SIMULATION OF HYBRID THERMAL INSTALLATIONS

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Abstract

Increased scientific and technological efforts have been made recently to reduce the carbon dioxide emissions in the environment as a main cause of the global warming. The general trend is using Renewable Energy Sources. The aim of the present work is a brief review of the advantages of the hybrid thermal systems (HTS) using Renewable Energy Sources. The article presents methods and instruments for mathematical modeling and simulations of the main components of the HTS and its operation as a whole.

Keywords: Hybrid thermal systems, Components, Modeling, Simulation

1. Introduction

There is a big interest worldwide in Renewable Energy Sources (RES) because of increasing energy consumption, high costs connected with its production and exhausting of the conventional energy sources. Therefore a permanent searching of alternative energy sources is needed. The construction of buildings possessing high energy efficiency at accessible prices and offering built in heating and cooling systems based on RES is an ambitious goal [1].

The European parliament passed a directive in 2010 concerning the energy characteristics of the buildings. It is aimed at rational usage of the exhaustible energy sources which are the main sources of carbon dioxide. The decreasing of the harmful gas emissions by means of the RES is its main goal. The energy efficiency program endorses a mandatory target of a 20 % share of energy from renewable sources by 2020 [2].

There are different green energy sources. The solar and geothermal energies seem to be the most important renewable energy sources. Their operational temperatures are relatively low (except of the geothermal sources with high water temperature). The solar energy has a wide application in the heating and cooling of buildings, in the domestic hot water production, in the agriculture and etc. A disadvantage of the solar energy is its unpredictability. The effective solar energy storage includes its accumulation during the periods when there is a big availability of solar energy and the usage of the stored energy when it is needed. The introduction of additional elements into the solar systems (like thermal storages, underground stores, heat pumps and any combinations between them) leads to the so called hybrid thermal energy systems [3]. The hybrid thermal systems are a perspective manner for optimal use of the green energy. That is why the investigation and operation of this type of installations is very popular.

2. Review of the components composing the hybrid thermal installations

The hybrid thermal systems (HTS) include components with different physical nature and operation principles. They can be divided into the following main groups (depending on their role in the energy distribution):

- ensuring the energy supply to the system;
- accumulating for a certain time period the energy supplied to the system;
- conversing the absorbed energy.

2.1. Components connected with thermal energy supply

The solar collectors are special heat exchanger type which converts the solar radiation that is a kind of RES into thermal energy. The received energy can be used for production of domestic hot water (DHW) or heating of buildings depending on the collector type [4]. There exist a lot of different collector types, but we will consider in the article only some of them.

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The flat plate solar collectors are to be mounted stationary which requires their appropriate orientation. The typical flat plate collector consists mainly of a glass cover, absorber, insulation, and tubes where the heated liquid is circulating [5]. The thermal energy received by the heated absorber is led by means of working fluid [6].
A high temperature can be reached in the concentrating collectors which contain sun following device. They possess higher thermal efficiency. Some of them consist of heliostats (flat mirrors) which are ordered in the so called system „YNES" with the aim to raise its efficiency [7].
The parabolic collectors are a type of concentrating collectors. Their main components are the parabolic mirrors in the form of dishes, which help the energy focusing on the receiver [8].
The so called PV/T (photovoltaic – thermal) collectors produce electrical and thermal energy as a result of the solar radiation influence. Their construction consists of photovoltaic panels and thermal absorber which is fastened to the back side on the PV panel [9].

2.2. Devices for thermal energy accumulation

There are some important elements in the thermal accumulation [10]: specific heat capacity of the operation substance in the storage; regulation manner of the thermal losses in the storage; temperature stratification in the storage; inlet and outlet device operation temperatures; charging and discharging manner of the storage; economic indicators.
There are two basic types of thermal storages (Fig.1): storages of sensible and of latent heat [11].

