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Cost reduction of solar thermal plants by advanced thermal-hydraulic design methods

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Cost reduction of solar thermal plants by advanced thermal-hydraulic design methods

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Abstract. Software programs for thermodynamic systems modelling and simulation, e.g. Polysun®, are well established and widely used. By comparison, there are few tools available for the dimensioning of pipe networks, pumps and expansion vessels. Furthermore, it has not been possible to prove operational safety numerically. This gap is closed by the software tools HYDRA and THD which are introduced in this article. HYDRA is used to design the pipe network of large thermal solar plants. THD allows the dimensioning of solar plants up to approximately 100 m^2 collector area, including proof of venting capabilities and proof of stagnation safety.

1. Introduction

Planning and dimensioning of solar thermal plants consists basically of two consecutive steps.

The first step involves the thermodynamic dimensioning using well-established simulation tools, e.g. Polysun®, T*Sol® or GetSolar®. Calculation of initial costs and amortization is also possible, provided the costs of the components or model elements representing groups of components are correctly filed. The main results are a suitable collector type and number, the size of the storage tank and the appropriate mode of operation (low- or high-flow). The collector field is mostly modelled as a black-box and represented by a single node, the mean fluid temperature. This simplification is tolerable because the influence of the flow distribution on the efficiency is usually far below one percent [1]. The above mentioned tools allow annual simulations of very complex energy systems including solar thermal plants. However, the pipe network is greatly simplified. As an example, the collector loop in Polysun can be modelled by only three pipes which connect the collector field with pump and heat exchanger, whereas the real network consists of many pipe sections, tee-junctions and branches of different length and diameter. The influence of heat losses and thermal inertia on the simulation results are realistically calculated if the properties of the real pipe network is transformed into a thermally equivalent pipe model.

Pipe dimensioning and routing and the sizing of pump and expansion vessel is done in a second step. Cost optimization requires iterative processing of the two steps. Frank [2] developed a procedure for the optimization of pipe routing, pipe dimension and pump power. He combined this model with an advanced model for unglazed solar collectors and applied it to design a large solar plant for district heating. However, in common practice dimensioning based on experience and rule of thumb prevails. The resulting planning uncertainty can lead to suboptimal plant design, especially in terms of costs. In addition, without model-based verification it is not possible to safely eliminate the two most important causes of malfunctions, excessive steam range and flow blockages caused by free gases.

2. Thermal-hydraulic dimensioning

Cost optimization means not only minimizing investment and operating costs, but also avoiding maintenance costs due to error-prone operation. For this reason, models are needed that can represent the dimensions of all plant components in detail and also realistically simulate the relevant operating states. It is advantageous not to treat individual phenomena such as pressure loss, stagnation and pressure maintenance separately. By exploiting the fundamental coupling of the three conservation equations for energy, momentum and mass, the interdependence of the phenomena can be taken into account. This approach is expressed by the term “thermal-hydraulics”.

Based on these considerations two numerical tools have been developed and published as open source software. HYDRA [3] allows detailed hydraulic modelling of very large, branched collector fields. THD [4] allows the specification of only one collector field with several identical arrays. Both HYDRA and THD run as VBA/Excel programs on Windows. Table 1 shows the capabilities of the three complementary tools Polysun®, HYDRA and THD. In the following section the latest development of HYDRA and THD are discussed with respect to application in the planning process.

Table 1. Functionality of different software tools.

Functionality	Polysun	HYDRA	THD
Thermodynamic modelling and simulation of complex systems	✓		
Pipe network and pump dimensioning		✓	✓
Flow- temperature and pressure distribution in collector fields		✓	
Dimensioning of membrane expansion vessels			✓
Proof of venting capability			✓
Proof of stagnation safety			✓

2.1. *Software tool HYDRA*

HYDRA was published together with a detailed user manual in German and French [3]. With HYDRA, the hydraulic network of a solar thermal plant can be modelled in detail, including the network of very large collector fields. Two collector fields in serial or parallel connection can be specified. Each collector field can consist of any number of collector arrays of equal or different sizes, with a combination of parallel and serial connection of collector elements. The collector field size is limited by the hydraulic design of the collector elements only. For flat-plate collectors with meander-type absorbers and integrated header tubes the practical limit is about 1000 m^2. HYDRA allows to transform the complex internal hydraulics of large collectors designed for district heating into an equivalent but hydraulically simpler element. It is thus possible to model collector field areas larger than 10000 m^2. Flow-, temperature- and pressure distributions are calculated for stationary boundary conditions using a fast converging, explicit scheme described in [1].

