Taylor & Francis
Taylor & Francis Group

Science and Technology for the Built Environment

ISSN: 2374-4731 (Print) 2374-474X (Online) Journal homepage: http://www.tandfonline.com/loi/uhvc21

Research on the performance of an adsorption heat pump in winter demand response

Weilin Li, Yongbao Chen, Peng Xu, Chirag Joshi & Ferdinand Schmidt

To cite this article: Weilin Li, Yongbao Chen, Peng Xu, Chirag Joshi & Ferdinand Schmidt (2016): Research on the performance of an adsorption heat pump in winter demand response, Science and Technology for the Built Environment, DOI: 10.1080/23744731.2016.1232113

To link to this article: http://dx.doi.org/10.1080/23744731.2016.1232113

Science and Technology for the Built Environment (2016) **00**, 1–8

ISSN: 2374-4731 print / 2374-474X online
DOI: 10.1080/23744731.2016.1232113

Research on the performance of an adsorption heat pump in winter demand response

WEILIN LI[1], YONGBAO CHEN[1], PENG XU[1,*], CHIRAG JOSHI[2], and FERDINAND SCHMIDT[2]

[1]*School of Mechanical Engineering, Tongji University, A434, Cao'an Road 4800, Jiading District, Shanghai 201804, China*
[2]*Karlsruhe Institute of Technology, Institute of Fluid Machinery, Huttenstrasse, Karlsruhe, Germany*

Demand response is an efficient method to flatten the demand curves of end-use customers. This article studies the feasibility of an adsorption heat pump in the demand response of a residential building under winter operating conditions. Stratified storage is introduced into the stratified heat pump system to realize heat recovery, which is also used as a buffer energy source when power shortages occur. This article studies the performance of an adsorption heat pump when the system disconnects the external energy source to simulate the situation of a demand response event occurring through experiments. Moreover, the heating loads of a typical residential building are obtained from the simulations on EnergyPlus. Two day types are selected to evaluate the demand response performance of the system in different situations. The coolest day presents an extreme situation, and the design day represents a normal situation. The demand response potential of the adsorption heat pump is estimated by comparing the heating capacity of the system and heating load curves of the residential building.

1. Introduction

The building sector is one of the largest energy consumers, accounting for more than 25% of the final energy consumption, of which the residential sector is responsible for approximately 50% in China (Delmastro et al. 2015). In addition to accumulated energy use, buildings tend to have high demands for electricity, which causes significant peak demand exertion on the grid (Ma et al. 2012). For buildings, HVAC systems account for approximately 65% of the total energy consumption (Yang and Li 2008). The 2010 final energy demand for heating and cooling made up more than 50% of the total final energy consumption in Germany (Brunner et al. 2013). Moreover, HVAC loads are influenced by the weather. Therefore, peak demands caused by extreme weather, such as hot weather or cold weather, are significant for the demand increase of HVAC systems.

Demand response (DR) is an efficient method to flatten the demand curves of end-use customers, which focuses on changing the electricity demand during peak times to balance supply and demand (Warren 2014). DR is a tariff or program that is established to motivate changes in electricity use by end-use customers in response to changes in the price of electricity over time or to give incentive payments that are designed to induce lower electricity use at times of high market prices or when grid reliability is jeopardized (U.S. Department of Energy 2006).

Renewable energies, such as environmentally friendly energy, are strongly supported in many countries and regions. After the implementation of the Renewable Energy Act (The Central People's Government of the People's Republic of China 2009) in China in 2006, renewable energies have expanded rapidly over the last decade (Wang 2010; Zhao et al. 2011). Moreover, renewable energies are being increasingly adopted across mainland Europe (Kreuder and Spataru 2015). Therefore, heat pumps have become popular for cooling and heating applications, which generally exploit renewable energies (Liu et al. 2013). Furthermore, heat pumps are seen as a promising technology for load management in building sides, in combination with smart grids. Heat pumps can couple with thermal energy storage to shift the power demand from on-peak to off-peak period, acting as an effective technology in DR or demand side management (DSM; Arteconi et al. 2013).

Several research investigations have identified the potential for combining heat pumps with DR. These studies presented two methods for combining them. One is utilizing DR to flatten the demand curves of heat pumps. Kreuder and Spataru (2015) estimated the effect of introducing heat pumps on the half-hourly load profile, which increased the peak loads in the winter, but after combining the DR, the peak loads were avoided successfully. Arteconi et al. (2013) analyzed heat pumps with radiators or underfloor heating distribution systems coupled with thermal energy storage, which achieved good control of the indoor temperature, even if the heat pump was turned off during the DR period.

Received April 30, 2016; accepted August 30, 2016
Weilin Li is a Doctoral Candidate. **Yongbao Chen** is a Doctoral Candidate. **Peng Xu, PE, PhD,** is a Professor. **Chirag Joshi, PhD,** is an Engineer. **Ferdinand Schmidt, PhD,** is an Engineer.
*Corresponding author e-mail: xupeng@tongji.edu.cn
Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uhvc.

