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MODELING AND SIMULATION ON ENERGY PERFORMANCE OF DISTRIBUTED SMALL-SCALE SOLAR HEAT PROSUMERS IN DISTRICT HEATING SYSTEM

Hua Meng[1], Hai Wang[2]*

1 School of Mechanical Engineering, Tongji University, Shanghai, China 200092

2 School of Mechanical Engineering, Tongji University, Shanghai, China 200092 (Corresponding Author)

ABSTRACT

There are already numerous small-scale solar energy collectors on the roofs of buildings in many cities in China, which are used to provide domestic hot water in most circumstances. However, these separated small-scale solar energy collectors usually do not work sufficiently as expected, particularly for fear of pipe freezing crack in severe cold winter. On the other hand, these distributed small-scale solar energy collectors would have very convenient access to local district heating system. Hence, the buildings can consume the thermal energy from local district heating system and simultaneously produce heat to local district heating system when the solar energy collectors on their roofs are available. Therefore, the buildings can become solar heat prosumers to local district heating system. In this study, a configuration on solar heat prosumers is proposed to integrate with a general district heating system. Then a thermo-hydraulic model is developed to simulate the energy performance of distributed small-scale solar heat prosumers in district heating system. The proposed model is validated in a real life case study in a north Chinses city. The simulation results showed that the solar energy penetration was about 13% of the total heat consumption in heating season of 120 days.

Keywords: energy performance, district heating, solar energy, solar collector, prosumer

1. INTRODUCTION

In recent years, district heating (DH) has shown distinguished advantages on energy saving and carbon emission reduction for its potential benefits of integrating local renewables, heat storages, heat pumps and surplus energies, etc. [1,2]. The solar DH system can be integrated with distributed and centralized seasonal thermal storages to improve system overall efficiency and reduce DH network heat losses. In [3-5] the solar energy was utilized as central solar heat source or solar heat plant to provide heat power. However, the solar energy can also be collected by the small-scale plate solar collectors, which are often installed on the roofs of the buildings. Then the buildings with their solar collectors can be transformed from final energy users to energy producers, i.e. prosumers.

Lots of theoretical and practical studies on the prosumer are originally conducted within the electric power systems [6-8]. Until recently, the issues of prosumer technical have been raised in DH fields. Thermal prosumers are introduced to smart DH networks in terms of small-scale solar collectors and heat pumps are proposed in low temperature DH system [9]. Moreover, the performance of prosumer-involved DH solution was evaluated from environmental impact via a realistic case study in the authors' later work [10]. The management of proper supply water temperature and flow rate from prosumer to DH network for both space heating and domestic hot water could be rather difficult to handle. To address this challenge, [11] presented several different layouts for utilities substations, and indicated that the "return to supply" scheme could be widely adopted considering the bidirectional exchange of thermal energy in existing DH networks. A model is proposed and validated by a case study of a biomass powered DH network in Germany. Different solar thermal energy supply strategies are investigated and the maximal contribution is estimated for the heating energy demands [12]. Many studies are given on various

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aspects of prosumer operation and optimal control within DH systems [13-15]. A decentralized solar heat prosumer substation is incorporated into DH networks to optimize the distribution of solar heat gains and feed-in into the DH network and/or partly to local consumption [16]. A simulation model is presented to depict energy performance of decentralized solar thermal system, the potential contribution of prosumers is evaluated to the network demands as well [17]. Besides, some researches concern about the operation safety and economy for the prosumer system. A bi-level model is developed to determine an optimal balance between the load of DH sources and prosumer-owned heat sources [18]. The same authors further presented models of ensuring reliabilities of DH with prosumers, a potential economic benefit and reliability effect is also demonstrated [19].

Although plenty of work has been done, it can still be a rather difficult problem in previous literatures to manage hydraulic and thermal balance in a prosumer integrated DH system. In this paper, on the basis of a configuration on solar heat prosumers integrated with a general DH system, a thermo-hydraulic model was developed to simulate the energy performance of distributed small-scale solar heat prosumers in DH system. The model was evaluated and the conclusions were summarized.

