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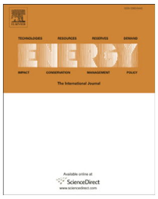

Solar thermal modeling for rapid estimation of auxiliary energy requirements in domestic hot water production: On-off flow rate control

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ABSTRACT

A simple mathematical model of active solar production of domestic hot water with on-off flow rate control was developed. Iterative techniques, implicit equations, and complex mathematical functions were avoided. Yearly climate and daily thermal load data were applied at hourly time steps. About 10 additional simulation days are necessary to obtain a yearly periodic simulation. A time step dependency analysis indicates that a one-hour period results in less than 2 % error from the exact solution. The solar fraction increases very rapidly with increasing collector area for low areas, tending to a constant value for high areas. For low collector areas, collector flow rate has virtually no effect on the solar fraction, but above a certain area, the solar fraction starts to decrease with increasing area; the area at which the solar fraction starts to decrease increases with increasing flow rate. Moreover, the solar fraction increases with increasing storage volume for low volumes, becoming virtually constant for high volumes. For an insulation thickness of 20 cm, the storage losses reduce the solar fraction by less than 3 %. In indirect systems, for the effect of the storage heat transfer efficiencies to be neglected, both efficiencies should be higher than 0.9.

1. Introduction

The main unit of any solar thermal conversion system is the solar collector, in which incoming solar radiation is absorbed by the receiver, converted into heat, and transferred to the working fluid. Solar heating involves a variety of applications, such as water heating, space heating and cooling, refrigeration, industrial process heat, desalination, thermal power systems, furnaces, and chemistry applications [1–3].

The most common solar thermal application is the production of domestic hot water, which, in 2013, accounted for 80 % of the solar thermal market [4]. Essentially, solar water heating systems include a collector unit, a storage tank to accumulate heat from the working fluid, an auxiliary heating device, and insulated interconnecting pipelines. Regarding the flow of the working fluid, these systems can be classified as active or passive systems [2,5]: active systems use a pump to force the fluid to flow; in passive systems, the fluid flows by natural convection. Considering the fluid of the collector, solar water heating systems can be further classified into direct and indirect systems [5]: in direct systems, collector and storage fluids are the same and are mixed in the storage tank; in indirect systems, the collector fluid is different from that of the storage fluid, and heat is transferred to the storage tank by means of a heat exchanger.

The performance of solar thermal systems depends on controllable (size and properties of system parts) and uncontrollable (climate and thermal load) parameters. Long-term estimation of the performance of solar thermal processes is an essential design step. Simple design methods for active solar systems have been proposed in the literature [2,3,6,7]: the F chart method [8], based on the correlation of a large number of simulation results; utilizability methods Φ [9] and $\bar{\Phi}$ [10]; the $\bar{\Phi}$-F chart method [11], a combination of correlation and utilizability methods. Simple methods are fast to compute and simple to apply, but they have the disadvantage that optimization of system parameters is limited, and not every system type can be analyzed, so that these methods are normally employed in

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preliminary design stages and in the design of small domestic systems [1–3]. Besides this, the results obtained from simple design methods are not as accurate or as complete as the results obtainable from simulations [6].

Due to the high processing speed of modern computers, in order to overcome the aforementioned disadvantages, simple design methods are being replaced by annual solar thermal simulations. Simulations are computer programs that concurrently solve sets of algebraic and differential equations, governed by the principles of heat transfer, thermodynamics, fluid mechanics, and mass transfer, representing the transient thermal behavior of the interconnected parts of the solar system. The solution for these equations normally involves highly iterative numerical techniques, applied to large systems of algebraic equations, often characterized by complexity, non-linearity, and implicitly [2,12]. These programs fall into two main categories [2,12]: special-purpose and general purpose programs. Special-purpose programs, which represent the performance of specific types of systems, are generally easy to use, but have a rigid structure. General-purpose programs, which can be applied to a wide range of systems, are more flexible but more difficult to use. The most well-known general-purpose computer program is TRNSYS [2,7,13], commercially available since 1975.

