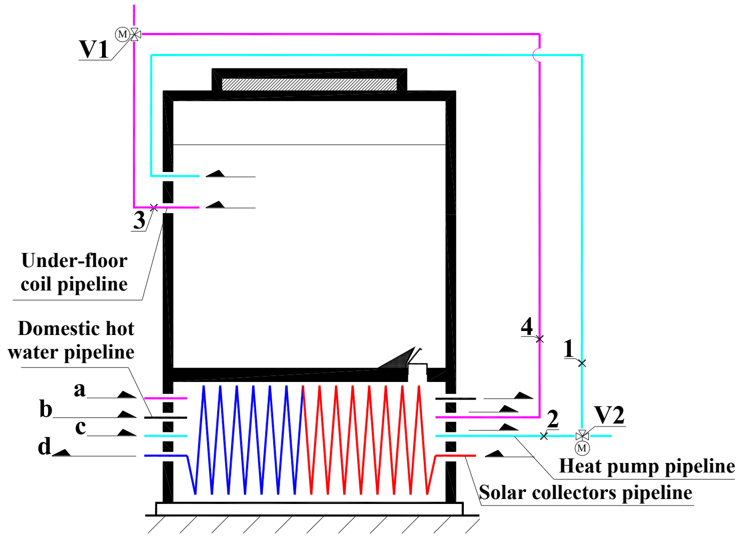

Fig. 14. Schematic of the novel fast-responsive HSEU

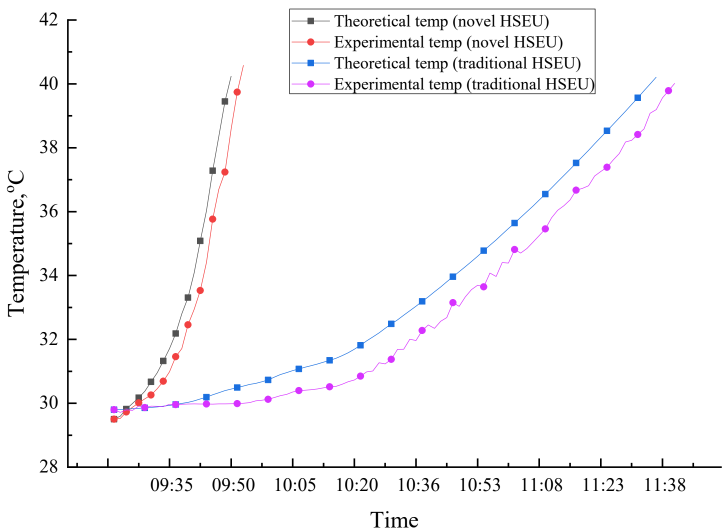

Fig. 15. Daily variation of the water temperature in the HSEU [75]

4. Future perspectives of the SAHP

Based on the previous research and development and recent pioneering progress in the SAHP technology, the future perspectives of the SAHP are analysed and outlined as follows:

4.1 Multi-source heat pumps

Energy efficiency is a great concern for heat pump development and implementation. Making effective use of multiple energy sources is the most practical and accessible way to achieve the improved energy efficiency and reduced fossil fuel energy consumption. The available energy sources include air, earth, sun, water, waste and others, depending upon the geographic, climatic and infrastructural conditions of the sites. Integration of the multiple sources into a heat pump system is a delicate process involving careful design and planning, simulation and optimisation, as well as lab-based and site test. The design theory, simulation method, components selection and characterisation, system's technical performance testing and valuation, as well as its socio-economic performance assessment are the major issues to be addressed to enable creating a mature and widely deployable multi-source heat pump system. A good example is the solar-assisted ground source heat pump system, as shown in Figs. 16(a) and Figs. 16(b).

Both geothermal and solar energy are renewable energy sources. Ground source has favourable temperature condition compared to the ambient air for space heating and cooling, and the temperature is relatively stable. However, the long-term operation of ground source heat pump can result in temperature degradation in ground around the borehole especially in heating-dominated areas. The efficiency of the heat pump will drop if there is no proper ground temperature recovery. Solar energy during the non-heating period usually accounts for about 70% of the annual solar radiation in the UK and many other countries. When the solar thermal panels are used for ground temperature recovery in summer, more efficient operation of the heat pump in winter is becoming possible [76].