2. CONFIGURATION

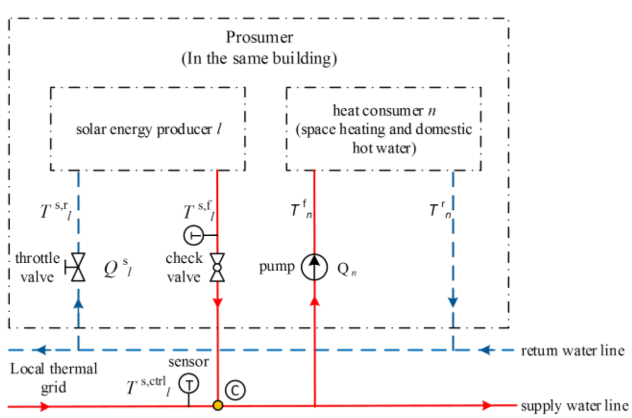

Fig.2.1 Hydraulic connection of a prosumer

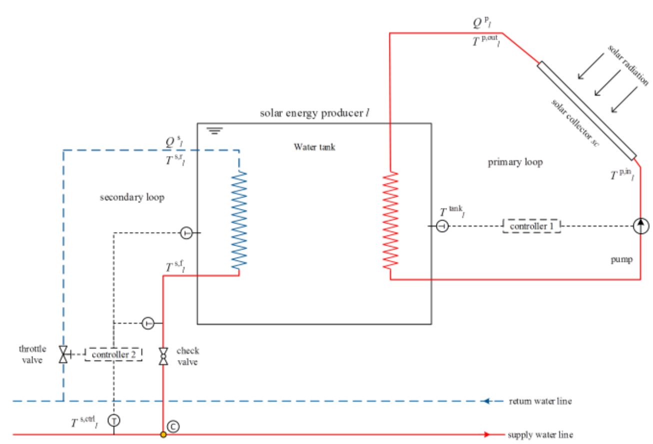

Fig.2.2 Configuration of a solar energy producer *l*

Fig.2. The proposed heating scheme of a solar energy prosumer in a district heating system

To the small-scale solar energy prosumers, how to arrange a suitable scheme to connect to the DH network would be the first issue to consider. A proposed heating scheme of the solar energy prosumers with solar collectors can be arranged as Fig. 2. In Fig. 2.1, the solar energy prosumer can involve two parts: (1) solar energy producer and (2) heat consumer. The former was deployed on the upstream of the supply water line to provide hot water to the local heat consumer part in the same building firstly. Besides that, the heat surplus would be provided to other buildings downstream. The solar energy can be collected by solar panels and transferred to return water via a heat exchanger. A schematic diagram of solar collection circuit configuration was shown in Fig. 2.2. The integration of a solar water heating prosumer can be of two hydraulic loops: the primary loop and the secondary loop. The primary loop is a small-scale solar energy collector subsystem which is comprised of panel solar collectors, a circulating pump, a water tank with heat exchanger coils inside, and valves, etc. The secondary loop is comprised of a check valve, a throttle valve and heating coils inside the water tank either. The check valve is installed by the outlet of the pipe from the tank in case of flow backwards. The throttle valve can adjust the flow rate of water from the return water line. Auxiliary heaters, such as air source heat pump or electric heater, often can be an alternative measure to increase water temperature of tank. Temperature sensors were also installed to control the circulating flow rate of both loops. The solar energy was collected as supplementary heat by some panel solar collectors on the roofs of the buildings and exploited as much as possible in a district scale

State the objectives of the work and provide an adequate background, avoiding a detailed literature survey or a summary of the results.

3. SOLAR PROSUMER MODEL

When the solar energy utilities were involved into the DH network, there would be always a challenge to manage the variant heat demands of consumers among the multiple heat producers in the context of changing outdoor temperature and intermittence of the solar energy collection. A steady-state hydraulic and thermal model was developed here.

For a solar prosumer, as shown in Fig. 2.2, controller 1 and controller 2 are installed to adjust flow rate of circulating water in the primary and secondary loops, respectively. The small-scale solar energy collectors can be panel solar collectors or vacuum tube collectors on the roofs of the buildings.

The modeling of a solar energy producer l is related to two hydraulic loops. The function of the primary loop is to collect solar energy as much as possible; the function of the secondary loop is to transfer the collected heat to the return water from local thermal grid.

In primary loop, the solar collector can be modeled according to European Standard EN12975 [20].

$$P^{\mathrm{sc}} = [a_0 G^{\mathrm{sc}} - a_1(\bar{T}^{\mathrm{sc}} - T_a) - a_2(\bar{T}^{\mathrm{sc}} - T_a)^2]A^{\mathrm{sc}} \quad (1)$$

Where, P^{sc} is the out power of the solar collector; G^{sc} is the global irradiance on the collector. $\bar{T}^{\mathrm{sc}}$ is the mean temperature of input and output of the collector water; T_a is the ambient temperature; A^{sc} is the surface area of the collector; a_0, a_1 and a_2 are the parameters related to the types of the collector which can be provided by the manufactory. The superscript "sc" is referred as "solar collector".

