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Уважаеми колеги,

Организационният комитет на международната научна конференция EE§AE 2015 одобри Вашата статия“ Investigation methods of hybrid Ground Source Heat Pump system with solar collectors“ за отпечатване в Proceedings of the Union of Scientists –Energy Efficiency and Agricultural Engineering 2015.
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Investigation methods of hybrid Ground Source Heat Pump system with solar collectors

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Abstract: *Methods to investigate a hybrid Ground Source Heat Pump (GSHP) system with solar collectors were devised. The aim of the methods is to determine the thermal characteristics of the system at different operation regimes depending on the season and the heating loads. The investigation procedure is mentioned in the article. The determination of the solar collector efficiency, the coefficient of performance (COP) of the heat pump, the efficiency of the borehole heat exchangers (BHE) and the efficiencies of the hybrid system at different operation regimes is presented. The investigation conditions, the processing of the test data and the accuracy of the measured parameters are discussed.*

Key Words: *Investigation methods, Ground Source Heat Pump, Solar collectors, Hybrid system.*

NOMENCLATURE

A - area, m^2;
c - specific heat capacity, J/kgK;
COP - coefficient of performance;
I - intensity of solar radiation, W/m^2;
m - mass, kg;
$\dot{m}$ - mass flow rate, kg/s;
N - electrical power, W;
$\dot{Q}$ - heat flux, W;
t - temperature, °C;
δ - declination, °;
η - efficiency;
φ - geographic latitude, °;
τ - time, s; h; d.

SUBSCRIPTS

150 - 150l water container;
2-3 - 200l to 300l water containers;
3-2 - 300l to 200l water containers;
2-sc - between 200l water container and solar collectors;
a - ambient;
ab - absorber;
AES – additional energy source;
BHE - borehole heat exchanger;
c - condenser;
cv - convector;
end - end;
ext - extracted;
ev - evaporator;
hp - heat pump;
i - inlet;
in - initial;
inj - injected;
lab - laboratory;
loss - loss;
o - outlet;
s - system;
sc - solar collector;
st – storage.

INVESTIGATION OBJECTIVE

The main methods objective is the determination of the thermal characteristics of a hybrid Ground Source Heat Pump system with solar collectors for heating at different operation modes dependent on the season and the heating loads. The set-up of the hybrid Ground Source Heat Pump system with solar collectors is presented in Fig. 1 [1].

