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Simulation Study of the Operation of Solar Thermal Systems Consisting of Uncovered Collectors and/or an Air-to-Water Heat Exchanger

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Abstract

For the operation of the district heating net in Bishkek (Kyrgyzstan) a huge amount of water of about 12°C has to be heated up to 60°C in summer and 90°C in winter. As in summer the ambient air temperature usually is higher than 20°C even during the night, the enthalpy of the air can be used to preheat the cold water additionally to the solar irradiance. A simulation study of the operation of an uncovered solar collector, an air-to-water heat exchanger and a serial connection of both has been carried out in order to optimize their operation and to compare their performances. It has been identified that for Bishkek conditions the effectiveness of all three options with suitable layout is almost the same. Furthermore, the potential of an optimal control of all configurations has been identified to be rather low. Therefore, as a preliminary result it can be recommended to plan and to operate such systems with constant flow rates.

Keywords: multicomponent system, district heating, operation investigations

1. Introduction

The district heating net in Bishkek (Kyrgyzstan)[1] as in many other cities of the former Soviet Union is usually constructed (unlike in Central Europe) as an open-circuit system. Domestic hot water is taken directly out of the net without any heat exchanger coupling. Thus, in Bishkek a huge amount of water of about 12°C has to be refilled into the net and heated up to 60°C. This is carried out at one central heat and power plant.

A new kind of solar heating system is being investigated theoretically and experimentally to preheat the cold water by the use of solar irradiance as well as heat of the ambient air, which in summer is almost always much warmer than 12°C even during the night. The so-called multicomponent solar thermal system [1] consists of unglazed transpired air collectors, an air-to-water heat exchanger and uncovered solar collectors (cf. Fig. 1).

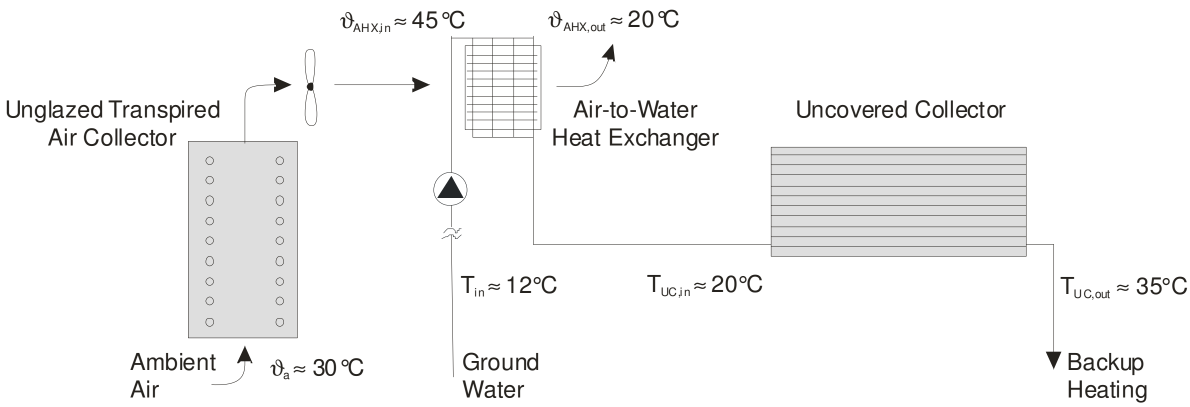

Figure 1: Scheme of the serial connection of a multicomponent solar thermal system with exemplary temperatures [1].

[1] Kyrgyzstan is located in Central Asia, strength intercontinental climate (hot summers and cold winters). The latitude of Bishkek is 43° north (comparable with Rome). Bishkek has about one million inhabitants.

The enthalpy of the air flow that is heated up above ambient temperature in the unglazed transpired air collectors is transferred to the water in an air-to-water heat exchanger. The water is further heated up by uncovered solar collectors. Finally, the water is led to the back-up heater and further to the district heat supply. If the water inlet temperature even lies below the dew point temperature, energy gains by condensation can be expected on parts or even all over the heat exchanger area and/or the uncovered collector surface. Such multicomponent systems can be operated without any storage due to the permanently high heat demand and existing hot water storages after a back-up heating.