The other method introduces a storage into the heat pump system as an alternate energy source when power shortages occur. Brunner et al. (2013) investigated the abilities of locally dispersed heat pumps connected to a thermal heat storage to perform DSM activities by developing a model connecting a thermal heating system to a power grid, which demonstrated the high potential of heat pumps to contribute to local DSM. Buber et al. (2013) identified that a significant load shifting potential, for example, DR potential, can be realized using heat pumps. This article studies the latter situation, which focuses on the DR performance of an adsorption heat pump and a stratified storage.

Adsorption heat pumps have sparked significant attention in recent years as they have the advantage of being environmental friendly and provide heating and cooling effects by employing thermal energy sources, such as solar and geothermal energies or waste heat of industrial processes (Demir et al. 2013). This article studies the peak load shifting potential of adsorption heat pumps with thermal storage systems in residential buildings during winter by combining experiments on an adsorption heat pump with stratified storage and simulations of a typical residential building. Section 2 introduces the relevant works that have been performed and the principles of an adsorption heat pump with stratified thermal storage. In the experiments presented in Section 3, the stratified thermal storage tries to store the thermal energy as much as possible and disconnects the outer heat source to simulate occurrence of a DR event. Section 4 analyzes the DR potential of adsorption heat pumps for residential buildings by combining the experimental results with the simulation results of the heating load for a typical residential building. Finally, the conclusions are presented in Section 5.

2. Principles

Adsorption heat pumps take advantage of the adsorption effect between a given working pair, for example, an adsorbent (e.g., silica gel) and adsorbate (e.g., water vapor). Adsorption and desorption alternate by cooling and heating the adsorbent periodically. During the adsorption half-cycle, the adsorbate liquid evaporates to absorb the heat of the environment, and during the desorption half-cycle, the adsorbent releases adsorbate gas and the adsorbate gas condenses into a liquid to produce the heating effect. Therefore, the heating and cooling procedures are conducted alternately. To realize the supply heating or cooling continuously, the heat pumps need to possess two or more adsorbers that operate alternately (Jiang 2001). The performances of these absorbers are independent of each other, and this article studies an adsorption heat pump system to analyze the DR performance of an adsorption heat pump.

2.1. Principle of heat recovery

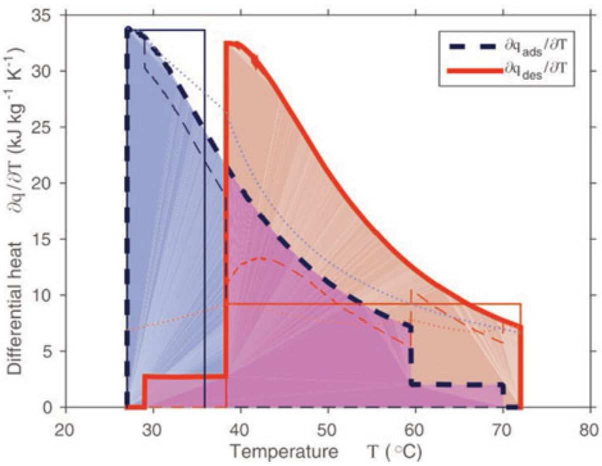


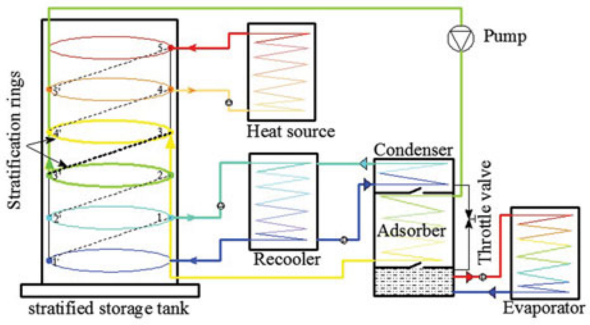
Fig. 1. Adsorption and desorption curves of silica gel–water working pair (Schwamberger and Schmidt 2013).

To improve the energy coefficient of performance (COP) of adsorption heat pumps, the Building Technology Group of Institute of Fluid Machinery (FSM) and Karlsruhe Institute of Technology (KIT) have been researching the heat recovery of adsorption heat pump systems for several years (Glück et al. 2013; Schwamberger et al. 2011; Schwamberger and Schmidt 2013). They introduced a stratified storage into an adsorption heat pump as the heat recovery unit. In the adsorption cycle, the stratified storage can reduce entropy production due to the external coupling of the adsorber to the heat source and sink.

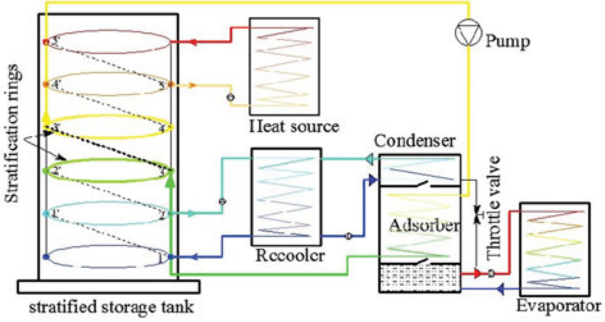
The use of stratified storage can achieve heat recovery in an adsorption heat pump system because there is an overlap between the adsorption and desorption differential heat curves. Figure 1 shows the adsorption and desorption curves of silica gel–water at a given working condition, fixed evaporation temperature, condensation temperature, and regeneration temperature. The area under the desorption curve (solid line) represents the heat required for desorption, and the area under the adsorption curve (dashed curve) is the heat released during adsorption under the given condition. The overlap indicates the heat that can be recovered in an ideal cycle, which is a considerable amount. In many cases, under different working conditions or different working pairs, considerable recoverable heat usually exists.