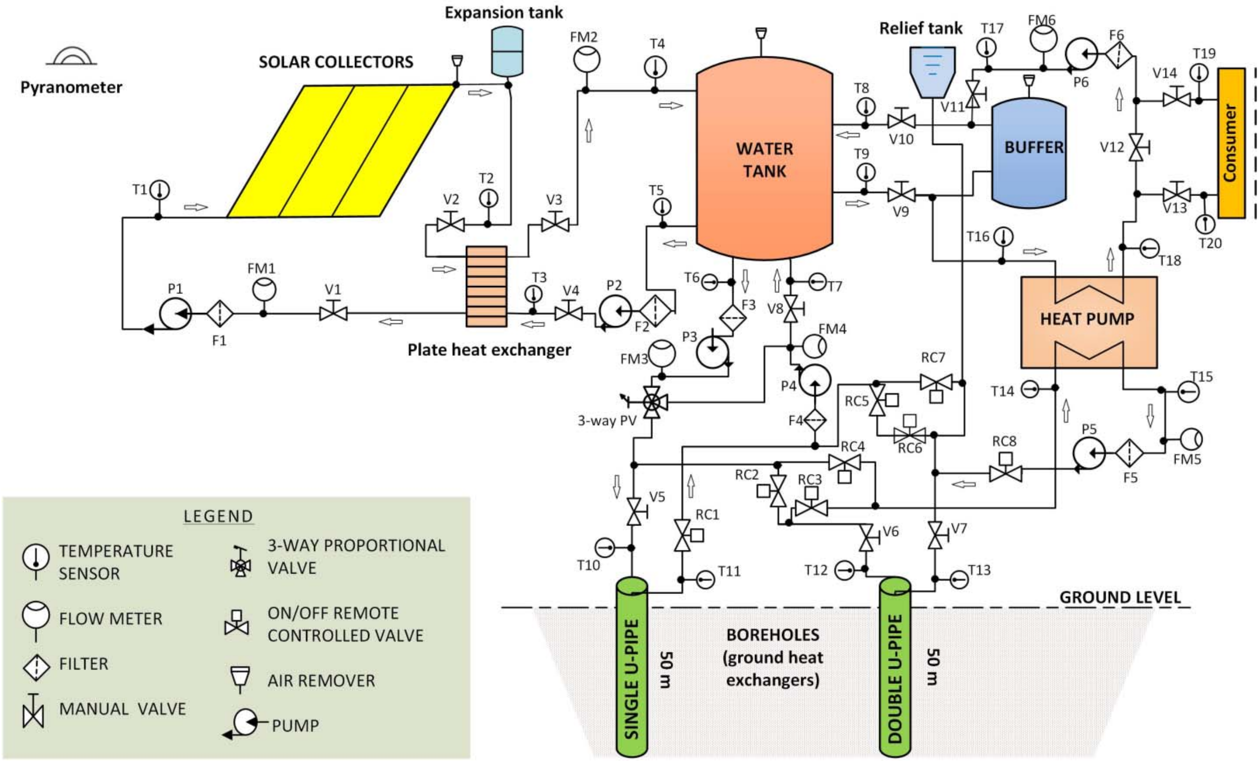

Fig. 1. Set-up of the hybrid Ground Source Heat Pump system with solar collectors [1]

TEST CONDITIONS

The following data must accompany every system component which is a subject to testing:

Solar collectors:

- collector size;
- receiving surface of the absorber;
- collector mass;
- collector fluid type and amount;
- operation pressure;
- absorber material and mass;
- characteristics of the absorber coating material;
- type, thickness and operation temperature of the thermal insulation;
- material and mass of the collector case.

Heat pump:

- heat pump (HP) type;
- compressor type;
- nominal electrical power of the compressor;
- refrigerant type;
- nominal evaporation temperature;
- nominal condensation temperature;
- nominal ambient temperature;

- evaporator heat transfer area;
- condenser heat transfer area;;
- fluid type through the evaporator and the condenser;
- heat pump size;
- heat pump mass.

Borehole heat exchangers (BHE):

- BHE type;
- BHE diameter;
- BHE depth;
- BHE filling type and composition;
- BHE tube diameter;
- temperature sensor disposition in depth of the BHE;
- thermal conductivity and thermal resistance of the BHE;
- lithographic structure of the ground surrounding the BHE.

Additional energy source (AES):

- AES type (for example electrical heater);
- nominal AES power;
- voltage;
- regulation and control ability of the AES power.

THEORY

Solar collector efficiency:

The efficiency of the solar collector is to be determined as the ratio of the heat flux extracted by the solar collector $\dot{Q}_{sc}, W$ and the solar collector area A_{ab} multiplied by the global solar insolation in the plane of the solar collectors I_{sc} [2, 3]:

$$\eta_{sc} = \frac{\dot{Q}_{sc}}{A_{ab} \cdot I_{sc}}. \tag{1}$$

The heat flux $\dot{Q}_{sc}, W$ is defined as follows:

$$\dot{Q}_{sc} = \dot{m}_{sc} \cdot c_{sc} \cdot \left(t_{sc,o} - t_{sc,i}\right), \tag{2}$$

where $\dot{m}_{sc}$ is fluid mass flow rate through the solar collectors, kg/s;

c_{sc} - fluid specific heat capacity in the solar collector, J/kgK;

$t_{sc,i}$ - inlet fluid solar collector temperature, °C;

$t_{sc,o}$ - outlet fluid solar collector temperature, °C;

A_{ab} - solar collector absorber area, m^2;

I_{sc} - intensity of the global solar insolation in the plane of the solar collectors, W/m^2.

Coefficient of performance (COP) of the heat pump:

The coefficient of performance of the heat pump is to be determined as ratio of the condenser heat flux $\dot{Q}_c$, W and the consumed electrical power $N_{hp,}W$ [3, 4]:

$$COP_{hp} = \frac{\dot{Q}_c}{N_{hp}}. \tag{3}$$

The condenser heat flux is to be determined as follows:

$$\dot{Q}_c = \dot{m}_c \cdot c_{pc} \cdot \left(t_{c,o} - t_{c,i}\right), \tag{4}$$

where $\dot{m}_c$ is fluid mass flow rate through the condenser, kg/s;

c_{pc} - fluid specific heat capacity in the condenser at constant pressure, J/kgK;

$t_{c,o}$ - outlet fluid condenser temperature, °C;

$t_{c,i}$ - inlet fluid condenser temperature, °C.