2.2.1. Storages of sensible energy

The sensible storages are divided in two main types: *rock and liquid storages*. *The liquid* thermal storages use mainly water because of the good thermophysical properties of that medium. This type of storages can be considered additionally like fully mixed storages (they have the same fluid temperature in all medium points) and like stratified storages (the fluid temperature is different in the height of the accumulating device).
The Rock energy storages are used for accumulation of gas energy (normally of preliminary heated air).
Underground thermal energy storages UTES: Sensible energy is accumulated in these storages. They are situated under the ground. The soil is used as an accumulating substance. The storage temperature is relative low but they are used like accumulators for a long time period (normally between 3 and 6 months), they are seasonal storages. The geothermal energy is used for heating during the winter (the energy is conversed to a higher energy level) [12]. The used energy is restored during the summer and the transitional seasons - a solar energy is supplied to the ground like thermal energy or waste heat of different industrial processes is used.
The systems connected to this storage type use low temperature geothermal energy which is ecological, accessible and relatively cheap kind of energy. There are the so called ATES (Aquifer thermal energy storages) and BTES (Borehole thermal energy storages). The ATES use water lakes with different temperature – the heat or cold are to be transferred from one to another depending on the season and the heating and cooling needs [13].
The BTES contains Borehole heat exchangers (BHE) consisting of tubes situated under the ground. Any type of fluid is circulating in the tubes (normally water). They can be situated in vertical [14] or horizontal position [15]. The vertical BHE have a depth of 20 till 1000 m (their minimal depth is determined on the surrounding influence which is negligible under 20 m). But the normal length of the BHE is between 30 and 300 m. There are to be distinguished a closed and an open system types.
There are possible combinations with Phase change materials (PCM), too. A combination of horizontal BTES with PCM situated directly in the reservoir is considered in [16].

2.2.2. Latent storages

The latent storages (devices containing PCM) are appropriate for accumulation of low temperature energy like solar, geothermal or waste energy. The PCMs accumulate thermal energy with high density at a constant temperature. Every latent storage system must contain at least the following three components [17]:

- appropriate PCM with the corresponding melting point and the desired temperature range;
- appropriate heat transfer surface;
- appropriate container corresponding to the chosen PCM.

The transfer of thermal energy is realized when the materials change their phase (solid to liquid or vice versa). The PCMs are latent materials of the thermal storages. The solid – liquid PCM play in the beginning the role of conventional storage materials – they raise their temperature during the charging. But the charging and discharging of the PCMs is realized at almost constant temperature. They accumulate 5 to 14 times more heat in a volume unit compared with the ordinary materials like water, bricks or gravel. There are a lot of materials which possess good latent heat of fusion in the desired range. But the use of PCM in storages requires additional thermodynamic, kinetic and chemical properties. The economic factor (price) is very important, too. There are many PCM types (organic, inorganic and eutectic). The choice for every concrete installation depends on their properties as follows [18]: density, kg/m^3; melting point, °C; specific heat capacity, J/kgK; latent heat of fusion, kJ/kg; thermal conductivity, W/mK; volume change, %.
Fig. 2 shows the difference between the above mentioned systems of heat accumulation – with phase change materials (PCM), water and rock [19]. It is obviously that the latent storage is the most effective.

