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SIMULATION OF CSHPSS SYSTEMS WITH A DUCT GROUND STORE

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ABSTRACT

The design of a solar heating system using a duct store in the ground requires design procedures that account for the different thermal processes involved. In order to obtain an accurate evaluation of the system heat balance, system performances have to be calculated with high resolution over several years, if not the lifetime of the system.

Reliable and accurate simulation tools which use the TRNSYS programme have been developed for the simulation of Central Solar Heating Plants with Seasonal Storage (CSHPSS) using a ground duct store. The simulated systems involve a collector array, a short-term water buffer store, a ground duct store, an auxiliary heat supply and a heat distribution network to the consumer. The version of the duct heat storage model (DST) for TRNSYS has been improved based on the results of analyses performed with more detailed programmes. The flexibility of the TRNSYS programme makes the tools easily adaptable to a particular problem.

The simulation tools are applied to a system defined for typical Swiss conditions. Optimal ratios between the main system parameters are sought for sizing purposes. The influence of the load size, load type (size of the proportion of domestic hot water) and load temperature levels are investigated. Several thousand simulations have been performed; these have helped to characterize and highlight important points in the design of such systems. Comparisons are made with systems having only a water store. They show that a duct store becomes economically more attractive for solar fraction larger than typically 50%, i.e. for seasonal heat storage. Cost reductions should be concentrated on cheaper collectors, as two thirds to three quarters of the solar cost is due to the collector array.

1. INTRODUCTION

Unlike conventional technologies, the design of a heating or cooling system using a duct store in the ground is based on heat and/or cooling output (kWh) rather than the heat and/or cooling demand (kW). It requires design procedures that take into consideration both the short-term and long-term performances. For example, the heat transfer along the ducts is influenced by different factors, such as the loading conditions of the last days of operation of the system, which determine the temperature profile in the ground around the ducts, and the average ground temperature in the store, which normally varies on a seasonal basis. A transient effect, due to the warming or cooling of the surrounding ground, is usually observed during the first years of operation, and affects the thermal performances of the system. The final design is generally established with the help of detailed computer simulations, and relies on the ability of the computer programme to reproduce the actual characteristics of the planned system for several years.

The new version of DST, the duct ground heat storage model (Hellström et al., 1996) is developed as a component for TRNSYS (Klein et al., 1990), a well-known modular programme for the simulation of partial or complete energy systems. The advantage of TRNSYS is the possibility of using a wide range of system component models and to combine them as desired. A large variety of energy systems can be simulated, such as central heating plants with a duct seasonal storage (solar heat source or else), duct cold storage and low temperature applications, multiple heat extraction boreholes, etc. The worldwide use of TRNSYS by consultant engineers and researchers improves international co-operation and the transfer of technological expertise.

2. DUCT GROUND HEAT STORAGE MODEL (DST)

A duct ground heat storage system is defined as a system where heat or cold is stored directly in the ground. A ground heat exchanger, formed by a duct or channel system, is used for heat exchange between a heat carrier fluid, which is circulated through the ducts, and the storage region. The heat transfer in the surrounding ground takes place by ordinary heat conduction.

The DST model is a simulation model for such ground heat storage systems. The store volume has the shape of a cylinder with a vertical symmetry axis. The ducts are assumed to be uniformly placed within the store volume. There is convective heat transfer in the ducts and conductive heat transfer in the ground. It is convenient to treat the thermal process in the ground as a superposition of a global and a local problem. The global problem handles the large-scale heat flows in the store and the surrounding ground, whereas the local problem takes into account the heat transfer between the heat carrier fluid and the store.

The short-time effects of the injection/extraction through the ducts are simulated with the local solutions, which depend only on a radial coordinate and cover a cylindrical volume exclusively ascribed to each duct (or borehole). The heat transfer from the fluid to the ground in the immediate vicinity of the duct (or borehole) is calculated with a heat transfer resistance. A steady-state heat balance for the heat carrier fluid gives the temperature variation along the flow path.