Efficiency of the Borehole Heat Exchanger (BHE):

The efficiency of the Borehole Heat Exchanger (BHE) is to be determined as ratio of the thermal energy extracted from the BHE and the thermal energy injected in the BHE for a period of time (annual or seasonal) [5]:

$$\eta_{BHE} = \frac{Q_{ext}}{Q_{inj}}, \tag{5}$$

where Q_{ext} is thermal energy extracted from the BHE, J;

Q_{inj} - thermal energy injected in the BHE, J.

Let us assume that the BHE temperature returns to the same value after a period of time (for example one year). So the BHE efficiency can be determined as follows:

$$\eta_{BHE} = \frac{Q_{ext}}{Q_{ext}+Q_{loss}} = 1 - \frac{Q_{loss}}{Q_{inj}}, \tag{6}$$

where Q_{loss} is BHE heat losses for a period of time, J,

and $Q_{inj} = Q_e + Q_{loss}$.

Efficiencies of the hybrid system at different operation modes:

Charging mode of the water storages with thermal energy from the solar collectors:

The system efficiency is to be determined in this mode as relation of the stored heat energy in the water accumulators and the global solar insolation in the plane of the solar collectors plus the nominal electrical power of the circulation pumps during the test period:

$$\eta_{s1} = \frac{m_{st}.c_p.(t_{st,end}-t_{st,in})}{\sum_{i=1}^{n}\int_0^{\tau_i}(I_{sc}.A_{ab}+N_{sc})d\tau+\int_0^{\tau_{end}} N_{2-3}.d\tau}. \tag{7}$$

Charging mode of Borehole heat exchanger (BHE) with thermal energy from the solar collectors:

The system efficiency is to be determined in this mode as relation of the thermal energy injected to the BHE and the global solar insolation in the plane of the solar collectors plus the nominal electrical power of the circulation pumps during the test period:

$$\eta_{s2} = \frac{\int_0^{\tau_{end}} \dot{m}_{BHE}.c_p.(t_{BHE,i}-t_{BHE,o})d\tau}{\sum_{i=1}^{n}\int_0^{\tau_i}(I_{sc}.A_{ab}+N_{sc})d\tau+\int_0^{\tau_{end}} N_{2-3}d\tau+\int_0^{\tau_{end}} N_{BHE}d\tau}. \tag{8}$$

Direct solar heating mode:

The system efficiency is to be determined in this mode as relation of the thermal energy supplied to the air convector and the global solar insolation in the plane of the solar collectors plus the nominal electrical power of the circulation pumps during the test period:

$$\eta_{s3}=\frac{\int_0^{\tau_{end}} \dot{m}_{cv}.c_p.(t_{cv,i}-t_{cv,o})d\tau}{\sum_{i=1}^{n}\int_0^{\tau_i}(I_{sc}.A_{ab}+N_{sc})d\tau+\int_0^{\tau_{end}}(N_{2-3}+N_{cv})d\tau}\,. \tag{9}$$

Heating mode with Ground Source Heat Pump (GSHP):

The system efficiency is to be determined in this mode as relation of the thermal energy supplied to the air convector and thermal energy extracted from the BHE plus the nominal electrical powers of the heat pump and the circulation pumps during the test period:

$$\eta_{s4}=\frac{\int_0^{\tau_{end}} \dot{m}_{cv}.c_p.(t_{cv,i}-t_{cv,o})d\tau}{\int_0^{\tau_{end}} N_{cv}.d\tau+\sum_{j=1}^{m}\int_0^{\tau_j}\{\dot{m}_{BHE}.c_p\left(t_{BHE,o}-t_{BHE,i}\right)+N_{BHE}\}d\tau+\sum_{k=1}^{m}\int_o^{\tau_k} N_{hp}.d\tau} \tag{10}$$

Heating mode with Solar Assisted Heat Pump (SAHP):