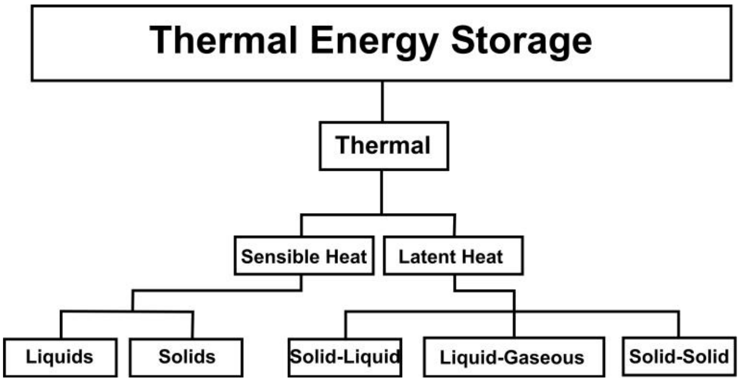

Figure 1. *Classification of the solar thermal energy storage types [11].*

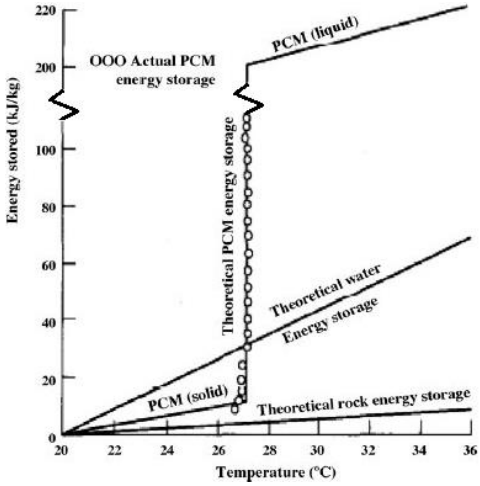

Figure 2. *Performance comparison of PCM, water and rock storage system [19].*

2.3. Components which converse the absorbed energy

The heat pumps (HP) are devices which accept the heat flow at lower temperature and supply it at higher temperature as a result of additionally delivered energy. The most used heat pumps consist of the following main parts - evaporator (the fluid passes through it at lower temperature level), condenser (the fluid passes through it at higher temperature level), compressor for the refrigerant vapors' compressing and throttling valve. The heat pumps are divided in 4 main types depending on the heat transfer medium: „air to air", „water to air", „air to water" and „water to water".

The heat pumps are very effective in heating of buildings. A big attention is paid in the last years to the so called Ground Source Heat Pump systems for heating and air conditioning [20]. They offer several advantages compared with the conventional installations: a system of this type for heating and cooling is practically without any support; it does not have any moving parts and is safe, clean from the ecological point of view, fully automatized and sustainable for a long time period (about 30 years). Additional advantages are their low exploitation costs, higher efficiency and environmental friendliness. Combining these systems with solar collectors can lead to additional advantages. This type of systems is used often in the last years in many countries in the world. They are called hybrid systems which behavior is still not enough investigated by means of experiments and simulations. The solar energy can be used in the hybrid systems for direct production of domestic hot water, heating, diurnal and seasonal accumulation of energy in the boreholes as well as for assist to the heat pump operation at some working regimes.

2.4. Supporting components

The hybrid thermal systems include (besides the above mentioned basic components) some other additional elements which make possible the installation operation. These are the heat exchangers, pipelines, circulating pumps, fans, hydraulic and air valves etc. Additional attention is paid during the HTS simulation to the modeling of the building where the installation is mounted and to the climatic conditions of the region where the object is situated.

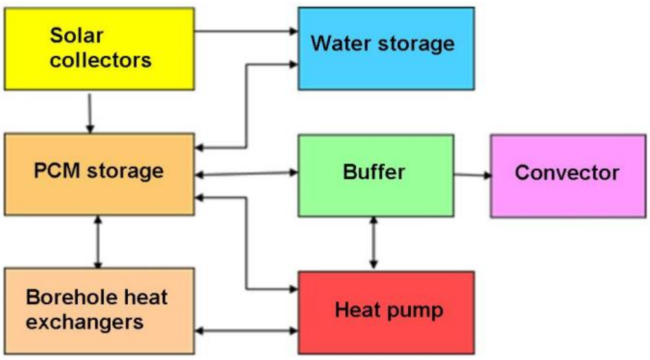

Figure 3. *Block scheme of the Hybrid installation situated at the TU Sofia, Plovdiv branch.*

2.5. Examples for experimental hybrid thermal systems

Nowadays worldwide, an intensive work is going on analysis of the possibility of using HTS to obtain benefits, compared to conventional systems in terms of efficiency. A number of hybrid test installations are built involving a

different set of components. In [21] the HTS, designed for residential heating, built in Trabzon, Turkey is presented. It represents a solar heat pump system with PCM energy storage.
The system consisting of PV/T panels, electricity storage battery and an inverter and on the other hand heating part composed of a cylindrical hot water tank, a pump and a differential thermostat was established and described in [22].
An experimental hybrid thermal installation is built at the Technical University of Sofia, branch Plovdiv [3]. It is composed of solar collectors, heat pump, underground thermal storage, storage with PCM, water buffer tank, fancoil and others (Fig.3). The plant has seven modes of operation, allowing to extract the maximum amount of energy. It allows efficient storage of energy in periods of excess, operation even in low water temperature and a direct use of heat.