For flat-plane collectors, the global irradiance on the collector can be estimated as [22],

$$G^{\mathrm{sc}} = G^{\mathrm{dir}} cos(\alpha) + G^{\mathrm{dif}} \frac{1+cos(\beta)}{2} + \gamma G^{\mathrm{gnd}} \frac{1-cos(\beta)}{2} \quad (2)$$

Where, G^{dir} is the irradiance from the direct radiation; G^{dif} is the irradiance from the diffuse radiation; and G^{gnd} is the radiance from the ground reflected radiation. α is the incidence angle between the solar beam and the normal to the collector; β is collector tilt angle; γ is an experimental parameter usually between 0.1-0.3.

To utilize solar energy more efficiently, the control strategies of the two hydraulic loops should be well designed. In the primary loop, a cooler input temperature $T_l^{\mathrm{p,in}}$ is preferred for the collectors, while a higher water temperature of tank $T_l^{\mathrm{p,out}}$ is required for heat coils. So the temperature of the tank T_l^{tank} needs to be compromised to keep in a reasonable range, such 50-90℃. In this model, a variable speed pump is installed. The temperature of the tank T_l^{tank} and the local solar irradiation information can be input signals for the controller "1" to adjust the rotation speed of the pump. In the secondary loop, the flow rate Q_l^s should be regulated by a throttle valve to keep the temperature difference, $\left|T_l^{\mathrm{s,ctrl}} - T_l^{\mathrm{s,f}}\right|$ to be as low as possible. The temperatures of $T_l^{\mathrm{s,f}}$ and $T_l^{\mathrm{s,ctrl}}$ as well as the temperature T_l^{tank} can be input signals for the controller "2" to adjust the openness of the throttle valve.

The pipe network can be modeled based on the Kirchhoff's law analogy to the electric circuit, according to the graph theory, more details refer our previous paper [23].

4. OPTIMIZATION

The optimization model for a DH scheme should considerate the minimization of operation costs and fulfillment of the heat users' demands simultaneously in a period of heating. Then the objective function in the model can be comprised of several indicators including the operation costs and the fulfillment extent of heat users' demands which was firstly proposed in this paper. The indicators are as following.

The first indicator can be the heat costs from boilers or substations. The total heat cost in a period of T_h (hour) can be written as,

$$C_F = \sum_{t=1}^{T_h} \left(\sum_{b=1}^{B} PriceH_b \cdot H_b + \sum_{m=1}^{M} PriceH_m \cdot H_m \right) \quad (3)$$

Where, C_F is the total heat costs of a DH scheme in a week, CNY/week; $PriceH_b$ is the heat price from a boiler *b*, CNY/GJ; $PriceH_m$ is the heat price from a substation *m*, CNY/GJ; H_b is the heat provided from a boiler *b*, GJ/hour; H_m is the heat provide from a substation *m*, GJ/hour.

The second indicator can be the costs of power consumption of all circulating pumps. The total electricity cost in a week can be written as,

$$C_E = \sum_{t=1}^{T_h} \left(\sum_{b=1}^{B} PriceE_b \cdot W_b + \sum_{m=1}^{M} PriceE_m \cdot W_m + \sum_{n=1}^{N} PriceE_n \cdot W_n + \sum_{l=1}^{L} PriceE_l \cdot W_l \right) \quad (4)$$

Where, C_E is the total electricity costs of a DH scheme in a week, CNY/week; $PriceE_b$, $PriceE_m$ and $PriceE_n$ are the electricity prices of the circulating pumps in a boiler *b*, substation *m*, heat user *n*, and prosumer l, respectively, CNY/kw.h; W_b, W_m, W_n and W_l are their power consumptions accordingly, kw.

The third indicator can be the extent of the fulfillment that measue the gap between the actual provided heat and the heat demand of each heat user. Then the gap in a week can be estimated as,

$$Gap_H = \sum_{t=1}^{T_h} \left[\gamma \cdot \left(\sum_{n=1}^{N} \left| H_n - H_n^{dem} \right| \right) \right] \qquad (5)$$

Where, γ is a penalty factor, which reflects the emphasis on the gap between the actual heat H_n and heat demand H_n^{dem}. The larger the γ is set, the more emphasis the gap would be. For an optimal heating scheme to fulfill the heat demands of all heat users, the value of Gap_H should be close to zero. To keep in consistent with other indicators, the penalty factor γ should be measured by "CNY/GJ" as well; and the indicator Gap_H is measured by "CNY/week". This indicator is firstly presented by this paper to search more possible heating schemes. And this indicator can reflects indirectly the heat losses during network transportation and the heat from solar prosumers. On the other hand, this indicator can also effectively avoid much iterating process during hydraulic simulation of a possible heating scheme. This advantage can be experienced particularly when some intelligent algorithms, such as genetic algorithms, are employed to solve this optimization model.