Due to the construction of the district heating net and excellent climatic conditions very high specific solar gains can be achieved with such a system. However, at different locations it might be advantageous to install less complex systems consisting of only one or two components mainly depending on the regional climate and the hot water consumption of a specific location. In the presented simulation study, only the operation of uncovered solar collector, an air-to-water heat exchanger and a serial connection of both has been investigated.

The simulation study is based on mathematical models of uncovered collectors [2] and fin-and-tube heat exchangers [3] which have been implemented in TRNSYS. The main assumptions of the uncovered collector model are a linear increase of the absorber surface temperature in direction of the fluid flow and an even distribution of the flow through all absorber channels connected in parallel. The heat exchanger model is based on heat transfer correlations and considers the coil geometry. The models have been adapted to the unconventional operating conditions using measurement data in case of the uncovered collector and an accurate producer-specific heat exchanger design software in case of the heat exchanger [4]. Both models take into account possible condensation energy gains.

2. Investigated system configurations

2.1 Simulation parameters

For the simulations the water inlet temperature of the system configurations had been set to 12°C. The simulation period is from May 1st until October 1st (3672 hours) with a time step of one hour. In this frost-free period no heat for space heating is needed in Bishkek, so that only domestic hot water has to be provided. Meteorological data for the simulation study has been generated with Meteronorm 3.0 [5]. According to these data, the average ambient air temperature in the investigation period is 28.5°C at day and 20°C at night with peaks of approximately 40°C. The average value of the relative humidity is 45%, that of the long wave sky radiation is about 360 W/m² and the average wind speed is about 2.2 m/s.

2.2 Uncovered solar collectors

Uncovered collectors are well-known in Central Europe for heating swimming pools and made of artificial rubber (EPDM). Some parameters of the applied uncovered collectors are listed in Table 1. Five system configurations of uncovered collectors have been selected for the investigations, each with 100 m² collector area, but with different hydraulics laid out for nominal specific flow rates of 80, 120, 160, 200 and 240 $l/m^2_{uc}h$.

Table 1 Parameters of the investigated uncovered collectors [6]

Manufacturer/Type	GEBaU-SolarAbsorber
Material	Ethylene-Propylene-Diene-Monomer
Thermal efficiency η_0	84,5%
Allowable operating pressure	1,5 bar
Recommended specific flow rates	80…120 l/m²h
Internal heat transfer coefficient h_i	200 W/m²K [7]
Effective emission coefficient ε	0,8 [8]
Absorption coefficient α	0,95 [8]
Convective heat transfer coefficients U_{c0} and U_{c1}	13,0 W/m²K and 9,0 Ws/m³K [9]

2.3 Air-to-water heat exchanger

Fin-and-tube heat exchangers proved to be very efficient for heat transfer between a gas and a liquid. This kind of heat exchanger is applied in a multicomponent solar thermal system that is being investigated experimentally in Bishkek [1]. Its parameters are listed in Table 2. The heat exchanger is laid out for a water flow rate of 6 m³/h and an air flow rate of 10000 m³/h (i.e. for a recommended heat capacity rate ratio (water/air) of approximately 2.0).

Five heat exchanger configurations with heat capacity rate ratios of 1.0, 1.5, 2.0, 2.5 and 3.0 have been investigated in the simulation study. The heat exchanger is the same in all configurations, but equipped with different fans. The water flow rate has been limited to 8 m³/h as the heat exchanger is only suitable for a water flow rates up to 9 m³/h according to the recommendation given by the producer. The heat capacity rate ratio has been set constant in each configuration.