3. Methods and tools for simulation of hybrid thermal systems

3.1. Physical processes in HTS and their mathematical representation

The basic physical processes in the relevant class of HTS, subject to mathematical description are: heat transfer by radiation and convection, heat transfer by heat conduction, mass transfer, fluid flows and phase changes in the heat transfer medium. These processes take place generally in heterogeneous environments and are mathematically described by nonlinear partial differential equations [22]. These equations are derived based on the laws of conservation of energy, mass, momentum and or chemical species, and are commonly known as a general transport equations. They are written in terms of specific quantities - i.e., quantities per unit mass in consideration volume basis and depending on its axes and the time. Most often they are in the form of elliptic, parabolic or hyperbolic partial differential equations. Additionally are set their initial and boundary conditions.

3.2. Methods for solving of the equations

There are two main methods for solving differential equations: analytical and numerical. Analytical solution of equations of the genus is possible only in some special cases, occurring after the adoption of a number of assumptions, simplifying equations. So now, in most practically important cases, the numerical methods for solving partial differential equations are applied. In the analysis of the fluids dynamics and heat transfer (as in HTS) they are known under the generic name computational fluid dynamics (CFD) methods.
The discretization in space is an approximation procedure, which converts the continuous area into crosslinked surface. The physical variables are looking at specific points in the mesh. Depending on the manner of sampling in space three basic methods are used [22], that allow to replace general transport equations by a set of discrete algebraic equations:

- Finite difference method (FDM). In it the derivatives are represented by a truncated Taylor's series. Typical of FDM is the smoothness of solving problems due to the better description of nonlinear parts of the Navier-Stokes equations. Variant of FDM is FDTD this is the method of finite differences in the time domain. It discretized a volumetric structure in space, exploring the evolution in time;
- Finite element method (FEM). In this method the problem space is divided into simpler subspaces, seeking for a close solution. A simple subspace is called a finite element, giving the name of the method. It is a special case of the method of finite differences. A drawback is the presence of boundary conditions.
- Finite volume method (FVM) is similar to FDM and FEM. The method is used for the study of inner and outer flows of compressible fluid. It applies more diluted, heterogeneous or moving meshes to monitor phenomena in the field of flow. The method name means small volume, occupying certain mesh node or a combination of several surrounding nodes. The advantage of the FVM is simple task reformulation in case of non-structural meshes - graphs, Voronoi meshes and other hybrid meshes. Furthermore, this method provides in most cases significantly better accuracy and higher performance benchmark that makes it preferable.

As a result of discretization in all three cases a set of discrete algebraic equations is obtained, which can be linear (if their coefficients are independent of the specific quantity) or nonlinear (if their coefficients are functions of the specific quantity). Their solution, regardless of discretization method, can be carried out using direct (e.g. tri-diagonal matrix algorithm (TDMA) [23]) or iterative numerical methods (e.g. Gauss-Seidel method [24]). Major impact on speed and accuracy of solution turns the way of forming the boundaries of the sampling areas - computing mesh.

3.3. Simulation instruments

Modeling and simulation of complex systems typically involves two stages. In the first stage the mathematical models of the major system components are created. In the second stage a model of the entire system is prepared by giving into account an interaction between individual components. Instruments for simulating HTS incorporate universal programming languages, universal simulation systems and specialized software. The universal languages most often are C, C++ and Fortran.
The most popular universal simulation system is **Matlab**. There are possible calls to subroutines written in Fortran, C, C++. For modeling of dynamic systems Matlab offers in addition a graphical environment tool - Simulink, which includes a number of specialized in different subject areas libraries - Blocksets. In [25] using Simulink Simscape library dynamic simulations are performed of a hybrid system with building integrated PV-PCM. In [26] a solar domestic water