The system efficiency is to be determined in this mode as relation of the thermal energy supplied to the air convector and the global solar insolation in the plane of the solar collectors plus the nominal electrical powers of the heat pump and the circulation pumps during the test period:

$$\eta_{s5}=\frac{\int_0^{\tau_{end}} \dot{m}_{cv}.c_p.(t_{cv,i}-t_{cv,o})d\tau}{\sum_{i=1}^{n}\int_0^{\tau_i}(I_{sc}.A_{ab}+N_{sc})d\tau+\sum_{l=0}^{p}\int_0^{\tau_l} N_{AES}d\tau+\int_0^{\tau_{end}}(N_{2-3}+N_{cv}+N_{ev})d\tau+\sum_{f=0}^{q}\int_0^{\tau_f} N_{hp}d\tau}\,, \tag{11}$$

where m_{st} is whole water mass in the storages, kg;

c_p - average fluid mass specific heat capacity, J/kgK;

$t_{st,end}$ and $t_{st,in}$ - end and initial water temperatures in the storage, °C;

I_{sc} - intensity of the global solar radiation in plane of the solar collectors, W/m²;

A_{ab} - solar collector absorber area, m^2;

n - activity period number of the solar circuit pump,-;

τ_i - *i*–th time period of the solar circuit pump operation, s;

N_{sc} and N_{2-3} - average nominal power of the solar circuit pump and the moment nominal power of the pump between the 200l and 300l containers, W;

τ – time (it is 0 at the experiment start), s;

$\Delta\tau$ - time step between two consecutive measurements, s;

τ_{end} - time at the experiment end, s;

$\dot{m}_{BHE}$ - average fluid mass flow rate through the BHE, kg/s;

$t_{BHE,i}$ and $t_{BHE,o}$ - inlet and outlet fluid BHE temperatures, °C.

N_{BHE} - moment nominal power of the BHE circuit pump, W;

$\dot{m}_{cv}$ - average fluid mass flow rate through the convector, kg/s;

$t_{cv,i}$ *and* $t_{cv,o}$ - inlet and outlet fluid convector temperature, ℃;

N_{cv} - moment nominal power of the convector water circuit pump, W;

m – activity period number of the heat pump and the BHE circuit pump in GSHP operation mode.-;

τ_j - *j*–th time period of the BHE circuit pump operation, s;

τ_k - *k*–th time period of the heat pump operation, s;

N_{hp} - moment nominal electrical power of the heat pump during its operation period, W;

τ_l - *l*–th time period of the AES operation (electrical heater), s;

p - activity period number of the AES,-;

N_{ev} – moment nominal electrical power of the evaporator circuit pump, W;

q - activity period (cycles) number of the heat pump operation in SAHP mode,-;

τ_f - *f*–th time period of the heat pump operation, s;

N_{AES} - nominal electrical power of the AES (electrical heater), W.

MEASURED PARAMETERS

The following parameters are measured directly during the tests:

Temperatures*:*

- ambient temperature - t_a , °C;
- laboratory temperature - t_{lab}, °C;
- inlet fluid solar collector temperature – $t_{sc,i}$, ℃;
- outlet fluid solar collector temperature – $t_{sc,o}$, ℃;
- inlet fluid 200l container temperature (from the solar collectors) - $t_{2\text{-sc,i}}$,℃;
- outlet fluid 200l container temperature (to the solar collectors) - $t_{2\text{-sc,o}}$, ℃;
- inlet fluid 200l container temperature (from the 300l container) - $t_{2\text{-3,i}}$, ℃;
- outlet fluid 200l container temperature (to the 300l container) - $t_{2\text{-3,o}}$, ℃;
- inlet fluid 300l container temperature (from the 200l container) - $t_{3\text{-2,i}}$, ℃ ;
- outlet fluid 300l container temperature (to the 200l container) - $t_{3\text{-2,o}}$, ℃ ;
- inlet fluid BHE temperature - $t_{\text{BHE,i}}$, ℃ ;
- outlet fluid BHE temperature - $t_{\text{BHE,o}}$, ℃ ;
- inlet fluid convector temperature - $t_{\text{cv,i}}$. ℃ ;
- outlet fluid convector temperature - $t_{\text{cv,o}}$, ℃ ;
- inlet fluid evaporator temperature - $t_{\text{ev,i}}$, ℃ ;
- outlet fluid evaporator temperature - $t_{\text{ev,o}}$, ℃ ;
- inlet fluid condenser temperature - $t_{\text{c,I}}$, ℃ ;
- outlet fluid condenser temperature - $t_{\text{c,o}}$, ℃ ;
- inlet fluid 150l container temperature - $t_{\text{150,i}}$, ℃ ;
- outlet fluid 150l container temperature - $t_{\text{150,o}}$, ℃ ;
- BHE temperatures at a depth of 1, 10, 20, 30, 40 and 50 m correspondingly – t_{BHE1}, t_{BHE10}, t_{BHE20}, t_{BHE30}, t_{BHE40} and t_{BHE50}, ℃.