2.2. *Software tool THD*

The software tool THD [4] covers all aspects of dimensioning except the analysis of branched networks. In contrast to HYDRA, the pressure loss is not calculated by pipe network analysis, but approximately by a correlation [5, Section 2.4.4]. The collector field is specified as a number of identical collector arrays connected by identical header tubes. The maximum size of a field of flat-plate collectors with meander type absorbers is therefore limited to about 100 m^2. Stagnation safety is proven by dynamic simulation of steam propagation into pipes using a two-phase mixture model in combination with drift-flux and flooding correlations [6, Chapter 3]. Stagnation models of the current version are applicable to collectors with meander-type absorbers only. These models were validated by dedicated lab experiments [7]. The uncertainty of the steam range is ±25%. Furthermore, THD calculates the clearing velocity of liquids at which gas pockets are mobilized and carried downstream to the location of an air vent. The correlation implemented for this purpose [5, Section 4.3.3] was developed based on experiments with water and a mixture of water-glycol. Furthermore, the membrane expansion vessel (MEV) is dimensioned automatically by a new model [5, Section 3.6.3], which accounts for the uncertainties of both the pre-set gas pressure in the vessel and the gauge pressure of the circuit. In a separate task within the project [3] Polysun® was extended by a functionality for exporting metadata of the solar plant and the simulation data relevant for the subsequent thermal-hydraulic dimensioning. These data can be imported by THD.

3. Design workflow for solar thermal plants

The design of a solar plant must be based on a comprehensive energy concept. The actual plant design begins with the thermodynamic dimensioning using simulation tools like Polysun®, T*Sol® or GetSolar®. The results, e.g. type and number of collectors, the size of the heat exchanger and the flow rate (high-/low-flow), are taken as input data for the subsequent thermal-hydraulic dimensioning. For the proof of stagnation safety and for the dimensioning of the MEV also the maximum irradiation and the upper and lower limits of ambient and circuit temperatures are needed. If Polysun® is used these data can be exported as an xml-file and imported by THD. Figure 1 shows the complete workflow of dimensioning solar thermal plants using THD and HYDRA. The dashed lines indicate iterative procedures requiring decision and manual input by the user. Dependency of steam volume on MEV dimensions is utilized to define an automatic, iterative procedure which results in the smallest possible MEV while the conditions of safe operation are met. THD can also be used to dimension the MEV of a plant designed with HYDRA.

