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STUDY ON INFLUENCE OF OPERATIONAL STRATEGIES ON PERFORMANCE OF SOLAR COMPOSITE HEATING SYSTEM

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ABSTRACT

From the perspective of improving energy efficiency and thermal comfort of solar heating system, the active solar heating system under different strageties is experimented in Hezuo city, Gansu province, China in the heating season of 2018 to 2019. The conclusions reveal that without increasing energy consumption, smaller the supply duration and the intermittent duration, higher the heating efficiency. The living room air temperature, average heating rate and cooling rate of the kang surface temperature change more slowly. Regarding the on-off time ratio of 50%, the optimal strategy of the system are to combine 15/15min mode with variable flow mode B to ensure the system own high energy efficiency and well thermal comfort.

Keywords: solar heating system, on-off modes, heating efficiency, variable flow mode, temperature change

Symbols	*Interpretation*
Q	heat flow(MJ)
M	the total mass of water in system(kg)
c_p	specific capacity of water[J /(kg·℃)]
m	mass flow rate(kg/s)
T	temperature(℃)
Δτ	duration of water-flowing(h)
η	heating efficiency(%)
P	rated power(W)
F	operating energy consumption(kW·h)
n	number of measured points on the kang （piece）
ϕ	average change rate on the kang(℃/h)
T	temperature(℃)
τ	time(h)
T_a	average ambient temperature during heating period(℃)
T_i	initial supply temperature(℃)
T_n	water temperature in storage tank(℃)
T_d	indoor air temperature difference during heating period(℃)

1. INTRODUCTION

Fossil energy is gradually depleted, mankind are facing an energy crisis [1]. Solar energy is a rich and widely available source of energy, which can replace fossil energy to a certain degree. There are large areas, numerous populations in rural areas of China but backward heating methods. Using of clean and green solar energy to solve rural heating problems has broad prospects.

Some researches have been carried out on the operational strategies of solar heating systems. [2-4] studied the operational strategies of the solar heating system with a purpose to optimize operational modes, reduce energy consumption and improve energy efficiency. J. P. Forsström et al. analyzed the impact of different prices of auxiliary heat source on the heating economy of the solar heating system, and obtained the best auxiliary energy solution with the lowest cost [5]. Chun W G found that solar heating systems experienced relatively large fluctuations in indoor air temperature in intermittent heating mode [6]. Kurtay et al. developed an operation strategy for rainy weather to improve performance of the system [7]. Wang Haitao used DeST to obtain the feasibility of the scheme and the best scheme among 4 different modes [8]. Zhang Zhicheng found that the solar air heating system adopts the variable air volume operation mode than the continuous constant air volume mode, which can save 37% of operational energy consumption [9]. Weeratunge H proposed a mixed integer linear programming method to minimize the operating cost of the solar-assisted ground source heat pump system. The results show that the system can improve peak shaving and reduce operating costs by up to 7.8% [10]. Schiller S R studied the heating efficiency of the solar ground source heat pump combined heating system in different operating modes [11]. Wei Wei et al. found the solar composite system under different operational modes that in the evening, the change of the surface temperature and air temperature is relatively flat [12].

Many related researches have found that the on-off modes have a significant impact on the performance of the district heating system. Cho S H found that the two-parameter control is better than the constant temperature control of the indoor air temperature [13]. Fang Lide got the on-off durations and start-stop frequency of the electric valve in the system during various time periods of the day [14]. In order to reduce power consumption of the circulating pump in the secondary network, Wang S L proposed an adjustment mode combining quantity adjustment and quality adjustment. The research results show that the adjustment mode has greater energy saving potential [15]. Liu L et al. found that the indoor air temperature control in a new heating regulation mode is within 0.5 °C of the set point, and the energy consumption of the household is reduced by about 30% [16,17]. Li Yemao et al. proposed a new on-off regulation method in the central heating system, which can effectively reduce the return temperature and improve the adjustment effect [18]. Ulpiani G et al. found that the reasonable fuzzy control heating performance is better than PID and on-off control, which can reduce heating energy consumption by 30-70% while maintaining the same comfort [19]. Xiang Xiangjian et al. Studied a replacement time in which the water-flowing time is equal to the retained water is used, and the mode of heating is continued by using the retained hot water in the coil during the intermittent period, which can greatly reduce the return temperature and improve the heat utilization efficiency [20].