heating system is presented, the system performance is simulated using Matlab. The model is very useful to study the system efficiency.
There is a large variety of specialized software for simulation of HTS. It is applied both to simulate the processes in the individual components of the system and to analyze the processes on a system level. In the first case the results of the simulations help mostly the process of designing specific components and in the second to optimize system performance. Here we list some of the most commonly used:, ANSYS fluent, COMSOL multiphysics, TRNSYS, HEATING, RADCOOL, DOE-2, BLAST, EnergyPlus, ESP-r, KoZiBu, BSim, PCM express, WUFI, EED.
COMSOL Multiphysics® is a general-purpose software platform, based on advanced numerical methods, for modeling and simulating physics-based problems. With COMSOL Multiphysics, you will be able to account for coupled or multiphysics phenomena [27].
ANSYS Fluent software contains the broad physical modeling capabilities needed to model flow, turbulence, heat transfer, and reactions for industrial applications ranging from air flow over an aircraft wing to combustion in a furnace, from bubble columns to oil platforms, from blood flow to semiconductor manufacturing, and from clean room design to wastewater treatment plants [28].
TRNSYS is an abbreviation of „transient simulation program". The program was developed at the University of Wisconsin. Written in ANSII Fortran-77, it has an extensive set of libraries specialized in models on HTS components. Mathematical models of the components are represented by algebraic or ordinary and partial differential equations. TRNSYS connects the system components in the desired manner by means of a graphical programming. To model of ground thermal properties TRNSYS uses type 557 and type 141 model of energy storage in PCM are developed standard types: Type 204; Type 222; Type 241; Type 260; Type 399 and Type 1270. All of them are working together with a building model - Type 56 [29].
EnergyPlus [30] is a system scale building energy simulation program. Modeling the performance of a building with EnergyPlus enables building professionals to optimize the building design to use less energy and water.
A Linux based Simulator **ESP-r** [31] allows an in-depth appraisal of the factors which influence the energy and environmental performance of buildings. ESP-r allows the designer to explore the complex relationships between a building's form, fabric, air flow, plant and control. ESP-r is based on a finite volume, conservation approach.
KoZiBu is a software used to analyze dynamic hygrothermal performance of building. It is aimed to conduct studies of heating and cooling strategy, air conditioning or ventilation options, insulating materials to be installed [32]. The main objective of KoZiBu is to forecast the energy consumption, and temperature and humidity evolution range.
BSim (Building Simulation) is an integrated PC tool for analyzing buildings and installations [33].
PCM express. In cooperation with Fraunhofer Institute for Solar Energy (ISE) in Freiburg and partners from industry, Valentin Energy Software has created PCM express [34] for planning and simulation for the use of Phase Change Materials (PCM). This software is specialized in turning the latest developments into user-friendly software programs for system design, yield calculation and economic efficiency calculation. It cannot simulate a HVAC system.
WUFI® PRO 5.3 [35] allows the one-dimensional investigation of the hygrothermal performance of building components including effects like built in moisture, driving rain, solar radiation, long-wave emission, capillary transport and summer condensation. WUFI® Pro is the standard tool for most building component simulations and the most user friendly program of the WUFI® family.

4. Conclusions

In the latest research in the field of heating and cooling of buildings the HTS represent a very perspective direction. Moreover, mathematical modeling provides a basis for conducting simulation studies, enabling to provide basic technical and operational features of HTS at the stage of their design. Due to the long duration of some processes in such systems it becomes impractical and too expensive to analyze their work only by using experimental methods. Therefore the analysis using simulation is cost-effective alternative.
There is a variety of methods and tools for modeling and simulation research of HTS. Due to the complex nature of the processes, there are still no sufficient universal, accurate and quick tools for their simulation, which leads the need to develop new models. Existing models of UTES, as well as those of storages with PCM are often not suitable for all applications, or require very large computational resources. One often reported problem is lack of validation for computer programs used in performance analyses of PCM-enhanced technologies. According to the IEA Annex 23 [36], many numerical models have not been experimentally verified, which, in conjunction with often used too simplified modeling parameters, makes it difficult to realistically describe the complex phase-transition physics needed to predict the actual performance of PCMs added to a building.

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