2.2. Principle of the adsorption heat pump system

The system sketch of an adsorption heat pump system with a stratified storage called "Stratisorp" (U.S. patent 8,631,667 B2) is shown in Figure 2. The system consists of a heater, cooler, adsorber, evaporator, condenser, and a stratified storage. Note that the experimental platform is an analog system; therefore, the heat source used in this experimental platform is an electrical heater. However, it can be replaced by other renewable energy sources, such as solar and industrial waste heat, because the heat grade of the heat source needed by the system is very low, that is, only 65°C∼75°C hot water. In a standard situation, the heater heats the top of the storage and keeps it at the regeneration temperature of the adsorbent (e.g., 75°C) and the cooler cools the bottom to keep it at the



(a) adsorption half cycle



(b) desorption half cycle

Fig. 2. System sketch of a "Stratisorp" cycle (Schwamberger and Schmidt 2013).

condensation temperature (e.g., 27°C). The rings of storage are the channels for supplying water to and extracting water from the storage. Fluid extraction is selected by an external multipass valve, and a stratification pipe enables the water to enter the level at the same temperature. The rings ensure that the whole process does not disturb the water of other temperature levels.

Obviously, different from a traditional adsorption heat pump (Demir et al. 2013), stratified storage will influence the performance of the "Stratisorp" system. A typical adsorption-desorption cycle is used to illustrate the function of the stratified storage (Figure 1).

Figure 2a is the sketch of an adsorption half-cycle. The numbers 1, 2, 3, 4, and 5 denote the water returned to the storage, and the numbers 1', 2', 3', 4' and 5' express the water extracted from the storage. The whole process is introduced as below. At the beginning of adsorption, the water of the second highest level (point 5') of storage is extracted from storage to cool the adsorber, so the water is heated by the adsorber and returns to a higher level (point 5) of storage. When the temperature difference between the supply and return water is less than a set-point value, for example, 1 K, which means that adsorption is nearly complete in this temperature region, the supply water moves to the next lower levels (4'/4, 3'/3, and 2'/2) and continuously cools the adsorber until the supply water reaches the bottom (point 1'/1) of storage. When the temperature difference between the supply and return water of the bottom level is less than a certain value, which means that the adsorption half-cycle is finished, the system switches to desorption.

In contrast to adsorption, the desorption half-cycle first uses the bottom water to heat the adsorber for regeneration, and when the temperature difference between the supply and return water is less than a certain value, the supply water is extracted from the next higher level until it arrives at the top of storage, which is shown in Figure 2b. At the beginning of desorption, the water from the second lowest level (point 1') of storage is extracted from storage to heat the adsorber, so the water is cooled by the adsorber and returns to a lower level (point 1) of the storage. When the temperature difference between the supply and return water is less than the setpoint value, the supply water moves to higher levels (2'/2, 3'/3, and 4'/4) and continuously heats the adsorber until the supply water reaches the top (point 5'/5) of storage.

After one cycle, the heat generated during the adsorption half-cycle is recovered into stratified storage; then, part of the heat that is available at a high enough temperature is used for desorption. For further details, please refer to the paper (Schwamberger et al. 2011).

2.3. Control strategy for DR

In addition to realizing heat recovery, stratified storage can also be utilized as a buffer storage for the driving heat, for example, as an alternative energy source to drive the adsorption heat pump continuously when an energy supply shortage happens (Schwamberger and Schmidt 2013). This article studies the performance of an adsorption heat pump after disconnecting the external heat source to simulate the occurrence of a DR event in winter.

In the DR control strategy, when the energy supply is adequate, storage is heated to store heat energy as much as possible. Then, the system disconnects the heater to simulate the occurrence of an energy supply shortage, for example, a DR event occurs. Thus, the entire storage is almost at the same high temperature right after the heater is disconnected, which is different from a typical cycle with a stratified temperature when the heater operates continuously.

At the beginning, the process of extracting water from one level to the next lower level will be very fast because the temperature of storage is almost uniform, which results in a difference between the supply and return water to become less than the setpoint value (1°C in this research) quickly. In this process, the cooler is kept off. When the supply water is extracted from the bottom of storage, the cooler is turned on to supply cooling water to cool the adsorber until adsorption ends. Keeping the flow rate of the cooler the same as or slightly less than the flow rate of the adsorber is important when the cooler is on; otherwise, the surplus cooling water from the cooler would enter storage and waste the heat energy stored in storage. When the system switches to the desorption half-cycle, the cooler is switched off again and the heat stored in the storage is used. Thus, storage will be cooled down level by level and become stratified. In the second cycle, the storage will be heated up to the heat recovered from adsorption.