Based on the results of a previous study (Pahud, 1995), the widely used duct store component DST has been improved, so as to be able to take into account finer phenomena related to the heat transfer from the fluid to the ground. The local solution may now take into account a radial stratification of the store temperatures (due to a coupling in series of the ducts (or boreholes)), as well as an increased resolution in the vertical direction. The local heat transfer resistance from the fluid to the ground (or borehole thermal resistance) may be temperature- and flow-dependent. In that case a two-entry table, containing the temperature- and flow-dependent thermal resistances, must be given as input to the DST component. In the case of pure heat conduction outside the ducts in a borehole, a computer programme called BOR (Pahud, 1996) uses the multipole method (Bennet et al, 1987) to compute the thermal resistances. Coaxial pipe, single, double and triple U-pipe in a borehole are implemented in the programme. Data bases for the thermal properties of various ground types and materials, fluid properties of different heat carrier fluid, as well as the characteristics of common pipes, are included. It may also take into account the unfavorable internal heat transfer between the downward and upward flow channels in a borehole.

Other components were also created for the needs of the simulation tools (pressure drop caused by the fluid circulation in a ground heat exchanger and pumping power, variable flow rate control, heat load component, etc.). For the purpose of a more general study, where only the main system parameters are investigated, finer effects, such as the optimum flow rate for a particular type of ground heat exchanger, are probably not of primary importance. On the other hand, such effects are susceptible to be investigated, once an optimum system sizing has been found.

3. CASE STUDY FOR SWISS CONDITIONS

A system has been defined to perform a case study applied to typical Swiss conditions. See Fig. 1. Several load types were defined to assess the influence of the load size, the proportion of domestic hot water in the heat load and the temperature levels of the heat delivered in the distribution network. In this study, only the influence of the main system parameters were investigated, in order to determine optimal ratios between the main parameters.

The parameter values and solar cost of the optimum systems that give a minimum cost at an average solar fraction of 70% during 25 years are given in Table 1. The load characteristics have a significant influence on the relative size of the different subsystems. Nevertheless, for the three load sizes investigated within a load type (500, 1,000 and 5,000 MWh/year), the ratio duct store volume per annual MWh load is mostly constant for a fixed solar fraction. Ratio of about 15, 22 and 25 m3/MWh were found for, respectively; the 50% domestic hot water and moderate-temperature heat distribution load, the 25% domestic hot water and moderate-temperature heat distribution load and the low-temperature heat distribution load without domestic hot water, and for a solar fraction of 70%. The borehole spacing tends to increase with larger ratio duct store volume over collector area. However, apart from the two smallest duct store volumes which have a spacing of 2.1 m, the borehole spacing is mostly constant and lies between 2.3 and 2.7 m. (The soil has a thermal conductivity of 2.5 W/mK and a volumetric heat capacity of 2.3 MJ/m3K.) The shape of the duct store, defined with the ratio duct vertical extension over duct store diameter, has an optimum value that lies between 1.8 and 2.8, depending on the duct store volume and the mean annual temperature level of the store. (These values are obtained for a duct store at the ground surface and covered by 20 cm of insulation.) The optimum ratio buffer store volume per square meter of collector is mostly constant for the nine load types and any solar fraction (>50%). It seems to indicate that the optimum buffer size depends principally on the collector area (given the thermal characteristics of the collectors), and the local weather conditions. For the studied cases, the optimum value is about 120 litres/m^2. The optimal collector area, for a solar fraction of 70%, strongly depends on the load characteristics. The ratio collector area over annual heat load varies from 1.8 to 4.3 m^2/MWh. With a small system and a moderate-temperature heat distribution, the relatively large heat losses of the duct store have to be paid for with solar heat.

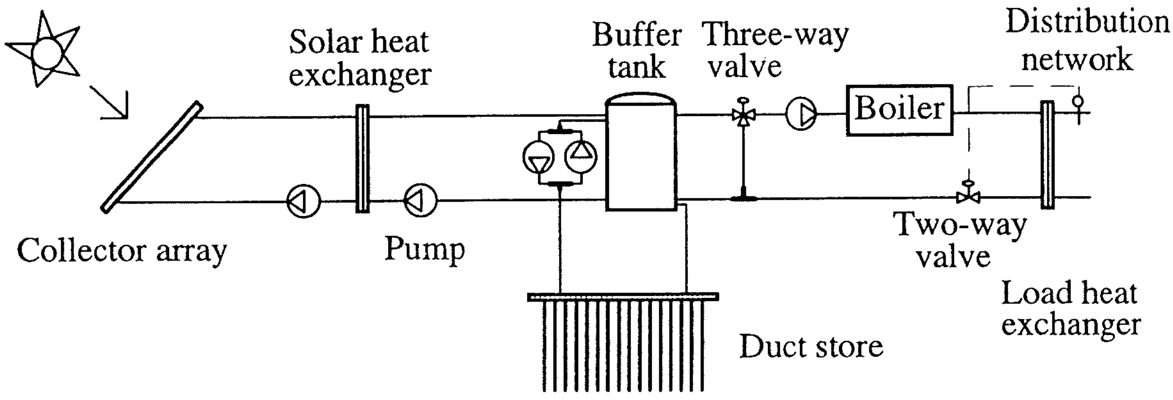

Fig. 1: Design of the system with a short-term buffer tank.