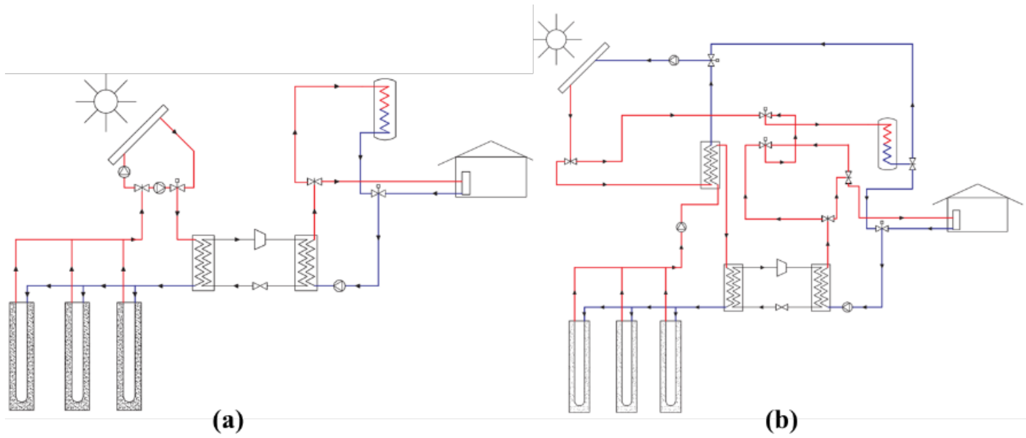

Fig. 16 Schematic of the typical SAGSHP systems [77]**: (a) Direct expansion SAGSHP system (DX-SAGSHP); (b) Indirect expansion SAGSHP system (IDX-SAGSHP)**

4.2 Heat pump defrosting using waste heat and renewable energy

Defrosting of the heat pump consumes significant amount of electrical energy which creates an obstacle for wide deployment of the heat pump technology in cold climate condition. Using high temperature exhaust air to defrost the heat pump is a solution to tackle the energy intensive problem of the heat pump which opens up an opportunity to use the waste energy in a building and infrastructure. Using air for defrosting has the advantages of low capital cost, free of reconstruction work, and easy control. The defrosting performance with ambient air had been investigated in the literatures [78]. However, the defrosting process was prolonged as the temperature difference between air and ice was small, leading to degraded indoor thermal comfort. This challenge can be tackled when the air comes from the building. The exhaust air generally has a temperature of about 20ºC higher than the ice. The defrosting duration may only account for less than 10% of the total heat pump operation time, which are shown in Figs. 10.

Apart from the exhaust air, other waste and renewable energy, e.g., drainage water, composite, bio-mass, solar, and earth, could also be applied to perform defrosting of the heat pump. Two waste and renewable driving defrosting processes are shown in Figs. 17(a) to 17(b). For example, the solar radiation in winter in the cold climate areas (e.g., UK) is generally too weak for space heating. The solar energy collection efficiency may be less than 20% under the conditions of hot water temperature of 40-50°C, ambient temperature of about 0°C and average radiation of 300 W/m^2. To avoid an extremely inefficient heat collection, the water temperature can be set to 10-20°C. The heat can be collected at an efficiency of more than 40%. Though unsuitable for space heating, it is sufficient for defrosting. The solar energy is thereby efficiently utilised in winter, resulting in a shorter payback period of the SAHP system.

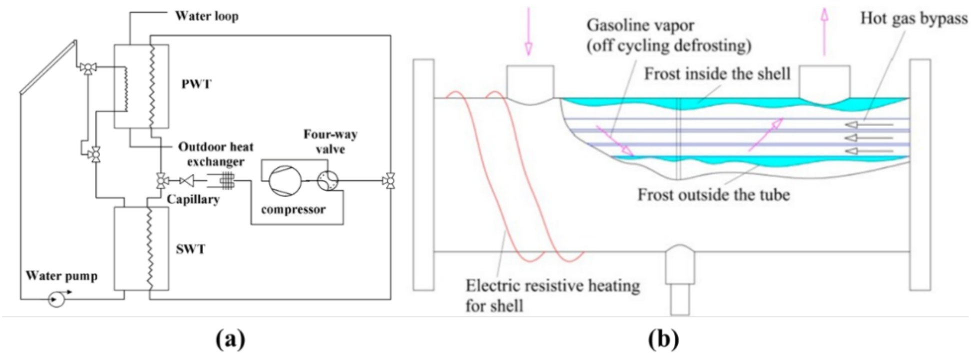

Fig. 17 Defrost process: (a) Using stored solar energy to defrost [79]**; (b) Using recovery heat in gasoline vapour** [80]