Equation 1 calculates the heating COP of one cycle. The denominator is the driving energy supplied to the system for desorption and the numerator is the heating amount, according to the definition of COP.

$$\mathrm{COP}_{heating} = \frac{Q_{heating}}{Q_{expensed}} = \frac{Q_{condenser} + Q_{cooler}}{Q_{desorp}} \qquad (1)$$

where $Q_{heating}$ is the total heating amount of one cycle (kWh or kJ); $Q_{condenser}$ is the heat production during desorption (kWh or kJ); Q_{cooler} denotes the heat production after turning on the cooler (kWh or kJ); and Q_{desrop} is the energy expensed during the desorption half-cycle, for example, the energy consumed in one cycle (kWh or kJ).

In the analysis of stationary cycles with stratified storage, the system boundary is usually drawn such that storage is part of the system. In that case, the heat supplied by the external heat source to the storage is taken as the "expense" for the COP calculation. Because the cycle is stationary, the temperature distribution in storage is stationary as well (i.e., it is the same at the beginning of each new cycle). In the operating mode analyzed here (i.e., storage discharge), this definition of the COP cannot be used. Here, the system boundary is drawn such that storage is excluded and all of the heat supplied from the storage to the adsorber during the desorption phase is counted as "expense." It should be noted that according to this definition, the degree of heat recovery is not reflected in the COP calculation. A suitable figure of merit taking heat recovery into account would be the utilization factor achieved over the complete discharge phase of the storage, for example, Equation 2:

$$F_{discharge} = \frac{Q_{heating}}{\Delta Q_{storage}} = \frac{Q_{condenser} + Q_{cooler}}{\Delta Q_{storage}} \qquad (2)$$

where $F_{discharge}$ is defined as the utilization factor and $\Delta Q_{storage}$ denotes the storage discharge of every cycle (kWh or kJ).

3. Experiments and results

3.1. Experiments

In this research, the DR strategy presented above is studied through experiments. The heating COP and heating capacity ($P_{heating}$) of each cycle are the assessment indexes of the strategy, which present a method to judge whether the heat pump is competent in a DR event by comparing the heating capacity and heating load during the DR period.

Figure 3 shows the platform of the adsorption heat pump system located in KIT. The path for the extraction and return of water can be controlled by two-way valve groups on the stratified storage, which are shown in the middle of Figure 3. Water can be extracted from and returned to storage from six different temperature levels according to these valves. Fifteen temperature sensors are installed vertically in the middle of storage to monitor the temperatures of storage. Sensor 1 monitors the bottom temperatures, and sensor 15 monitors the temperatures of the top. The adsorption module is a silica gel–water unit with a single vacuum chamber and a combined evaporator/condenser heat exchanger. The adsorber is a lamella heat exchanger containing approximate 8 kg of silica gel. The value of each operation parameter for the DR strategy is shown in Table 1.

Fig. 3. The adsorption refrigeration system experimental platform.

3.2. Results

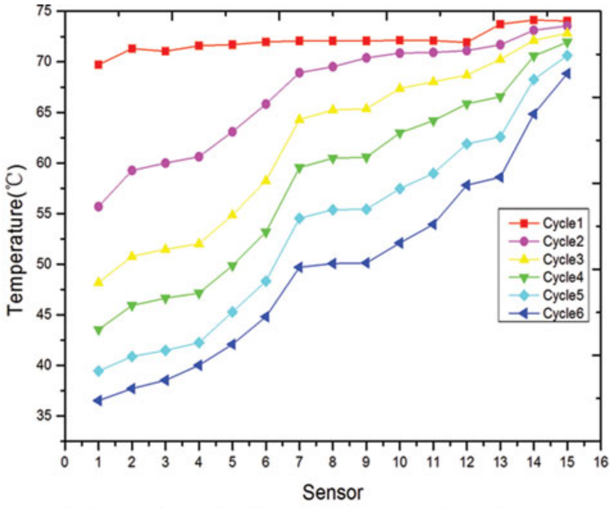
To analyze the heating COPs and utilization factor $F_{discharge}$ variations of different cycles, the temperature profile of storage at the start of each cycle is shown in Figure 4a. It can be seen that storage initially has an almost uniform temperature and a stratified cycle after the cycle, which shows the heat consumption of each cycle. The temperature variations during the last cycle are shown in Figure 4b, where an obvious temperature increase at the beginning of each cycle for the heat recovered from adsorption (e.g., T5) is observed. Therefore, during each adsorption half-cycle, some of the heat of adsorption is recovered in storage, but the amount of heat recovery is less than the heat utilized in desorption.

The experimental results are shown in Table 2. $Q_{heating}$ keeps decreasing, which means that the quantity of heat produced by the system decreases cycle by cycle. However, the reduction amounts are relatively small after six cycles. $Q_{heating}$ is only reduced by approximately 30% after six cycles. Due to the experimental limitation, only six cycles are conducted. However, it can be seen that the energy stored in the storage is still enough to drive the adsorber.