As modelling and simulation of solar thermal systems involves solving ordinary differential equations, several computer routines, using time marching numerical schemes, often involving numerous iterations per time step, have been reported in the literature [14–19]. Alternatively, Badescu [20] employed third-party software modules to compute a system of ordinary differential equations. Simulink, a block-oriented environment, developed by MathWorks [21] to model, simulate, and analyze dynamic systems, has also been applied to solve the governing equations of different solar thermal models [22–28]. Kulkarni et al. [29,30] developed analytical explicit solutions, valid for small time steps, to model active thermal solar systems. TRNSYS has also been extensively used to simulate various transient thermal processes of solar heating systems [31–34].

In summary, simple design methods require few computation steps, but they are not flexible, and their results can be rather inaccurate; these methods were more valuable when computation performance was low. Simulations can model any type of system, can incorporate different system details, but due to the transient non-linear nature of the dynamics of solar thermal systems, their governing equations may become very complex, so that their solution may require highly sophisticated numerical methods, often involving iterative calculations.

There are two important sources of uncertainty in any solar thermal simulation: climate data and consumption profile. All simulations use past climate data, but year-to-year weather variations cause different year-to-year solar process outputs [2]; therefore, simulation results based on a specific climate database may be quite different from those of the year under consideration. Hot water consumption profiles are generally time-dependent functions, depending on many factors, e.g. the number of consumers, their ages, hot water consuming appliances, and the season of the year [2]; therefore, simulations based on a predefined consumption profile may provide quite different results from those based on real consumptions. Interestingly, climate and consumption reproducibility is an advantage of simulations over physical experiments, making simulations particularly appropriate for parametric studies, which would be unpractical in real systems, due to the irregular nature of real weather and consumption profiles [2,35].

The objective of the present work is the development of a mathematical model of hot water production from solar radiation, which should not be as inflexible and inaccurate as simple design methods, but should be simpler than detailed simulation routines, so as to avoid the computational complexity of lengthily iterative solutions. The model, based on thermodynamics and heat transfer phenomena occurring in solar thermal systems, is directed towards domestic hot water production and should provide the long-term simulation performance of a system, specified by its most relevant design parameters. However, in the present work, for the regulation of the fluid flowing through the collector, only the on-off control type is considered. Due to the unpredictable variables in any solar thermal simulation, e.g. weather data and consumption profile, unnecessary model details can be avoided, if only long-term system performance is to be determined. Moreover, the intention is that the model can be used as an objective function for optimization problems, in which the objective function has to be calculated repeatedly before an optimal solution is reached, indicating the need for rapid model simulations. The proposed model and computation procedure are described next, followed by long-term simulations based on some Portuguese climate databases and parametric studies with the most relevant design variables. Simulations are also performed with the purpose of quantifying the validity of the assumed model simplifications.

2. Energy model

The main purpose of the proposed solar water heating model, named energy model, is to evaluate the consumption of auxiliary energy during long-term simulations. The energy model is composed by three submodels: the radiation model, the thermal model, and the mains water model. While these submodels work for a predefined time step (Δt), the energy model works for several successive time steps, invoking the three submodels at each time step. The radiation model computes the useful solar radiation reaching the solar collector during Δt; the thermal model computes the auxiliary energy (Q_A) consumed during Δt; the mains water model computes the temperature of the mains water. The main output of the energy model is the summation of the various auxiliary energy outputs (ΣQ_A) from the thermal model.

2.1. Radiation model

The radiation model computation procedure, depicted diagrammatically in Fig. 2, calculates the useful solar radiation reaching the solar collector (G, kWh m^{-2}). The collector surface is orientated according to two angles, as illustrated in Fig. 1: collector slope (β, rad) and collector azimuth (γ, rad). Two additional angles define the orientation of the collector relatively to the sun: the time

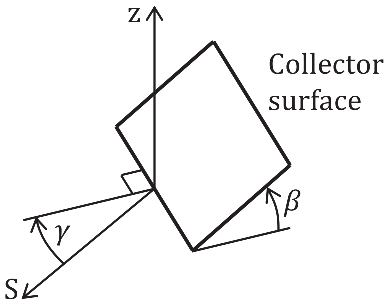

Fig. 1. Collector surface orientation.

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