Table 2 Parameters of the investigated fin-and-tube heat exchanger

Parameters	Value	Unit
Manufacturer	Güntner GmbH	
Fin and coil width and height	1275 x 1050	mm
Fin thickness; fin pitch	0.25 ; 3	mm
Outside and inside diameter of tube	12 and 11.36	mm
Number of tube rows	12	-
Number of passes in a tube row	10	-
Heat transfer area	126	m²
Fin type	Smooth wavy	
Fin/tube material	Aluminium/copper	

2.4 Serial connection

The operation of a serial connection of one fin-and-tube heat exchanger and 100 m² uncovered collectors is also investigated with water flow rates up to 8 m³/h and heat capacity rate ratios of 1.0, 1.5, 2.0, 2.5 and 3.0.

2.5 Pipes, pumps and fans

To take into account parasitic energy, hydraulics (pump and pipes) and axial fans have been laid out for each system configuration. In case of the operation with matched flow rates, pumps and fans have been equipped with speed control by frequency inverter. The power consumption was determined using technical data and producer design software.

3. Operation and planning investigations

Each system configuration has been simulated with water flow rates constant over the simulation period (25, 37.5, 50, 62.5, 75, 87.5 and 100% of the nominal flow rates without any control). Furthermore, simulations with matched flow rates have been carried out. There, in each time step the flow rate leading to the maximal net solar heat gains (the difference between energy gains and parasitic energy demand[2]) for boundary conditions at this time step has been set. In this way an optimal constant flow rate and a control potential can be determined for each configuration. The control potential is represented by a difference between the energy gains of the system operated with the optimal constant flow rate and the energy gains with matched flow rates.

The system configurations have also been compared regarding their solar heat prices. The solar heat price SHP has been calculated as the quotient of annuity AN and system energy gains Q_{use} neglecting interest rates.

$$SHP = \frac{AN}{Q_{use}} = \frac{I/L + W_{par} \cdot EP + M}{Q_{use}} \qquad \frac{€}{kWh} \qquad (1)$$

The capital investment I consists of the system purchase costs and installation costs, which are assumed to be 10% of the system purchase costs. Annual maintenance costs M are

[2] Hereby, parasitic energy is evaluated with a factor of 3 to be able to consider the different kinds of energy (electrical and thermal).

assumed to be 2% of the system purchase costs. The component prices[3] are valid for Germany including 16% VAT, which have not to be paid if installed in Kyrgyzstan. Transport costs to Kyrgyzstan and possible Kyrgyz import duties are not considered due to the wide range of prices and the lack of necessary data. The operation time L is 10 years; however, solar heating systems are often calculated with an operation time of 20 years. Assuming 10 years instead of 20 and using prices with 16% VAT would increase the SHP and in this way partially compensate the neglect of interest rates, transport costs etc. The electricity price EP in Kyrgyzstan is currently 0.02 €/kWh$_{el}$. Q_{use} is the annual energy gain and W_{par} is the annual parasitic (electrical) energy demand.

3.1 Uncovered solar collectors

The results show that the highest specific solar energy gains of about 1760 kWh/m²$_{uc}$a can be expected at the operation with a constant specific water flow rate of 200 l/m²$_{uc}$h, cf. Fig. 2a. Such high energy gains can be explained by high irradiance (54% of the simulated annual energy gains) and convective energy gains (50%[4]) as in this application the ambient air temperature is higher than the fluid temperature. Condensation energy gains (1%) and long-wave losses (5%) have only minor contributions. The control potential for all configurations is less than 1% so that it can be recommended to operate all configurations with an optimal constant water flow rate without any control.