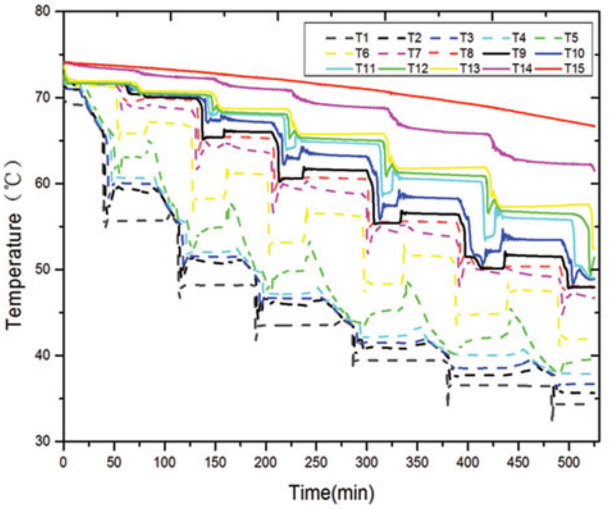
The heating COP and utilization factor $F_{discharge}$ reflect the efficiency of energy utilization, and both of them remain nearly stable, which means that the efficiency of energy utilization is

Table 1. Operation parameters of the DR control strategy.

Parameter description	Value
Evaporation temperature	18°C
Condensation temperature	27°C
Regeneration temperature	(Initial) 72°C
Adsorber flow rate	800 L/h
Storage temperature	(Initial) 68∼72°C



(a) Temperature profile of the stratified storage at the start of each cycle



(b) The temperature variations during each cycle

Fig. 4. Temperature profile of the storage at the start of each cycle.

not obviously reduced with the reduction of energy stored in the storage.

The heating capacity of the adsorption heat pump is determined to assess whether the heat pump is competent in a DR event. The $P_{heating}$ of each cycle is shown in Table 3. Note that the $P_{heating}$ of each cycle is the average heat capacity of the desorption half-cycle, but the desorption and adsorption are conducted alternately, which means the heating procedure is intermittent. As mentioned previously, to supply heat continuously, two or more adsorbers are needed.

Table 3. The heating capacity variation of each cycle.

Cycle number	1	2	3	4	5	6
$P_{heating}$ (kW)	10.09	9.00	7.00	8.19	5.80	5.31

Through these experiments, it is found that the durations of desorption and adsorption are approximate for each cycle. Thus, during the subsequent DR analysis, we assume that two identical adsorbers are integrated together and that both of them are the same as the one tested here.

4. DR potential of adsorption heat pump

4.1. Building model and heating load simulation

According to the heating capacity of the adsorption heat pump, a typical residential building is modeled in EnergyPlus. The residential building consists of a lobby, two bedchambers, a kitchen and a washroom, as shown in Figure 5. Among them, the living room and two bedchambers are the air conditioned areas. Table 4 shows the input parameters of the building information in EnergyPlus. An ideal air-conditioning system is utilized because only heating loads are needed in this research and the COPs of different systems make no difference.

The model simulates the heating load of a residential building under winter conditions. Because it is a residential

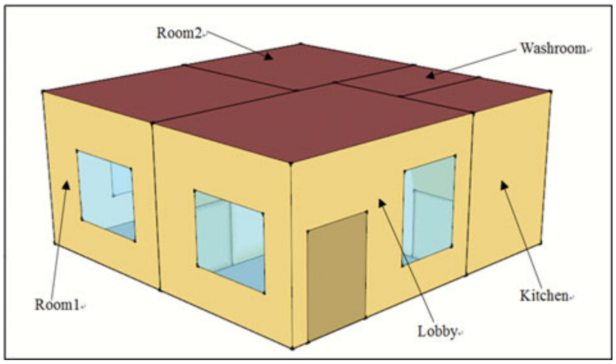


Fig. 5. The model of a residential building.

Table 2. Results of the experiments.

Cycle	$Q_{heating}$ (MJ)	$Q_{expensed}$ (MJ)	$\Delta Q_{storage}$ (MJ)	COP	$F_{discharge}$
1	19.74	8.95	15.93	2.21	1.24
2	19.70	10.02	16.17	1.97	1.22
3	15.86	9.68	13.28	1.64	1.19
4	18.47	10.13	14.57	1.82	1.27
5	15.65	9.40	12.55	1.66	1.25
6	13.60	8.01	10.28	1.70	1.32

Table 4. Building information set in EnergyPlus.

Input parameter	Value
Heat transfer coefficient of the external wall	$0.46\ \mathrm{W}/(\mathrm{m}^2\cdot\mathrm{K})$
Heat transfer coefficient of the roof	$1.46\ \mathrm{W}/(\mathrm{m}^2\cdot\mathrm{K})$
Heat transfer coefficient of the window	$1.99\ \mathrm{W}/(\mathrm{m}^2\cdot\mathrm{K})$
Shading coefficient of the window	—
Floor area	150 m^2
Air-conditioned area	120 m^2
Window–wall ratio	0.16
Air-conditioning system	Ideal air-conditioning system

building, there is no heating load during the office hours (0900–1700) of workdays and the set-point of indoor air temperature is 13°C. During occupied time, the indoor air temperature is set to 23°C from 0000–0700 and 1700–2400, and from 0700–0900, the set-point is 18°C. The weather file is the typical meteorological parameters of Stuttgart, Germany, which is near Karlsruhe, that is, the experimental site.