For the solar active heating system, the operation strategies [21] not only should ensure safe and reliable of the system, but also have the effect of improving heating performance and user's thermal satisfaction. With a certain collecor area, how to utilize the limited heat collectored by the solar heating system effectively to improve the system cost is an important issue that should be solved by operational strategies.

The application of the on-off modes in solar heating systems has not yet existed, and the application of variable flow in solar hot water heating systems has not yet appeared. Therefore, studying the impact of operational strategies on the performance of active solar heating systems by experiment to explore effective ways to optimize the systems.

2. MATERIALS AND METHODS

2.1 Solar composite heating system

The active solar composite heating system consists of the collector array, circulating pumps, valves, heat-dissipating devices (floor and solar kangs), heating cables, insulation materials and a controller. During the day, the vacuum tubes collect heat, which was stored in the tanks. The circulating pumps are used to supply the room at night. The collector array of the system consists of 7 sets of all-glass vacuum tube solar collectors. The vacuum tube of collectors are directly connected with the storage tank with an effective volume of 200 L, and the heat exchange of hot water between the vacuum tube and the storage tank is realized by convection. There are 30 all-glass vacuum collector tubes with a length of 1.8 m and a diameter of 58 mm in a solar collector. The total collectors area of the system is 20.2 m^2. In order to collect more solar radiant energy, the heat collector array is placed in the south direction, and the angle between the vacuum tube and the horizontal plane is 45°.

The power of the system mainly comes from 3 parallel pumps, all of which are 15WBX0.9-15, with rated power of 90 W, a maximum head of 15 m and a maximum flow rate of 0.9 m^3/h. The heat-dissipating device of the system are floor and kangs. The floor and kangs have the same pipe material of PPR and the diameter of 20 mm. The heating pipe is laid in a double-pass mode to ensure that the temperature distribution on the heat-dissipating devices surface during heating is more uniform. The pipes under floor with the distance between the pipes of 200 mm, and the distance from walls of 150 mm. The polystyrene foam board is used as the insulation layer under the floor heating pipes with a thickness of 50 mm, and 50 mm thick cement mortar is used as the filling layer. The screed layer has a thickness of 20 mm, and the surface layer is a wooden floor with a thickness of 8 mm.

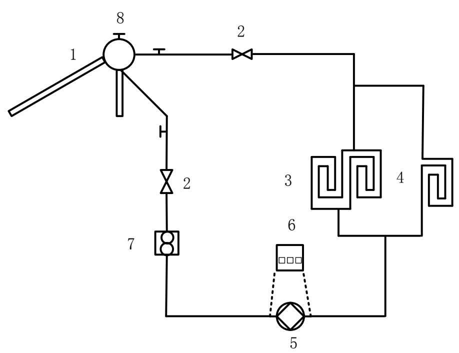

Fig.2. Diagram of the solar heating system. 1. Solar collector array. 2.Valves. 3.Floor heating pipes. 4. Kang pipes. 5. Water pump. 6. Controller. 7. Flow meter. 8. Temperature sensors.

The heating target is a rural single-storey building with a height of 2.8 m and total area of 170 m^2. There are no windows and doors in the east wall, west wall and north wall, but a passive house in the South. The actual heating room of the building is a living room, a bedroom and a study. The east side of the building is a kitchen without being heated, the actual heating area is about 60 m^2. The interior of the single building is equipped with 3 solar kangs, which all have the same size of 2.5 m long and 1.25 m wide. The physical plan view of the heating single building are shown in Fig.1 and Fig.2. There are 3 solar kangs in the single building. Each kang is the same size, 1.4 m long and 1.25 m wide. The supporting structural parameters and thermal performance of the heating single building of the solar composite heating system are shown in Table1 and Table2.

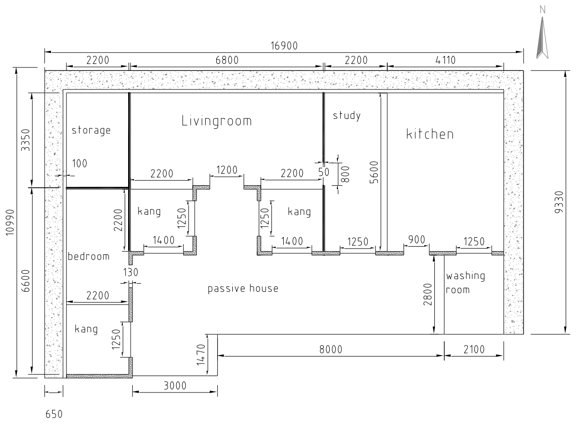

Fig.1. Plan of the single building.