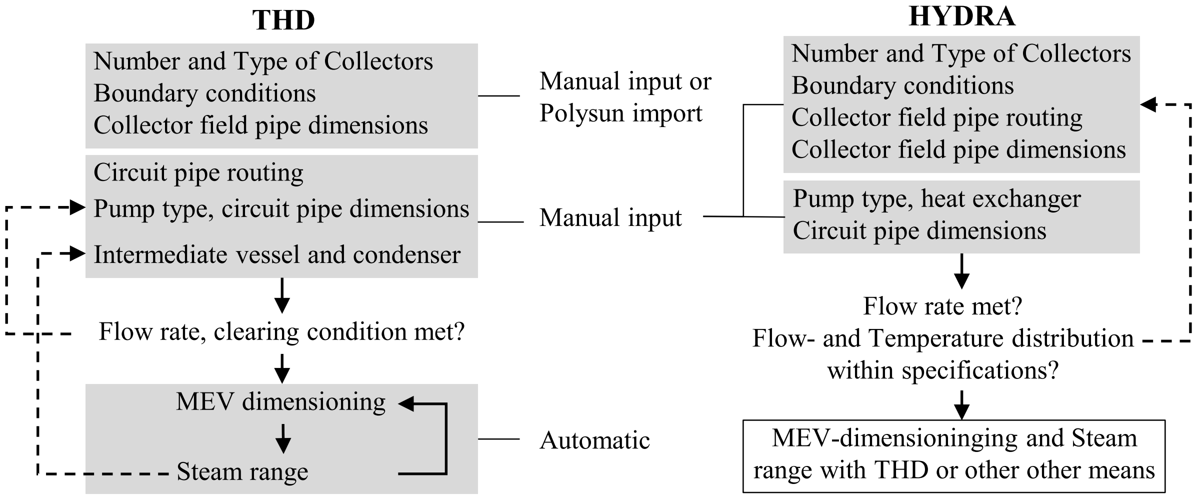

Figure 1 Design processes using THD (left) and HYDRA (right)

4. Practical example using THD

The following example illustrates the thermal-hydraulic design of a solar plant using THD. The detailed specification of the circuit, its operating conditions and all its components can be looked up in a special version of THD on https://sourceforge.net/projects/thd/, located in a folder named CISBAT. The final report of the THD project [4] might serve as a manual for the tool.

A solar plant shown in Figure 2 consists of 3 arrays with 10 flat plate collectors each. The meander-type absorbers are connected in parallel by integrated header tubes. The collector field pipes are routed in a C-configuration [1]. The total length of the pipe route between the field connection and the buffer tank is 20 m. A helical heat exchanger is located in the lower part of the buffer tank. The reference point of the MEV is on the pressure side of the pump. The circuit is to be designed for a flow rate of 30 l/hm^2.

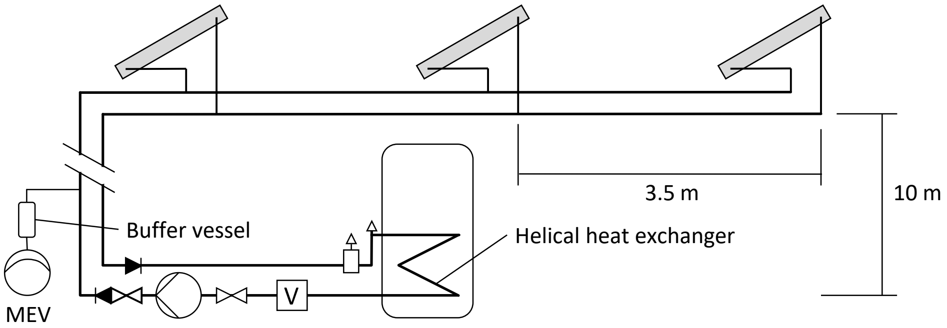

Figure 2 Solar plant with 30 flat-plate collectors.

The dimensioning is performed in four steps:

1) The collector field is specified by collector type and a number of identical collectors arrays. THD pre-calculates the pipe dimension for the main circuit automatically upon data input. Based on this information the desired dimensions of pipe and circuit components can be chosen by the user.

2) Each pipe section and circuit component is specified subsequently along the flow path starting at the reference point. THD offers product-specific catalogues for all circuit components such as collectors, pipes, pumps and valves. Figure 3 shows the pressure and flow velocity curves along the flow path. Also shown is the clearing velocity at which air pockets are mobilized and carried downstream.