The model simulates the heating load of the air conditioned area from October 1st to April 30th of the next year. The simulation result of the average heating load per day is shown in Figure 6. The peak load appears on December 10th, corresponding to the lowest ambient temperature. Supposing that a DR event occurs on that day, the air-conditioning system has to shut down to reduce the power demand. Then, the energy stored in the storage of the adsorption system is used to meet the heating load. This means that the adsorption heat pump is feasible in the DR of the residential building if the heating capacity of the adsorption heat pump can cover the load curve for a period of time.

The design day, that is, January 21st, is selected to represent a normal situation. The highest dry-bulb temperature is 5°C. The heating loads of the coldest day and the design day are shown in Figure 7.

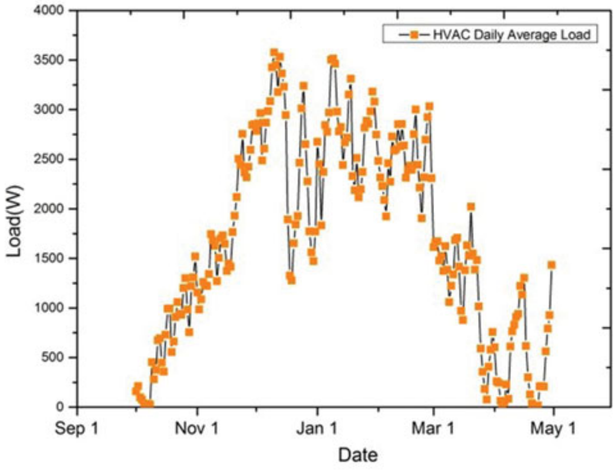
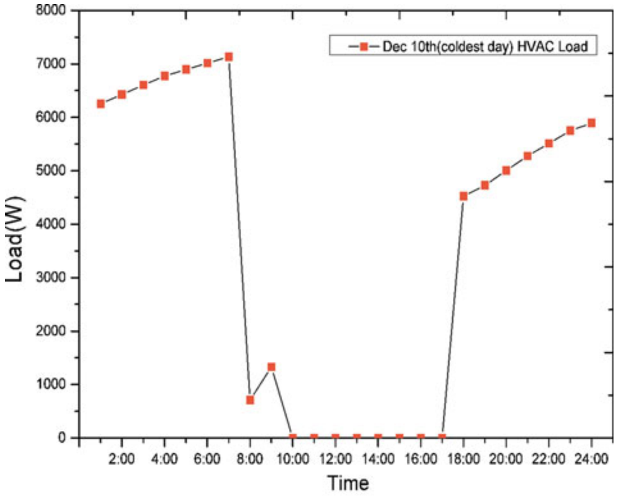
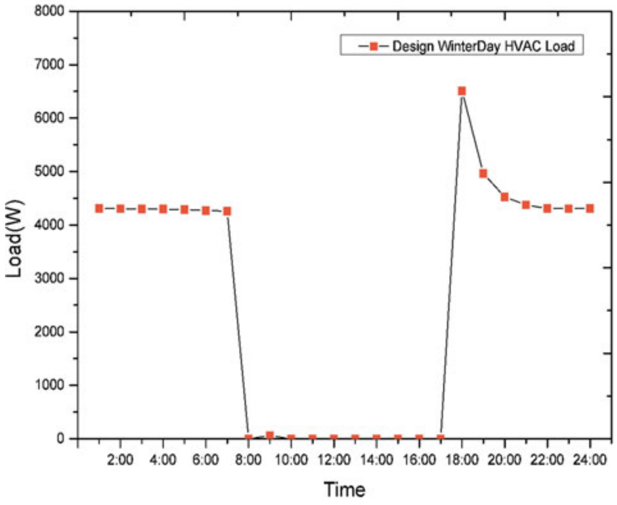


Fig. 6. The average heating load per day from October 1st to April 30th of the next year.



(a) Coldest Day



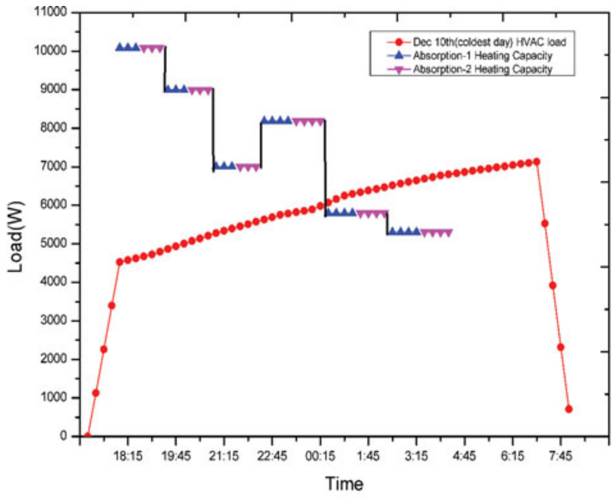
(b) Design WinterDay

Fig. 7. Heating load profiles of different day types.