4.3 Advanced heat storage & exchanger unit (HSEU)

The HSEU is a vehicle to establish balance between the heat demand of a building and heat supply of a SAHP. It is also expected that a HSEU has a function to quickly respond the heat demand of the building and provide immediate heat supply by utilising solar energy. This will enable the extended service time of a solar system and reduced operational time of the heat pump, thus significantly reducing the electrical demand of the whole SAHP. A fast responsive HSEU developed by the authors is ideally suited to this application. However, the structure optimisation, fluid selection and characterisation, and associated control strategy development are still required to create the most effective HSEU operation. This will enable the maximised use of solar energy and minimised use of electrical energy for heat pump operation. Furthermore, non-complementary between the heat supply and demand will be mitigated.

4.4 Advanced machine learning and multi-objective evolutionary optimisation models for performance prediction and optimisation of the SAHP technology using big datasets

Empirical success and great performance of the Machine Learning (ML) and Multi-Objective Evolutionary Optimisation (MOEO) models in diverse engineering applications have disclosed the necessity of developing the ML models for the SAHP technology. A large number of research studies, as well as engineering applications on SAHP, have led to the availability of big datasets for the technology which can serve as the foundation of the ML models for performance prediction and optimisation of the SAHP technology. The raw data is collected from the previous computer modelling, experimental testing and site measurement to be analysed, pre-processed and cleaned using the combined data mining and data pre-processing techniques, e.g., data transformation, data reduction, to form the regulated and refined big dataset. The data stored in the dataset is then applied to train several ML models using diverse algorithms such as advanced Deep Learning (DL) method. In addition, the MOEO based models will implement the developed ML models to optimise the SAHP performance employing the evolutionary optimisations, e.g., Genetic Algorithms (GA), to maximise the solar and energy efficiencies as well as to minimise the construction and design costs of the system.

These models, with the capability of performance prediction and optimisation, will be able to independently predict the performance of the technology using the main operating and design parameters of the system, and can also solve the biggest challenge, the optimal control by considering the stochasticity of solar energy. Taking into account the predicted future weather data and socio-economic SAHP data, the technical and socio-economic performance of the SAHP can be estimated for the next 50 to 100 years. The developed ML and MOEO models will pioneer in providing the predictive models in the SAHP field, which can create a revolutionary and game-changing impact on this important field.

5. Conclusions

This perspective paper made a critical review of the SAHP research and development works. This enable a clear understanding of the current status of the SAHP and identification of the critical challenges with the SAHP. It is found that the current SAHP development faces a number of challenges that have hindered the further development and deployment of SAHP: (1) poor energy performance at low ambient temperature; (2) difficulty in coupling solar thermal panels with a heat pump to achieve the increased solar system operational time and reduced electrical energy usage; (3) mismatch between heat demand of the building and heat supply of the SAHP; and (4) lack of multifunctional simulation tool.

A novel SAHP system employing the multiple-throughout flow solar thermal panels array, double-evaporators and vapour injection compressor was introduced and its operational performance was characterised and presented. The system was found to be able to effectively tackle the challenges remaining with the current SAHP. The system comprises three major innovations: (1) A novel multiple-throughout-flow solar panel array, which achieves 8~15% higher solar efficiency, 50~60% lower flow resistance and 10~25% higher energy efficiency compared to the conventional series laid solar panel array; (2) A novel ventilation heat recovery heat pump which, incorporating the double evaporators and vapour injection compressor, leads to over 30% higher COP, compared to conventional heat pump; (3) A fast responsible heat storage/exchanging unit which, comprising a small volume heat exchanging tank, a large volume heat storage tank and controllable flow path alteration device, achieves 20-40 mins heat response to the building's heat demand, while conventional heat storage/exchanging unit requires 3-4 hours to respond the heat demand of the building.

Based on the presented critical review and specific technology case study, the future perspectives of the SAHP were investigated, leading to identification of potential pathways to promote the SAHP development to meet the requirement of a carbon neutral future.

These include development of: (1) multi-source heat pumps; (2) heat pump defrosting using waste and renewable energy; (3) advanced heat storage & exchanger unit (HSEU) technology; and (4) advanced machine learning and multi-objective evolutionary optimisation models for performance prediction and optimisation of the SAHP technology using a big dataset.

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