Flow rates*:*

- fluid mass flow rate through the solar collector - $\dot{m}_{sc}$, kg/s;
- fluid mass flow rate between the 200l and 300l containers - $\dot{m}_{2-3}$, kg/s;
- fluid mass flow rate through the convector - $\dot{m}_{cv}$, kg/s;
- fluid mass flow rate through the BHE - $\dot{m}_{BHE}$, kg/s.
- fluid mass flow rate through the evaporator - $\dot{m}_{ev}$, kg/s

Global solar insolation intensity in the plane of the solar collectors - $\mathbf{I_{sc}}$, W/m^2

Nominal electrical powers of:

- solar circuit pump - N_{sc} , W;
- pump between the 200l and 300l containers - N_{2-3}, W;
- convector water circuit pump - N_{cv} , W;
- BHE circuit pump - N_{BHE} , W;
- heat pump during operation period - N_{hp} , W;
- additional energy source (AES) - N_{AES} , W.

INVESTIGATION PROCEDURE

- The measurements are made under quasi-stationary conditions;
- All parameters are measured simultaneously every one minute during the measuring period;
- The tested solar collectors are orientated towards the sun and tilted to the horizon at an angle *(φ – δ)*;
- The following must be observed during the measuring period:
  - the fluid mass flow rates through the solar collector $\dot{m}_{sc}$, the evaporator $\dot{m}_{ev}$ and the condenser $\dot{m}_c$ must be kept within precision of ± 5%;
  - the measured temperatures must be kept within precision of ± 1°C;
  - the solar collector construction error relating to the angle tilted to the horizon must not exceed ± 2°;
  - the change of the measured electrical powers must not exceed ± 5%.

PROCESSING OF THE EXPERIMENTAL DATA

- The semi-integral temperatures are to be determined during a period of *n* min as follows:

$$\bar{t} = \left(\frac{t_1+t_n}{2} + \sum_{i=2}^{n-1} t_i\right) \cdot \frac{\Delta\tau}{\tau} \tag{12}$$

where t_1 and t_n are the temperature values - obtained at the first and the last measurement of the period of *n* min, °C;

t_i - temperature value - obtained at the *i-th* intermediate measurement, °C;

$\Delta\tau = 1\, min$ - time step between two consecutive measurements;

$\tau = n$ - time period of the measurement, min;

- The semi-integral intensity of the global solar insolation on the solar collector plane is to be determined during a period of *n* min analogically:

$$\overline{I_{sc}} = \left(\frac{I_{sc1}+I_{scn}}{2} + \sum_{i=2}^{n-1} I_i\right) \cdot \frac{\Delta\tau}{\tau} \tag{13}$$

- The semi-integral fluid flow rates are to be determined during a period of *n* min analogically:

$$\bar{\dot{m}} = \left(\frac{\dot{m}_1+\dot{m}_n}{2} + \sum_{i=2}^{n-1} \dot{m}_i\right) \cdot \frac{\Delta\tau}{\tau} \tag{14}$$

- The semi-integral electrical powers are to be determined during a period of *n* min analogically:

$$\overline{N} = \left(\frac{N_1+N_n}{2} + \sum_{i=2}^{n-1} N_i\right) \cdot \frac{\Delta\tau}{\tau} \tag{15}$$

ACCURACY OF THE MEASURED PARAMETERS

Acceptable deviations of the directly measured parameters:

- intensity of the global solar insolation - ± 2%;
- temperatures - ± 2%;
- flow rates - ± 2%;
- electrical powers - ± 5%.

Acceptable deviations of the indirectly measured parameters:

- condenser heat flux of the heat pump - ± 6%;
- solar collector heat flux - ± 6%;
- solar collector efficiency - ± 6%;
- heat pump coefficient of performance (COP) - ± 6%;
- system efficiency by different operation modes - ± 6%.

CONCLUSIONS

The presented methods are used to investigate a hybrid Ground Source Heat Pump (GSHP) system with solar collectors. The described procedure can be used also in other types of GSHP systems and solar collectors for the determination of their thermal characteristics.

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