Table 1

Construction envelope structure

Enclosure structure	structural materials
East Wall(kitchen)	65 cm Earthen wall
East Wall(bedroom)	11.5 cm Red brick+1.5 cm Cement plaster
South Wall	11.5 cm Red brick+1.5 cmCement plaster
West Wall	5 cm Wooden partition+10 cm Air layer+65 cm Earthen wall
North Wall	5 cmWooden partition+10 cmAir layer+65 cmEarthen wall
Window	Single glazed wooden window
Roof	50 cm Clay+30 cm hay+10 cm wood

Table 2

Envelope structure area and heat transfer coefficient

Enclosure structure	Area/ m^2	Heat transfer coefficient/$W·m^{-2}·K^{-1}$
East Wall(kitchen)	18.2	1.17
East Wall(bedroom)	8.7	2.26
South Wall	24.9	2.26
West Wall	30.5	0.81

North Wall	47.3	0.81
South Window	7.4	4.7

2.2 Research method

The paper make some researched on the effect of operational strategies on the heating performance of active solar composite heating system through experiment and theoretical analysis. By ensuring the values of other influencing factors being basically same, the interference caused by these factors on the heating performance of the system under different operating modes is eliminated, and the influence of the operational modes on the heating performance of the system is obtained, and then the comparative analysis of different weathers and different system heating parameters are carried out.

The average heating effect of the system explain the difference heating performance in the operational modes and the effect of accidental factors on the results is reduced, so that the accurate and reliable results are obtained. Finally the optimal operational strategy is finally obtained.

2.3 Experiment

The experiment measured various relevant parameters including supply temperature , return temperature, living room temperature, floor surface temperature, kang surface temperature, circulating flow rate, ambient temperature, ambient wind speed, and solar radiation intensity. The data was automatically acquired and recorded every 4 s by the Agilent 34970A.

The layout of the measuring points, the model and specifications of the instrument fully comply with the relevant testing standards, and the basic information of the experimental instruments are shown in Table 3.

There are 9 temperature measuring points on each kang surface and 2 measuring points of the living room air temperature and 2 temperature measuring points on the floor surface of living room. Select the two equal points on the diagonal of the living room as the measuring point to test the floor surface temperature at that point and the air temperature at 1.7 meters vertically. Place a measuring point for the return temperature and supply temperature at the inlet and outlet of the collector array. The measurement position of ambient temperature is at vertical height 1.5 m above the outdoor, 0.5 meters away from the wall. Place the radiometer on the open space of the roof without any obstruction testing solar radiation intensity, and use the compass to locate the south and fix it. Ambient wind speed measurement point is unobstructed at the roof. The turbine flow meter is mounted on the heating straight line supply pipe away from the curve.

Table 3

Test instruments and related parameters

Instruments	Model specification	Test parameters
Temperature sensor	Pt100; range -50 ~ 100 ℃; accuracy ± 0.1℃	Ambient temperature, indoor air temperature, supply temperature and return temperature
Patch temperature sensor	Pt100; range -50 ~ 100 ℃, accuracy: A grade ± 0.15 ℃	Floor surface temperature, kang surface temperature
Total solar radiation meter	TBQ-2;spectral range 0.3μm ~ 3μm; test range 0 ~ 2000W/ m^{-2}	Solar radiation intensity
Flow meter	Range: 0.45 ~ 9 m^3 / h; accuracy: 0.5%	Circulating flow rate
Ambient wind speed sensor	YGC-FS; range: 0 ~ 45 m / s, accuracy: 0.3 m / s	Ambient wind speed

2.4 calculation method

During the heating period from 18:00 to 8:00 next day, the internal energy variation of the active solar composite heating system can be mainly divided into two parts, one part is supplied to the single building through the heat-dissipating devices, and the other part is heat loss of the system.

The heat balance equation of the system is as follows:

$$Q_t = Q_w + Q_s \tag{1}$$

Where: Q_t is the amount of internal energy change of the system, Q_w is heat supply to the water-flowing side of the system, Q_s is the amount of heat loss of the system.

