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The use of thermal-electric analogy in solar collector thermal state analysis

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A R T I C L E I N F O

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A B S T R A C T

The paper presents a review of publications devoted to the use of thermal-electric analogy in the analyses of solar collectors' performance, with special focus on the shortcomings of the proposed models of the equivalent thermal network (ETN). Additionally, the study describes the principles of construction of the ETN, especially for large-scale solar thermal circuits. The process of heating the working medium flowing through the collector battery was also shown. The ETN model was presented both analytically (nodal potential method) and with the use of the Simulink package (MATLAB), which made it possible to investigate the effect of operating conditions on the parameters of the solar collector.

1. Introduction

Limited resources of traditional energy carriers and the trend towards enhanced efficient energy use make it necessary to search for more and more refined techniques of interaction between traditional and unconventional energy sources. Hybrid power supply systems that combine various energy sources are being created [28,30]. Electric energy is more and more frequently aided with PV solar panels or wind turbines. Domestic hot water is ensured with the use of solar liquid collectors (flat-plate or tube vacuum collectors), while enclosed spaces are heated, among others, with shallow geothermal systems [1].

Interaction between various renewable energy sources induces the need to expand the system with equipment for processing and accumulation of the surplus energy. There is also significant need for optimization of the flows of the produced and used energy, in order to ensure factual energy savings in the traditional carriers and top efficiency of the entire hybrid system. Such a combination of various renewable energy sources is more than a mere sum of individual structural elements, such as solar collector, PV panels, wind turbine, heat pump and ground heat exchanger, as it is also necessary to provide a system that would control all these [27,29,31]. A coherent method must be developed to create the hybrid system and to analyze its operation already at the designing stage, under any working conditions. The method referred to above should be based on diagrams presenting energy flow in particular segments, which could be linked into a single common diagram, regardless of the type of the energy (electric, thermal, mechanical). The energy used in hybrid systems might vary significantly. The solar radiation energy is converted into electric energy (in PV panels) or into thermal energy (in collectors). Wind power plants convert the wind energy into mechanical energy and then into electric energy. By using the common diagram, it will be possible to perform a functional simulation of the entire hybrid power supply system, both for the steady and non-steady state. On the one hand, such a diagram is needed to develop an energy flow control and management algorithm while on the other, it will enable assessment of the technical condition of particular segments and their usability in diagnostics.

It seems that the development of diagrams for particular segments of the hybrid power supply system as electric circuits to be interconnected into a single whole would be a satisfactory solution. The electric circuit theory is well developed and information tools needed for its operation are progressing remarkably. The relevant packages (e.g. MATLAB) are being created and shall be expanded and updated on a regular basis. Such packages offer a wide range of possibilities concerning signal analyses in different variants. However, the basic condition for circuit theory applicability is finding an analogy between the thermal and mechanical phenomena as well as dependencies describing current flow in electric circuits.

This paper contains a review of references concerning electric diagram applicability in creating descriptions of heat exchange in solar collectors. The progress of the thermal phenomena that occur in the solar collector is represented by electric passive elements, like resistances and thermal capacities, and by active elements, including current generators.

The application of electric diagrams in analyses of solar collector thermal states was already mentioned in previous publications on the subject. However, such actions were merely contributory in nature and only indicated an analogy between thermal and electrical phenomena

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Nomenclature

G	solar irradiance [W/m^2],
P	thermal power, heat flux [W],
Q	flow of the working medium [m^3/s],
R	thermal resistance [K/W],
S	area [m^2],
T	temperature [K],
Λ	thermal conductivity [W/K],
Θ	temperature increase [K],
a	absorptivity,
c_p	volumetric specific heat [J/(m^3 K)],
(mc)	heat capacity [J/K],
τ	transmittance / time constant [-/s]
t	time [s],
u_l	heat loss coefficient of the collector [W/(K m^2)],
v	speed [m/s],
w	relative humidity,
α	heat transfer coefficient [W/(K m^2)],
δ	thickness [m],
ε	emissivity,
η	efficiency,

List of indexes

a	absorber,
f	medium,
g	glass (cover of collector),
i, j	current parameters (node numbers),
o	ambient,
w	wind,
av	average value,
in	input,
out	output.