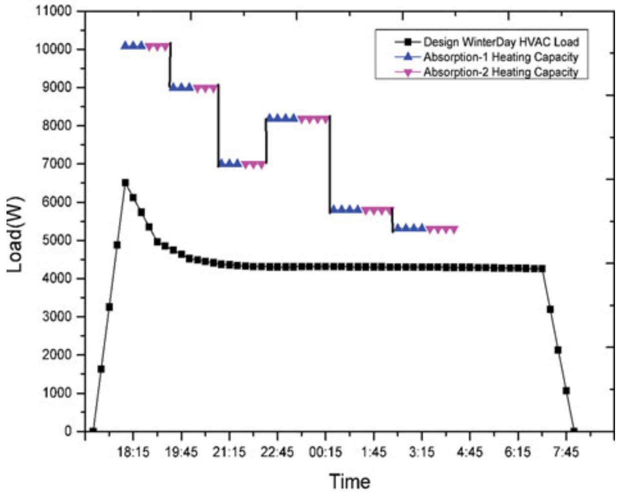
4.2. DR potential analysis

In general, DR events occur when grid reliability is jeopardized (U.S. Department of Energy 2006). Extreme weather and plant breakdowns will trigger DR events. Thus, two different day types, that is, the coldest day and design day, which represent extreme weather and normal conditions, respectively, are analyzed to assess the DR performance of the adsorption heat pump. Suppose that when the DR event occurs the residential building has to switch-off its electric heating system and use an alternate heating source.

Because one adsorber has to conduct adsorption and desorption in turn, the performances of two identical systems are integrated, as in the experiment, making them operate alternately to supply heat continuously. Therefore, the heating capacity profile is a combined curve (shown in Figure 8).



(a) Coldest Day



(b) Design WinterDay

Fig. 8. Heating capacity of the adsorption heat pump versus the heating load.

Obvious step changes between each cycle are observed because either adsorber produces heat intermittently, leading to differences in the heating capacity between each cycle. For each cycle, in the first half-cycle, one adsorber conducts adsorption first and the other implements desorption and generates heat; then, in the second half-cycle, the two adsorbers exchange operating modes.

A comparison between the heating capacity and heating load on the coldest day is shown in Figure 8a. As mentioned in Section 3.2, the energy stored in the storage is still enough to drive the adsorber after six cycles. However, for the coldest day, the heating capacity of the adsorption heat pump cannot cover the heating load any more, which means that auxiliary heating in other forms is needed. However, it can still be concluded that the adsorption heat pump is competent in the DR for two normal situations. The first normal situation is when the duration of a DR event is less than 5 h, when the heating capacity is higher than the heating load; the other normal situation is when the required amount of reduction of the DR event is less than the heating capacity.

A comparison between the heating capacity and heating load on the design day is shown in Figure 8b. For the design day, the heating capacity of the adsorption heat pump remains higher than the heating load. Because the heating capacity reduces cycle after cycle, it cannot be concluded that the adsorption heat pump is competent during a longer DR. However, on the design day, the adsorption heat pump can at least realize an 8 h DR event.

The results show a large surplus of the heating capacity of the heat pump system for both the coldest day and design day. Therefore, it can be inferred that if the heat served by the adsorption heat pump is the same as that of the heating load, more satisfied hours can be achieved. The total heat production of the adsorption heat pump is assumed to be the same as the experiment, while the heat pump accurately supplies heat as the heating load. The longest satisfied hours are prolonged to 13 and 17 h for the coldest day and design day, respectively. A longer satisfied hour can be achieved by enlarging storage. The surplus heat remaining after the DR events can continuously supply heat to satisfy the heat load during a nonDR period.

4.3. Electrical demand reduction

It is can be concluded that the adsorption heat pump system is competent for a DR event on both the coldest day and design day from the comparison between the experimental and simulation results. Electrical demand reduction is a pivotal factor to evaluate the DR effect of the control strategy and the heat pump system. In this research, the electrical demand reduction is evaluated by comparing the system with an ideal air-conditioning system with a constant COP (COP = 3.2). The electrical demand reduction is show in Table 5.

The electricity demand reduction is considerable for a residential building. If the system continues to operate by charging storage after reaching capacity and is not able to satisfy the heating load, more electricity demand reduction can be realized.

5. Discussion

The adsorption heat pump system examined in this article is still in the experimental stage and is not used in actual buildings yet. Therefore, this article represents a performance study that focuses on the technical feasibility of the system in the winter DR of residential buildings. However, the economy of

Table 5. Electrical demand reduction on the coldest day and the design day.

Day type	Satisfied hour	Total heating load (kW)	Electricity demand reduction (kWh)
Coldest day	5	28.17	9.06
Design day	8	47.54	14.85

the system is another important factor for practicality. Every device of the system was purchased from different companies and assembled by the current research group, for example, the stratified storage was a normal tank before and was improved by adding a diversion channel. It can be inferred that the cost of the system will be decreased after mass production, and an integrated system will be smaller and more convenient in production and utilization.