The formula for calculating the internal energy variation of the system is as follows:

$$Q_t = \Sigma M c_p \frac{dT_s}{dt} t \tag{2}$$

Where: M is the total mass of hot water in the system, c_p is the specific heat capacity of hot water, T_s is the temperature of water in the tank during heating at night.

The calculation formula of the heat supply of the system is as follows:

$$Q_w = \sum_{i=1}^{n} m(T_i - T_o) c_p \Delta\tau \tag{3}$$

Where: m is mass flow rate of hot water, t_i,t_o are the supply temperature and return temperature of the system, $\Delta\tau$ is the duration that circulating pump operates.

The heating efficiency calculation formula of the solar active heating system is as follows:

$$\eta = \frac{Q_w}{Q_t} \tag{4}$$

The operating energy consumption [21] of the system is calculated as follows:

$$P = P_d(a + b \bullet PLR + c \bullet PLR^2) \tag{5}$$

Where: P_d is the rated power of the circulating pump, *PLR* is the partial load ratio of the heat source utilized, the ratio of the actual output power to the rated output power. And a, b, c is the thermal load factor of the system. The load of the pump is constant and the flow rate is constant so that: a=1, b=0, c=0.

The average kang temperature is the mean temperature of measuring points on the kang surface during the heating period. The formula is as follows:

$$\overline{T}_k = \sum_{j=1}^{n} T_{kj} \tag{6}$$

Where: $\overline{T}_k$ is the average temperature of the kang surface, T_{kj} is instantaneous average temperature of the facet, n is the number of measuring points.

The change rate of the kang surface is the difference between the average temperature on the kang surface per unit time and the initial average temperature of the kang surface, which affect thermal comfort at night. Calculated formula is as follows:

$$\varphi = \left| \frac{\overline{T}_k - \overline{T}_{ka}}{\tau_2 - \tau_1} \right| \tag{7}$$

Where: φ is the average change rate of the kang surface, including the rate of rising φ_r and the rate of cooling φ_c, $\overline{T}_k$ is the average temperature of the kneading surface, $\overline{T}_{ka}$ is initial average kang surface temperature, τ is the experimental duration during heating stage.

3. RESULTS AND DISCUSSIONS

3.1 Living room temperature changes in on-off mode

Taking Nov. 10, 2018 as an example, the variation law of living room air temperature and floor surface temperature in active solar composite heating system in on-off regulation mode is analyzed. The average value of the two measuring points in the living room at a height of 1.7 m from the floor surface in the vertical direction is taken as the living room air temperature. Since the indoor air temperature of the residential building differs from the operating temperature by a small difference, it is considered that the living room air temperature is equal to the operating temperature [22]. As shown in Fig.3, the surface temperature of the heating floor gradually rises from the 18:00 to the highest value, and as the floor gradually descends, the air temperature in the living room changes slowly during this period. As the ambient temperature drops more, the heat dissipation of the single building increases, and the air temperature in the living room gradually decreases. As shown in Table 4, the air temperature fluctuation of the living room at night is in full compliance with the ASHARE-55-2004 standard.

Table 4

Indoor temperature fluctuations of heating period.

Time limit/h	0.25	0.5	1	2	4
Operating temperature/℃	1.1	1.7	2.2	2.8	3.3
Living room air temperature/℃	0.08	0.1	0.3	0.6	1.4

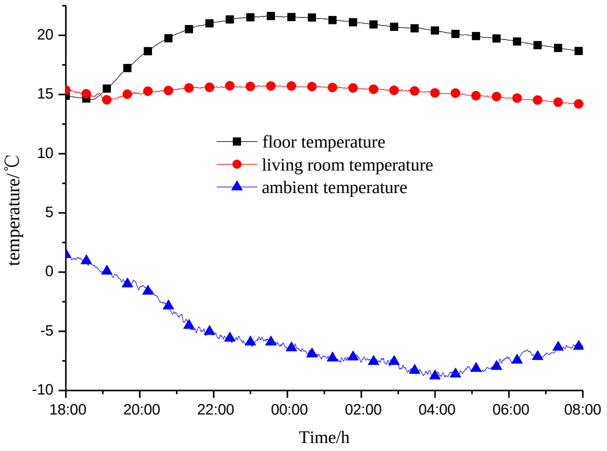

Fig.3. Change of floor temperature and living room air temperature during heating in Nov. 10 2018.