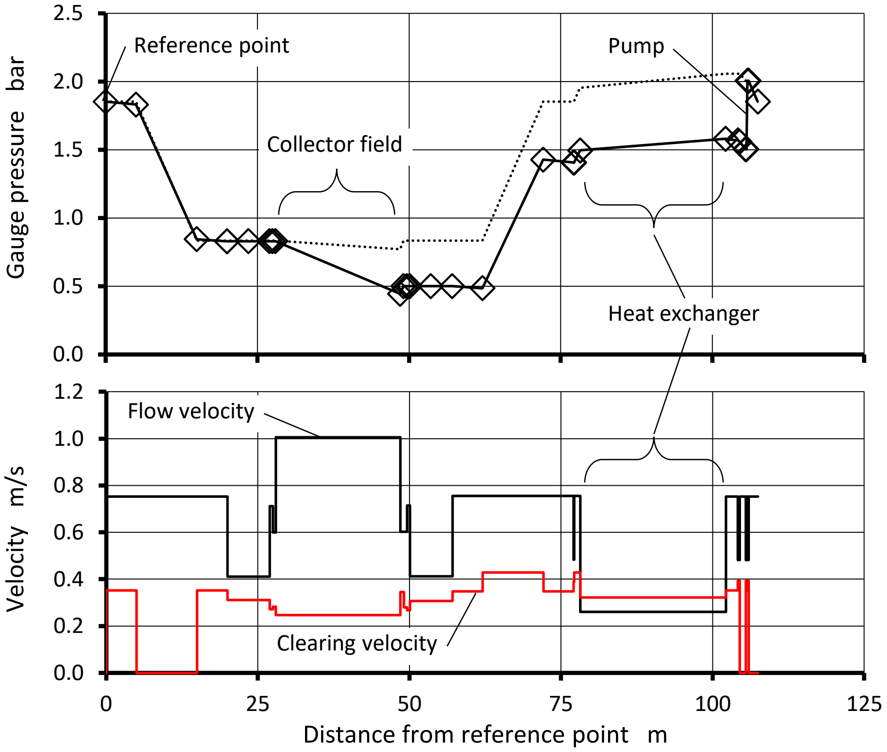

Figure 3 Pressure, flow- and clearing velocity within the circuit.

In this example, the flow velocity is always higher than the clearing velocity, except in the heat exchanger. It can be concluded that the venting capability of the circuit is good. The appropriate position of an automatic air vent is the lowest point of the supply line upstream of the heat exchanger. Since free gasses tend to accumulate in the heat exchanger a bleeding valve must be fitted at the inlet.

3) The design-relevant result in Figure 4 is the steam range during a stagnation event which stays within safe limits, as required. It reaches its maximum as soon as the steam power and the heat losses of the pipes coincide. Also shown is the steam power of the collector field, i.e. the enthalpy flow of steam entering the circuit.

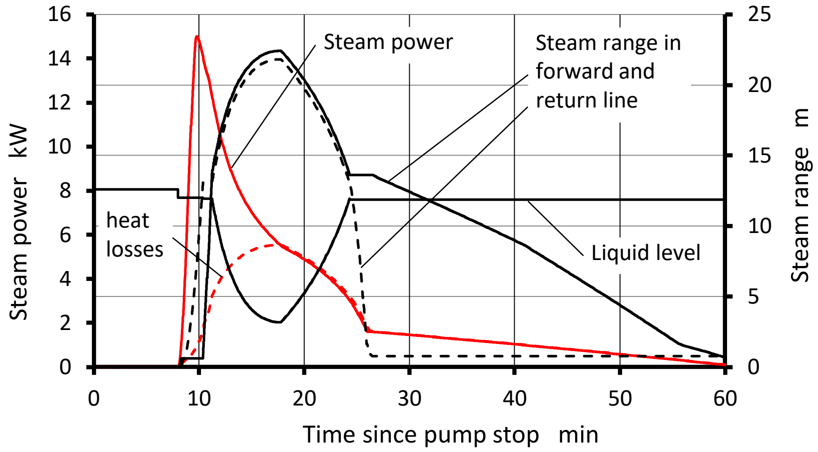

Figure 4 Steam power and steam range during stagnation.

The temporal evolution of steam power depends strongly on the residual liquid within the parts of the absorber. After reaching its maximum 10 min after pump stop the steam power decreases as the liquid within the meander and header tubes of the absorbers evaporates. 26 min after pump stop the meander tubes have dried-out and only the header tubes contribute to the steam power.

4) The MEV is dimensioned automatically in an iterative process involving steps 2) and 3). Only the safety valve had to be specified beforehand. In this example a 6 bar valve with a closing pressure difference of 0.3 bar was chosen. The dimensioning process results in the vessel size of 250 l and the diagrams shown in Figure 5.