A larger proportion of domestic hot water makes the solar cost lower, but also makes the optimum size of a duct store smaller, making a ground duct store attractive for larger solar fractions. A heat load of 500 MWh/year is a critical size if the temperature levels of the heat distribution correspond to those of the moderate-temperature heat distribution (forward temperature 50-55 °C; return temperature 35-40 °C). Relative to a larger heat load, a parameter deviation from the calculated optimum design has more influence on the solar cost. The risk of having unexpected thermal performances is greater with a smaller heat load. For a solar fraction of 70%, the solar cost is calculated at 490 CHF/MWh for 25% of domestic hot water and at 420 CHF/MWh for 50%. With a low-temperature heat distribution (for space heating only: forward temperature 25-30 °C; return temperature 22-23 °C), the solar cost drops to 310 CHF/MWh. A load size of 500 MWh/year is very small for a CSHPSS system; a heat load ten times larger would drop the cost to respectively 320, 280 and 220 CHF/MWh, without taking into account the effect of a larger scale installation of the collector area, which would decrease its specific price, set to 600 CHF/m^2. Even these last prices are expensive, if compared to conventional heating with oil, which is around 120 CHF/MWh. A smaller annuity factor than 0.1 could be expected. Nevertheless, cost reductions should be concentrated on cheaper collectors, as two thirds to three quarters of the solar cost is due to the collector array. Present Swedish costs in Switzerland would drop the solar cost to the price level of conventional heating!

Table 1. Characteristics of the optimum systems that give a solar fraction of 70%.

Heat distribution temperature	Space heating	DHW	Coll. area m^2	Buffer volume m^3	Duct volume m^3	Borehole depth m	Solar cost CHF/MWh
			2130	230	10,700	35	490
Moderate	75%	25%	3650	400	22,000	44	420
			13,900	1670	111,000	76	320
			1860	220	6500	30	420
Moderate	50%	50%	3250	420	14,600	38	360
			12,700	1650	83,000	75	280
			1200	130	12,600	43	310
Low	100%	0%	2150	240	24,000	53	270
			9,200	1200	120,000	105	220

A duct store seems to be more attractive than a water store for seasonal storage only, i.e. for large values of the solar fraction. For low solar fractions (typically lower than about 50%), the main function of the duct store is to cool down the buffer store during the summer. In this situation, a system without duct store is cheaper, but the fluid temperature in the collector array reaches higher values, and may cause overheating problems.

Even with a low-temperature heat distribution, the fluid temperatures sometimes reach high values during normal operation, which are close to 100 °C in the collector array. Even the ground heat exchanger has to withstand high temperatures. A low-temperature application is not only a prerequisite for the efficient use of a duct store in the range of systems investigated, but also to reduce the risk of overheating in the collector array to unexpected situations (pump failure, etc.). Domestic hot water could be partly covered by a system designed for a low-temperature heat distribution, as the temperature level of the solar heat during the summer is high enough for the domestic hot water needs. This would make the economy of such systems more attractive. However, care should be taken in order to avoid designs that would increase the return fluid temperature in the solar heating plant or make the system operate at higher temperatures (undersized heat exchangers, the way the auxiliary heat is delivered to the heating plant, fluid mixing, etc.).

The influence of the control strategy is expected to increase with a larger buffer store in a system. An optimum strategy would aim to cover most of the short-term heat requirements with the buffer store, whereas the ground duct store would primarily be used to cover the seasonal heat requirements.

The thermal performances of a CSHPSS system with a seasonal duct storage in the ground are very sensitive to the temperature levels of the fluid in the distribution network, especially if the load size tends to be small for such a plant (below 1'000 MWh/year). The load characteristics, including the temperature levels of the forward and return fluid temperatures from the heating plant, need to be determined with the best possible accuracy. A more accurate load model than that used in the simulation tools should be used to characterize a known consumer, once a final design has to be assessed and optimized.

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