3.2 Heating performance in different on-off modes

The heating experiment days at the same heating time ratio of 50% are 18. From the ambient temperature at night, the initial supply temperature of the heating and the water temperature in storage tank, the factors that may affect the test results were compared. The factors affecting the nighttime heating were similar on Nov. 19 and Nov. 22, and Nov. 25 was compared and analyzed.

Table 5 shows the operation results of the solar active heating system in different on-off modes. It can be seen from Table 5 that the initial heating supply temperature on Nov. 19, Nov. 22, and Nov. 25 is about 70 °C. Under the condition that the environmental conditions are similar and the initial supply temperature is similar, the heat supply of different on-off modes indicates that in different modes, the heat supply is different. Therefore, in the case where the initial supply temperature of the system is about 70 °C, the solar heating system in different on-off modes has different heat supply, compared with 30/30 min and 20/20 min, the system provides the most heat supply in the 15/15 min mode.

Table 5

Comparison on thermal performance of the system in different on-off modes.

Date	T_a(℃)	T_i(℃)	Mode (min)	Q_w(MJ)
11-19	-7.1	55.7	15/15	313.84
11-22	-8.1	57.1	30/30	224.69
11-25	-5.9	56.4	20/20	229.05

The long-term results of calculating the nighttime average heating efficiency of the system in the 3 on-off modes in Table 6 reveal that the shorter the on-off time length of the circulating pump, the higher the average heating efficiency of the system, and the mode corresponded by average heating efficiency from high to low is: 15/15 min>20/20 min>30/30 min. Without increasing the running time of the circulating pump, the average heating efficiency of the system is increased by 4.15% from 30/30 min to 15/15 min. The energy consumption calculated in the 3 on-off modes at 18:00-day 8:00 are all 1.89 kW·h.

For the active solar heating system, longer the supply duration, more heat is supplied, but the average heat supply rate in the corresponding period is decreasing; during the intermittent duration, the law is same. Smaller the supply duration and intermittent duration, higher the heating efficiency. Therefore, the supply duration and the interruption duration of the active solar heating system should be smaller on the basis of safe and reliable operation.

Table 6

Long-term heating effect in different on-off modes.

Date	Mode(min)	T_i(℃)	T_a(℃)	Q_t(MJ)	Q_w(MJ)	η(%)
11-22	30/30	69.8	-8.1	592.49	224.05	37.81
11-28	30/30	68.8	-4.2	559.64	213.91	38.22
11-29	30/30	56.2	-1.7	443.79	164.71	37.11
12-05	30/30	61.0	-10.5	520.53	193.32	37.14
12-06	30/30	66.1	-10.2	562.82	207.86	36.93
12-07	30/30	47.3	-8.8	364.71	145.58	39.92
Mean						37.86
11-20	20/20	66.2	-8.4	545.56	207.28	37.99
11-21	20/20	63.9	-9.4	518.07	196.09	37.85
11-25	20/20	71.3	-5.9	573.35	222.05	38.73
11-27	20/20	63.2	-6.2	508.17	206.09	40.56
12-02	20/20	58.7	-8.9	457.12	175.76	38.45

12-04	20/20	57.1	-7.5	451.91	177.75 39.33
Mean					38.82
11-09	15/15	74.3	-2.8	582.26	250.03 42.94
11-19	15/15	70.1	-7.1	521.17	227.87 43.72
11-23	15/15	62.8	-3.9	452.86	189.20 41.78
11-24	15/15	55.6	-7.6	407.07	166.46 40.89
12-03	15/15	47.9	-8.9	359.31	144.38 40.18
12-09	15/15	57.3	-8.8	402.59	171.34 42.56
Mean					42.01

3.3 Variable flow rate modes

From 18:00 to 8:00 the next morning, 3 variable flow modes of the system have been designed, as shown in the table 7.

Table 7

Three variable flow rate modes.

Mode (kg/s)	18:00-0:00	0:00-4:00	4:00-8:00
A	0.26	0.20	0.32
B	0.20	0.26	0.32
C	0.32	0.26	0.20

As shown in Table 8, on Jan. 4, Dec. 30 and Jan. 8, the initial supply temperature all are about 61 ℃, the initial tank temperatures are about 51 ℃, and the average ambient temperature at night are 18:00-day 8:00 is approximately -11 ℃.

The heating effects in the 3 variable flow modes shows that the temperature changes more slowly of living room in the mode B, in which the average room temperature decline amplitude of the living room at night is 1.7 ℃, which is 1.5 ℃ and 0.5 ℃ lower than the temperature in the mode A and mode C, respectively.