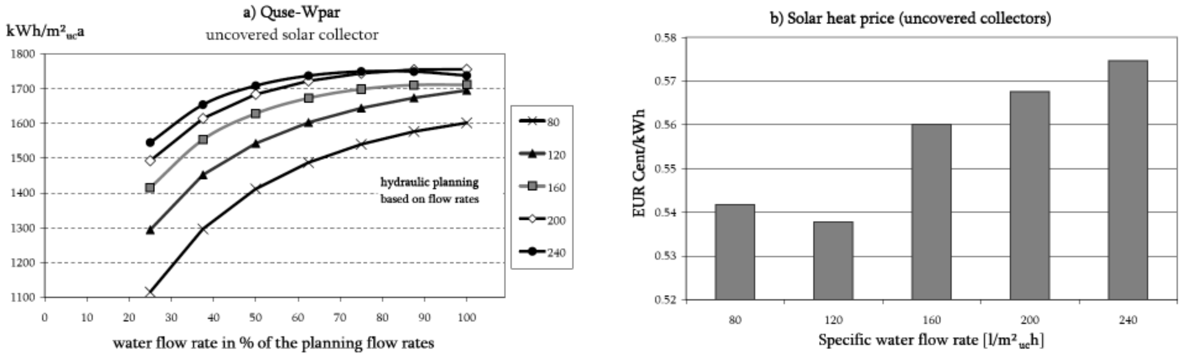

Figure 2: Net solar heat gains without any control at constant flow rates (a) and solar heat price (b) of uncovered collectors used in the described application.

According to Fig. 2b the planning and operation of uncovered collectors is the most cost-effective at the specific water flow rate of 120 l/m²$_{uc}$h for preheating of water in the district heating nets in Bishkek. At this operation a solar heat price of about 0.54 Cent/kWh has been calculated. However, solar heat prices at the specific water flow rates of 80, 160 and 200 l/m²$_{uc}$h are only slightly higher (less than 5%) due to the very low electricity price.

3.2 Air-to-water heat exchanger

The highest energy gains of about 112 MWh/a can be achieved at the maximal water flow rate of 8 m³/h and a heat capacity rate ratio of 1.5 (cf. Fig. 3a). The highest control potential of 7.5% is that of the configuration with a heat capacity rate ratio of 1.0. However, for this configuration energy gains with matched flow rates are 108 MWh/a. The control potential of the other four configurations is less than 1.5%, so that in case of the heat exchanger also no control is necessary. The optimal operation has been identified to be at a constant water flow rate of 8 m³/h and a heat capacity rate ratio of 1.5 (cf. Fig. 3 a, b).

However, Fig. 3a indicates that the water flow rate may be increased which would cross the limit set by the manufacturer for reasonable operation. The heat exchanger seems not to be adapted for this application and as far as the authors know no standard heat exchanger exists so far to heat up huge amounts of cold water with ambient air.

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[3] Following component prices have been assumed: uncovered collectors 5000 EUR (50 EUR/m²$_{uc}$); heat exchanger 2550 EUR; pipes, pumps and fans according to price lists.

[4] High convective energy gains could be caused by high values of convective heat transfer coefficients U_{c0} and U_{c1}

At the optimal operation the investigated model of the air-to-water heat exchanger can deliver heat at 0.57 Cent/kWh, which is 5% higher than that of uncovered collectors. However, as transport costs are not taken into account (the heat exchanger is much more compact than uncovered collectors), it can be said that both are equally effective for given boundary conditions (water inlet temperature, permanent water demand, climate, electricity price). With higher electricity prices it would be advantageous to apply uncovered collectors instead of heat exchangers due to the significantly higher parasitic energy demand of the latter.