The feathers of the operation optimization model are illustrated in the Table 1.

Table.1 The operation optimization model for a DH scheme.

Objective function	$\min\left(C_F + C_E + Gap_H\right)$			
Decision variables	$T_b^f,\ T_m^f,\ T_l^f,\ \dot{M}_b,\ \dot{M}_m,\ \dot{M}_l,\ \dot{M}_n$			
S.T	$\dot{M}_b^{min} \le \dot{M}_b \le \dot{M}_b^{max}$ (6.1)	$\dot{M}_m^{min} \le \dot{M}_m \le \dot{M}_m^{max}$ (7.1)	$\dot{M}_l^{min} \le \dot{M}_l \le \dot{M}_l^{max}$ (8.1)	$\dot{M}_n^{min} \le \dot{M}_n \le \dot{M}_n^{max}$ (9.1)
	$\Delta P_b^{min} \le \Delta P_b \le \Delta P_b^{max}$ (6.2)	$\Delta P_m^{min} \le \Delta P_m \le \Delta P_m^{max}$ (7.2)	$\Delta P_l^{min} \le \Delta P_l \le \Delta P_l^{max}$ (8.2)	$\Delta P_n^{min} \le \Delta P_n \le \Delta P_n^{max}$ (9.2)
	$T_b^{f,min} \le T_b^f \le T_b^{f,max}$ (6.3)	$T_m^{f,min} \le T_m^f \le T_m^{f,max}$ (7.3)	$T_l^{f,min} \le T_l^f \le T_l^{f,max}$ (8.3)	
	$b \in \{1, \cdots, B\}$	$m \in \{1, \cdots, M\}$	$l \in \{1, \cdots, L\}$	$n \in \{1, \cdots, N\}$
	(6.1)	(7)	(8)	(9)

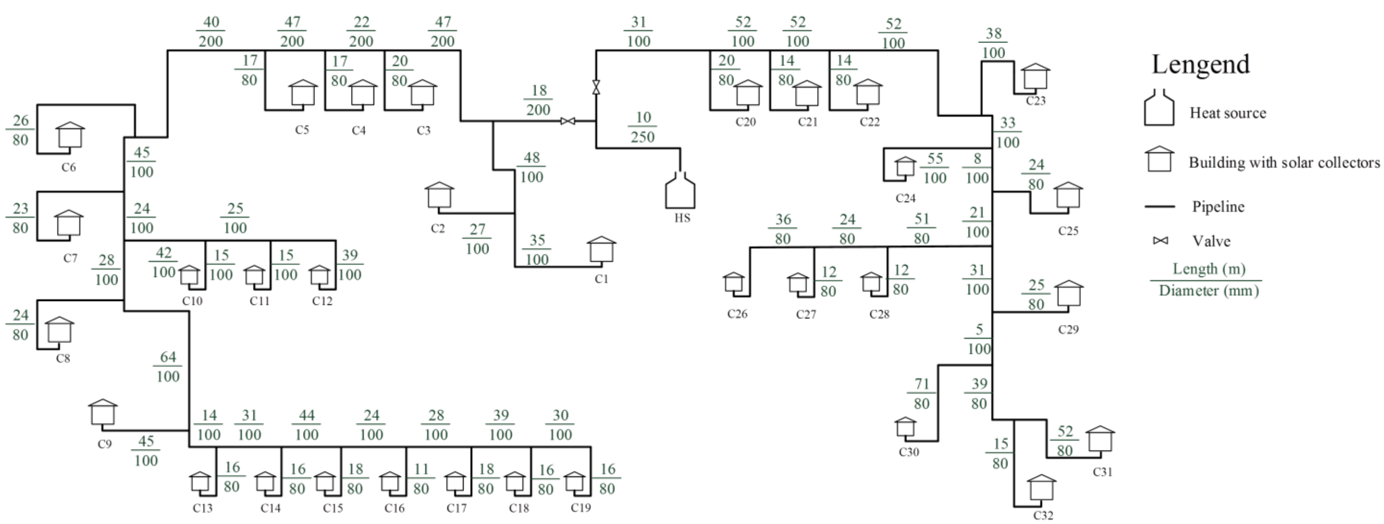

Fig.3 A DH system with solar heating prosumers.