It is should be emphasized that this system is not only applicable during the occurrence of DR but it can also supply heat to a building during a nonDR period. Therefore, the users only need one system to meet the heating load for both DR and normal periods. Furthermore, the system is a heat pump that can supply cooling during the summer. This system is still in the technical research stage for improving the performance and exploring feasible fields. The economics and cooling supply performance will be key tasks in future work.

6. Conclusions

This article examined the feasibility of an adsorption heat pump in the DR of a residential building under winter operating conditions. Stratified storage was introduced in the heat pump system to realize heat recovery, which was also used as a buffer energy source when power shortages occurred. This article first studied the performance of the adsorption heat pump using one adsorber, and when the DR potential was analyzed, two identical heat pump systems were integrated together to allow for the continuous supply of heat. The heating loads of a typical residential building were obtained from the simulations on EnergyPlus. The coolest day represented an extreme situation, and the design day represented a normal situation. Through the comparison between the heating capacity curve of the integrated heat pump system and the heating load on those two days, the following can be concluded.

The heating capacity of the heat pump was reduced cycle after cycle after disconnecting the outer heat source, but the reduction was relatively small. The energy stored in the storage was still able to drive the adsorber after six hours.

For the coldest day, the adsorption heat pump satisfied at least 5 h of the heating demand of the residential building. If the reduction goal of DR was less, the adsorption heat pump can accomplish a longer DR; the design day was used to represent a normal situation, where the adsorption heat pump can realize at least 8 h of DR.

Therefore, the authors presented a promising method for achieving DR by an adsorption heat pump with stratified storage, which represented a reliable alternative heat source for a DR event occurring in the winter. However, more research is still needed in this field. For example, more experiments for the adsorption heat pump should be conducted to obtain its performance after six cycles; field tests are needed to examine the system performance in a real building.

References

Arteconi, A., N.J. Hewitt, and F. Polonara. 2013. Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems. *Applied Thermal Engineering* 51(s 1–2):155–65.

Brunner, M., S. Tenbohlen, and M. Braun. 2013. Heat pumps as important contributors to local demand-side management. *Powertech* 2013:1–7.

Buber, T., S. Von Roon, A. Gruber, and J. Conrad. 2013. Demand Response potential of electrical heat pumps and electric storage heaters. *39th Annual Conference of the IEEE Industrial Electronics Society, IECON 2013, Vienna, Austria, November 10–13*, 8028–32.

Delmastro, C., E. Lavagno, and G. Mutani. 2015. Chinese residential energy demand: Scenarios to 2030 and policies implication. *Energy & Buildings* 89:49–60.

Demir, H., M. Mobedi, and S. Ülkü. 2013. A review on adsorption heat pump: Problems and solutions. *Renewable & Sustainable Energy Reviews* 12(9):2381–403.

Glück, C., F. Schreiner, and F.P. Schmidt. 2013. Simulation study of a new type of solar combi system with a sorption heat pump for solar heating and cooling of residential buildings. *Proceedings of Sustainable Building Conference (sb13), Munich, Germany, October 10–13*.

Jiang, Z. 2001. *Theoretical and Experimental Study of Adsorption Refrigeration*. Shanghai, China: Shanghai Jiaotong University.

Kreuder, L., and C. Spataru. 2015. Assessing demand response with heat pumps for efficient grid operation in smart grids. *Sustainable Cities & Society* 19:136–43.

Liu, X., L. Ni, S.K. Lau, and H. Li. 2013. Performance analysis of a multifunctional heat pump system in heating mode. *Applied Thermal Engineering* 51(1–2):698–710.

Ma, J., J. Qin, T. Salsbury, and P. Xu. 2012. Demand reduction in building energy systems based on economic model predictive control. *Chemical Engineering Science* 67(1):92–100.

Schwamberger, V., C. Joshi, and F.P. Schmidt. 2011. Second law analysis of a novel cycle concept for adsorption heat pumps. *Proceedings of International Sorption Heat Pump Conference, ISHPC11, Padua, Italy, April 6–8*, 991–8.

Schwamberger, V., and F.P. Schmidt. 2013. Smart use of a stratified hot water storage through the coupling to an adsorption heat pump cycle. *8th International Renewable Energy Storage Conference and Exhibition, IRES, Berlin, Germany, November 18–20*.

The Central People's Government of the People's Republic of China. 2009. Renewable Energy Act. http://www.gov.cn/fwxx/bw/gjdljgwyh/content_2263069.htm.

U.S. Department of Energy. 2006. Benefits of demand response in electricity markets and recommendations for achieving them. http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/DOE_Benefits_of_Demand_Response_in_Electricity_Markets_and_Recommendations_for_Achieving_Them_Report_to_Congress.pdf.

Wang, Z. 2010. Prospective for China's solar thermal power technology development. *Energy* 35(11):4417–20.

Warren, P. 2014. A review of demand-side management policy in the UK. *Energy Reviews* 29(7):941–51.

Yang, L., and Y. Li. 2008. Cooling load reduction by using thermal mass and night ventilation. *Energy & Buildings* 40(11):2052–8.

Zhao, Z.Y., J. Zuo, L.L. Fan, and G. Zillante. 2011. Impacts of renewable energy regulations on the structure of power generation in China—A critical analysis. *Renewable Energy* 36(1):24–30.