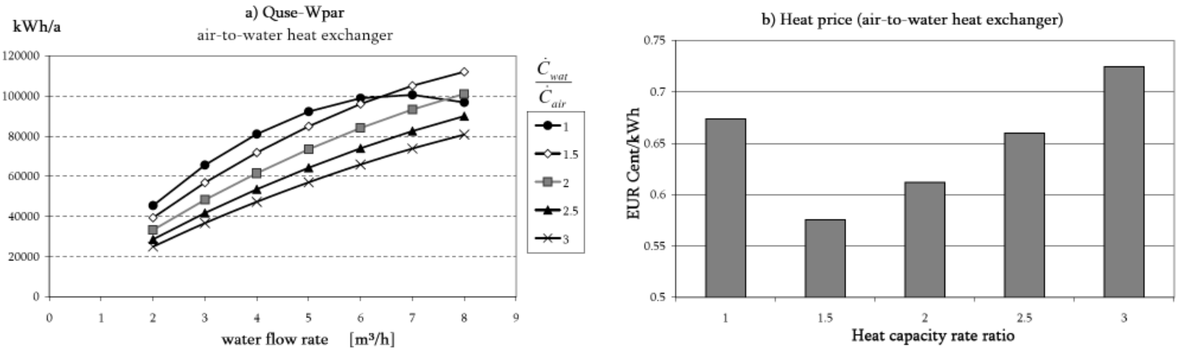

Figure 3: Net heat gains without any control at constant flow rates (a) and heat price (b) of an air-to-water heat exchanger used in the described application.

3.3 Serial connection

For a serial connection of an air-to-water heat exchanger and 100 m² uncovered collector the optimal operation has been identified to be at a constant water flow rate of 8 m³/h and a heat capacity rate ratio of 1.5 (cf, Fig. 4 a, b). Again, the control potential is lower than 1%, so that no advanced control strategy is necessary. At the optimal operation energy gains of approx. 235 MWh/a can be achieved. In a serial connection the uncovered collector achieves approx. 75% of its solar energy gains if it would be operated without the heat exchanger, which increases the water inlet temperature of the uncovered collector. Nevertheless, the serial connection is almost equally effective as the uncovered collector and the heat exchanger (SHP=0.55 Cent/kWh) because of the reduction of the specific hydraulic costs.

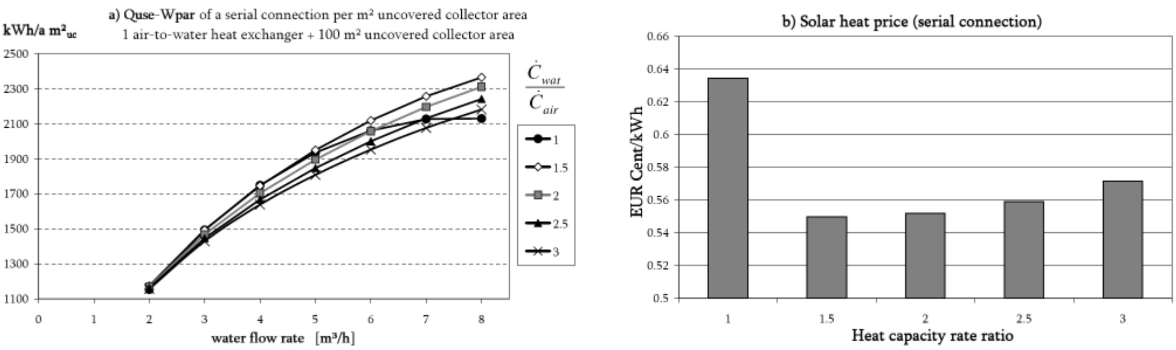

Figure 4: Net heat gains without any control at constant flow rates (a) and solar heat price (b) of a serial connection

4. Conclusions and Outlook

Investigations of the operation of solar thermal systems, consisting of uncovered collectors and/or an air-to-water heat exchanger, for the preheating of water in open-circuit district heating nets showed that these systems can achieve remarkably high energy gains at prices of about 0.5 Cent/kWh, which is below today's world market prices for oil and gas. Furthermore, for each system the optimal operation has been identified and in all cases the control potential has been estimated to be rather low. For given boundary conditions (water inlet temperature, permanent water demand, climate, electricity price) an uncovered collector, an air-to-water heat exchanger and a serial connection of both are almost equally effective so that for the selection of the most appropriate system technical constraints are decisive, e.g. the area on the roof or tolerable noise emissions etc.

However, these results are only valid for the investigated systems, which have not been yet optimized regarding dimensioning of the components and the configuration of the heat exchanger. Therefore, in a next step optimization calculations shall be carried out coupling with system simulations and using component cost functions. The described investigation method of the operation could be either directly implemented in the optimization calculations or applied later on the optimization results.

Furthermore, the described investigation method of the operation can be extended to the consideration of interest rates, transport costs, customs etc. if necessary.

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