[5,8–11,16,18], but no analyses were carried out with the use of electric circuit theory methods. Only in the works of [2–4,20,21,24] are the thermal problems fully solved with the use of the aforementioned methods.

This publication aims to review scientific articles, which in any way, refer to thermo-electrical analogy and using equivalent thermal networks (ETN), those articles analyze the states of thermal solar collector applying electrical methods. In available publications, these works vary in terms of methodologies using different approaches to the problem. The above in a result of different purposes of researches, their assumptions and variously defined concepts. Therefore, constructed thermal networks (ETN) are not unequivocal. For example, the following problems are doubtful:

- Should the thermal resistance be calculated as a total one or should it be calculated per unit area? The authors propose to calculate total resistance. How should we interpret the environment in the electrical sense? In the paper the authors are presenting this problem as the ground about potential on level ambient temperature. Ground (earth) is the place trailing the heat losses.
- Should the heat capacity be calculated in relation to the level of ambient temperature or should we take other temperature? The authors propose to calculate the heat capacity relative to ambient temperature.

For electric engineer such scheme should be clarified. Therefore it is worth reviewing publications presenting works published also in non-English journals, including 8 papers of authors. They have verified their researches using other methods and tools (MATLAB-Simulink) than equivalent thermal networks (ETN).

2. Analyses of thermal states of a flat-plate liquid collector based on thermo-electric analogy

In the classical energy balance Eq. (1) by Hottel-Whillier-Bliss (H-W-B) [7]:

$$q=(\tau_g a_a)G-u_l(T_a-T_o) \tag{1}$$

where T_a, T_o – absorber temperature and ambient temperature, respectively,

G – solar irradiance,
τ_g – glass transmittance,
a_a – absorptivity of the absorber,
u_l – heat loss coefficient of the collector (total),
q – useful heat flux,

commonly used by many researchers eg. [7,32] to analyze the steady states of solar installations, the solar collector is treated as a homogeneous body of certain averaged thermal parameters.

In non-steady states, the thermal capacity (C_f) of the working medium is used. This approach is most often presented by researchers in their analyses of the collector's operation dynamics. Although substantially simplified, it is so commonly used due to this very simplicity.

In his investigations on non-steady states of the solar collector, Kamminga [16] used a system of 3 homogeneous bodies as the model, distinguishing between: a transparent cover, an absorber and the working medium. However, the author assumed that the only energetically active element is the absorber, as only in the absorber is the solar radiation energy converted into heat, which is then received by the flowing working medium. Heat losses from the absorber through the transparent cover are taken over by the environment, with no heat losses directed from the absorber towards the collector's bottom. Fig. 1 presents the proposed electric diagram reflecting the energy exchange..

The elements of this diagram have the following physical interpretation:

- all physical properties of the transparent cover, together with the corresponding thermal capacity C_g, were assigned to the node that represents the glass cover, with the average T_g temperature,

- properties including the corresponding thermal capacity C_p were assigned to the node that represents the absorber, with the average T_p temperature, where the energy of the absorbed solar radiation E(t) is generated,

- properties with the corresponding thermal capacity C_f were assigned to the node that represents the working medium, with the average T_f temperature.

The network nodes are interconnected with the use of thermal resistances with heat fluxes, including the thermal loss flux from the cover to the environment (T_a temperature).

Neither the electric diagram nor electric methods were used to solve the collector's thermal states. The electric diagram does not clearly

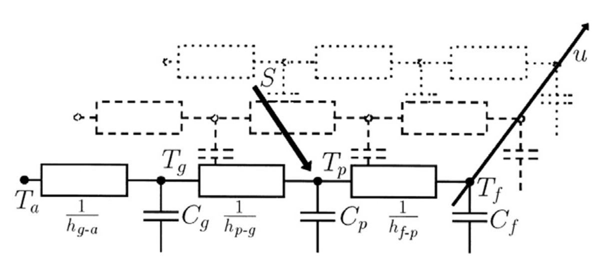

Fig. 1. Equivalent thermal network of a solar collector according to [16].