Table 8

Variations of indoor air temperature in variable flow modes.

Date	T_a(℃)	T_n(℃)	T_i(℃)	T_d(℃)
01-04	-11.4	43.9	54.5	3.2
12-30	-12.5	44.3	53.4	1.7
01-08	-10.9	42.5	52.8	2.2

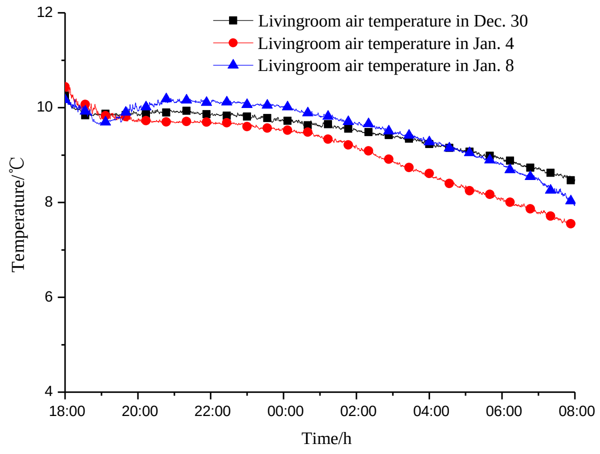

Fig.4. Indoor air temperature change in 3 variable flow modes.

During 18:00 to 8:00 next day, the average temperature on the kang surface basically reached the maximum during 2.5 h, and the average rising rate of the kang surface during the period is analyzed. Kang surface experienced a gradual decline during 22:00 to 8:00 next day, and the average cooling rate during the period is analyzed. The average rising rate in mode B is 2.6 °C/h lower than mode A and C by 0.8 °C/h and 1.8 °C/h, the average cooling rate of the kang surface is reduced by 0.2 °C/h and 0.4 °C/h, respectively.

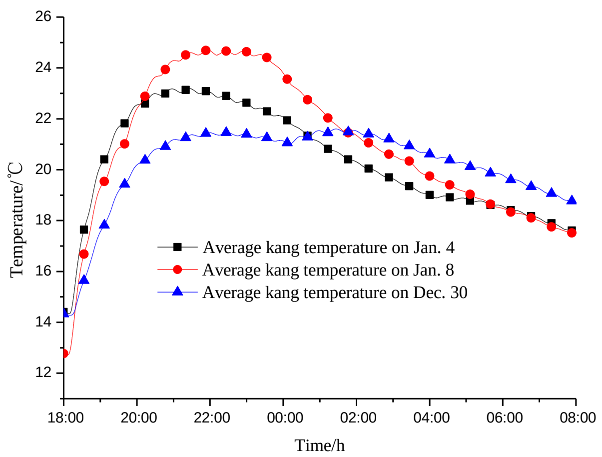

Fig.5. Average temperature change on kang surface in variable flow modes.

Table 9

Average temperature change on kang surface in variable flow modes.

Date	φ_r(℃/h)	φ_c(℃/h)
01-04	3.4	0.5
12-30	2.6	0.3
01-08	4.4	0.7

Considering the heating capacity of active solar heating system during heating period gradually decreasing, the use of small to large variable flow mode can significantly improve the heating process and thermal comfort of the system.

4. CONCLUSIONS

From the above researchs, we can get some conclusions. With the on-off time ratio is 50%, the operation energy consumption of the system is same in the 3 on-off modes. Compared with the 30/30 min, the average heating efficiency in the 15/15 min mode is increased by 4.15 %. The air temperature of the living room in variable flow mode B decreased by 1.7 °C, which is 0.5 °C and 1.5 °C lower than the variable flow mode A and mode C. The average heating rate of the kang surface in mode B is 2.6 °C/h, which is lower than that of mode A and mode C by 0.8 °C/h and 1.8 °C/h, respectively. the average cooling rate of the kang surface is reduced by 0.2 °C/h and 0.4 °C/h, respectively.

In comclusion, under the on-off time ratio of 50%, the optimal operational strategy of the system is to utilize 15/15 min mode combined with variable flow mode B to adjust the heating process to ensure that the system has high energy efficiency and thermal comfort.

Finally, we can infer that heating efficiency in the same heating time ratio of 50% has a maximum, the corresponding mode is that the supply duration is equal to the water replacement duration retained in the heating pipes, the hot water is continuously heating during the intermittent duration.