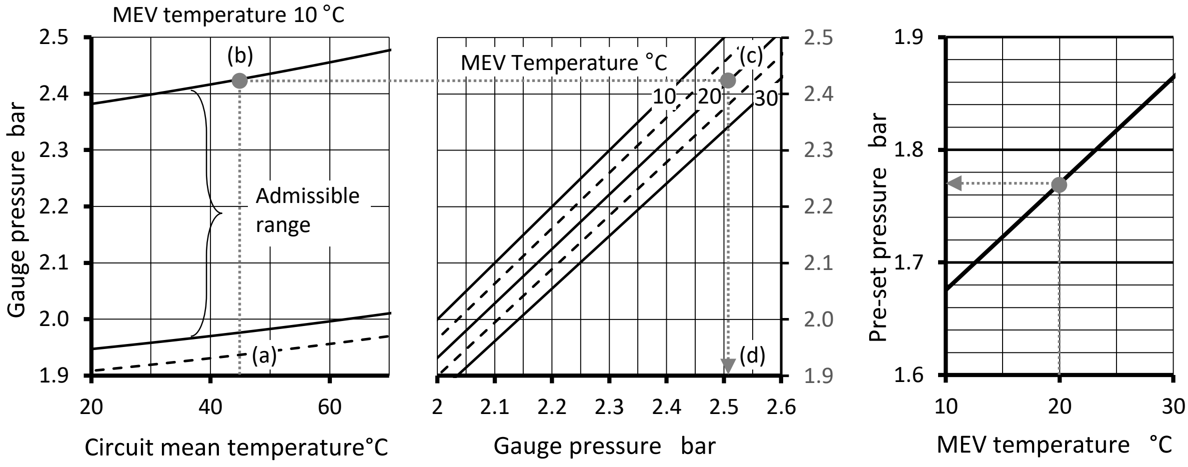

Figure 5 Diagrams for plant commissioning and maintenance.

These diagrams are extremely useful for plant commissioning which is conducted as follows. First, the gas pressure inside the MEV has to be adjusted (pre-set) according to the height of the circuit and the actual temperature. For a temperature of 20 °C the appropriate pressure of 1.77 bar can be read from the diagram on the right. The circuit is filled and vented by circulating the liquid. The advantage of the dimensioning method becomes apparent in the next step. Because the uncertainties of the pressure measurement are accounted for the circuit can be filled up to the maximum pressure limit indicated by the continuous line in the left diagram. The MEV then contains the maximum amount of liquid reserve. For an average circuit temperature of 30 °C (a) and a MEV temperature of 10 °C the maximum gauge pressure is 2.42 bar (b). This pressure is transformed for the actual MEV temperature (c) by the middle diagram which shows the actual maximum gauge pressure of 2.51 bar (d). The same diagrams can also be used for maintenance.

5. Conclusions

For a given collector type and mode of operation (high-/low-flow), a technically optimum plant design can be found by thermal-hydraulic dimensioning. Consequently, the design represents also the economic optimum. The two major causes for malfunctions, i.e. excessive steam range and flow blockages caused by free gases, can be avoided by model-based verification. With accurate dimensioning and numerical proof of safe operation the preconditions for minimizing initial costs and avoiding failure costs are fulfilled.

So far, validation is based on experimental results of rather small plants. For large fields, exchange processes within the field must be expected, the effects of which are not known. Therefore, stagnation safety measures of large plants should be dimensioned with large safety margins. For two reasons, however, the proof of stagnation safety for systems with more than 100 m^2 collector area is only possible with considerable uncertainties. Field hydraulics of very large collector fields are usually much more complex than can be represented with THD.

While simulation based thermodynamic and thermal-hydraulic design is a precondition for efficiency, minimum costs and safe operation, application of software alone is not sufficient. Suitable heat carrier liquids, pipe materials, fitting systems, pump types as well as types and locations of venting valves and membrane expansion vessels must be chosen based on state of the art and experience.

Costs can be further influenced by the choice of materials, suppliers and sales structure.

Acknowledgements

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