Eqs. (6.1)-(6.3) are the constraints for the circulating flow rate, head of the circulating pump and supply water temperature of each boiler, respectively. Similarly, Eqs. (7.1)-(7.3) and Eqs. (8.1)-(8.3) are constraints for each substation and prosumer, respectively. The Eqs. (9.1)-(9.2) are constraints for the circulating flow rate and head of the circulating pump of each heat user.

5. CASE STUDY

A real-life DH system in Tianjin, China was illustrated to validate the model of solar heat prosumers integrated with a general DH system. The diagram of the DH system was shown in Fig. 3.

There were one heat source (HS) and 32 buildings (C1~C32) in this DH system. The total heating area was about 26000 m2. The total solar collector area on the roofs of the buildings was about 1982 m2. By considering the weather condition of Tianjin from Nov. 2017 to Feb. 2018, the simulation by the proposed model can be performed in a heating season (totally 120 days). According to the total heat demand of the customers, the solar heat that can be utilized was simulated each day in the heating season, as shown in Fig. 4. The total heat that was supplied to the customers came from the heat substation and solar collectors. The solar heat that can be collected mainly depended on the weather condition and the collectors' area. Therefore, the total utilized solar heats were fluctuated and averaged to 0.012 GJ/day.

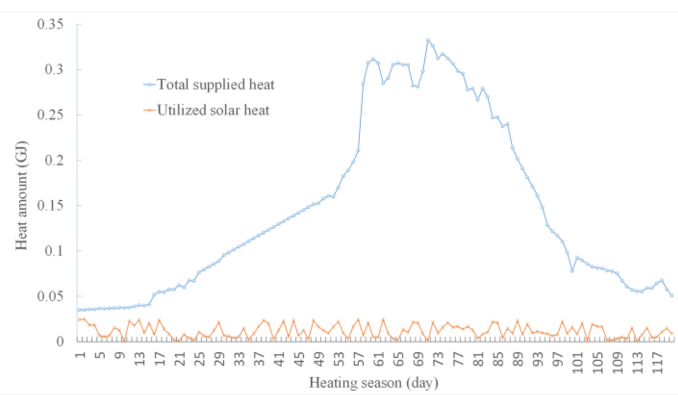

Fig. 4 the total supplied heat and utilized solar heat

The ratios between the utilized solar heat and total supplied heat each day in the heating season were shown in Fig. 5. The maximum ratio was 70.58 %; the minimum ratio was 0.36%; the average ratio was 13.02 %. Therefore, the solar heat from roof collectors can be a well supplementary energy source for local DH system.

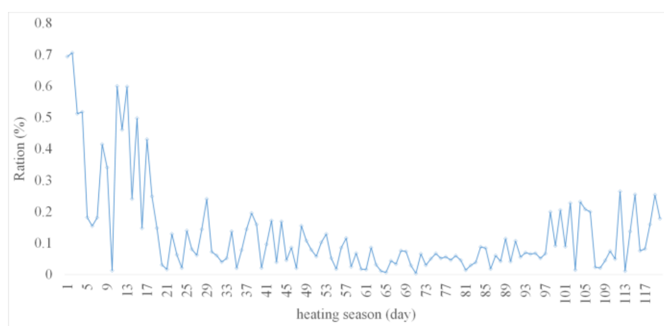

Fig. 5 the ratio between the utilized solar heat and the total supplied heat

6. CONCLUSION

There are numerous small-scale solar energy collectors on the roofs of buildings in many cities in China, which can be used to provide hot water to local DH system. Hence, the buildings can be prosumers which consume the thermal energy from local district heating system and simultaneously produce heat to local DH system. In this study, a method is presented to integrate solar collectors to local DH system. The main conclusion can be summarized here.

(1) A configuration of prosumer is proposed to connect solar collectors on roofs to local DH system. Then the heat costumers can provide their solar heat to DH system without disturbing their consumption simultaneously.

(2) A thermo-hydraulic model is developed to simulate the energy performance of distributed small-scale solar heat prosumers in DH system. The model can be used to evaluate the solar heat utilization in such a solar prosumer involved DH system.

(3) The proposed model is validated in a real-life case study in Tianjin. The simulation results showed that the solar energy penetration was about 13 % in average of the total supplied heat in a heating season of 120 days

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