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REFERENCE

[1] Marco N , Jinzhang L , Kristy V , et al. Synthesis and applications of carbon nanomaterials for energy generation and storage[J]. Beilstein Journal of Nanotechnology, 2016, 7:149-196.

[2] Dai L , Li S , Duanmu L , et al. Experimental performance analysis of a solar assisted ground source heat pump system under different heating operation modes[J]. Applied Thermal Engineering, 2015, 75(75):325-333.

[3] Li H, Wei X, Zhen Y, et al. Discussion of a combined solar thermal and ground source heat pump system operation strategy for office heating[J]. Energy & Buildings, 2018, 162:42-53.

[4] Li W T , Thirugnanam K , Tushar W , et al. Improving the Operation of Solar Water Heating Systems in Green Buildings via Optimized Control Strategies[J]. IEEE Transactions on Industrial Informatics, 2018, PP(99):1-1.

[5] Forsström J P, Lund P D . Optimization of operating strategies in a community solar heating system[J]. Applied Mathematical Modelling, 1985, 9(2):117-124.

[6] Chun W G, Jeon M S, Lee Y S, et al. A thermal analysis of a radiant floor heating system using SERI-RES[J]. International Journal of Energy Research, 1999, 23(4):335-343.

[7] Kurtay C, Atilgan I, Ataer O E. Performance of solar energy driven floor heating system[J].Thermal Sciences and Technology, 2009, 29(1): 37—44.

[8] Wang Haitao. Research on thermal load characteristics of active solar heating intermittent operation [d]. Xi'an University of Architecture and Technology, 2010.(in Chinese).

[9] Zhang Zhicheng. Research on Optimization Method of Variable Flow Operation Strategy for Solar Air Heating System[D]. Dalian University of Technology, 2010. (in Chinese)

[10] Weeratunge H , Narsilio G , De Hoog J , et al. Model predictive control for a solar assisted ground source heat pump system[J]. Energy, 2018:S0360544218304882.

[11] Schiller S R , Warren M L , Wahlig M . Dynamic modeling and experimental simulation of active solar energy systems for the evaluation of control strategies[J]. American Society of Mechanical Engineers, 1980, -1.

[12] Wei Wei, Ji Jie, Luo Chenglong, et al. Experimental study on operation mode of composite solar energy enthalpy system[J]. Journal of Solar Energy, 2017, 38(3): 806-812 (in Chinese).

[13] Cho S H, Zaheer-Uddin M. An experimental study of multiple parameter switching control for radiant floor heating systems[J]. Energy, 1999, 24(5): 433-444.

[14] Fang Lide. Research on Dynamic Characteristics of New Heating Metering Control System [D]. Hebei University of Technology, 2005. (in Chinese).

[15] Wang S L, Yang X L, Chen J J. The Analysis of Adjustment Modes of District Heating System[J]. Advanced Materials Research, 2014, 919-921:1730-1734.

[16] Liu L, Fu L, Jiang Y. A new “wireless on-off control” technique for adjusting and metering household heat in district heating system[J]. Applied Thermal Engineering, 2012, 36(1):202-209.

[17] Liu L, Fu L, Jiang Y. An on-off regulation method by predicting the valve on-time ratio in district heating system[J]. Building Simulation, 2015, 8(6):665-672.

[18] Li Yemao, Xia Jianjun, Jiang Yi. Reducing the temperature of the return water of the heating network through the end-off control [J]. District Heating, 2015 (4): 45-49(in Chinese).

[19] Ulpiani G , Borgognoni M , Romagnoli A , et al. Comparing the performance of on/off, PID and fuzzy controllers applied to the heating system of an energy-efficient building.[J]. Energy and Buildings, 2016,（23）116-123.

[20] Xiang Xiangjian, Zhang Tao, Wu Mingyang and so on. Performance analysis of new on-off regulation method for concrete floors [J]. Warm air conditioning, 2017, 47 (3): 63-67 (in Chinese).

[21] Li L, Zaheeruddin M. A control strategy for energy optimal operation of a direct district heating system[J]. International Journal of Energy Research, 2004, 28(7):597-612.

[22] ASHRAE．Simplified Energy Analysis Using the Modified Bin Method[M]．Atlanta：America Society of Heating，Refrigeration and Air Conditioning Engineer Inc，1983：64—68．