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A numerical model to evaluate the flow distribution in a large solar collector field

Federico Bava *, Janne Dragsted, Simon Furbo

DTU Civil Engineering, Technical University of Denmark, Brovej, Building 118, 2800 Kgs. Lyngby, Denmark

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ABSTRACT

This study presents a numerical model to evaluate the flow distribution in a large solar collector field, with solar collectors connected both in series and in parallel. The boundary conditions of the systems, such as flow rate, temperature, fluid type and layout of the collector field can be easily changed in the model. The model was developed in Matlab and the calculated pressure drop and flow distribution were compared with measurements from a solar collector field. A good agreement between model and measurements was found. The model was then used to study the flow distribution in different conditions. Balancing valves proved to be an effective way to achieve uniform flow distribution also in conditions different from those for which the valves were regulated. For small solar collector fields with limited number of collector rows connected in parallel, balancing valves are not strictly necessary if the pressure drop across the collector rows is much higher than the pressure drop along the longest distribution pipe.

1. Introduction

1.1. Background

An increasing number of large solar collector fields have been built in Europe in the last years. The main market for this technology has been Denmark, with 77% of the total collector area installed in European large scale solar heating plants at the end of 2015 (Mauthner et al., 2016). This development has been driven by some specific factors, such as high taxation on fossil fuels and widespread use of district heating (DH), to which large collector areas can be connected (Furbo et al., 2015). At the end of 2015, Denmark had more than 800,000 m^2 of solar collector fields, and more plants are expected to be installed in the next years (Fig. 1). Also the size of the collector fields has been increasing. In 2015 the current largest collector field was installed in Vojens, with a collector area of 70,000 m^2 (Mauthner et al., 2016). In 2016 a 150,000 m^2 collector field is expected to be completed in Silkeborg (EnergySupply, 2016).

The larger the solar collector field and the number of collector rows, the higher the risk of non-uniform flow distribution from one row to another and decreased thermal performance. In fact, identical collector rows supplied with different flow rates reach different outlet temperatures. Mixing flows at different temperatures causes a lower temperature rise across the collector field compared to the case with uniform flow distribution and identical outlet temperatures. If different rows have a different number of collectors (and different aperture areas), these should be supplied by different flow rates, proportional to the collector row area, resulting in the same outlet temperature for all rows.

1.2. Literature review

Flow distribution in solar thermal systems has been the topic of many investigations, both at collector level and array level. The negative effect of the flow maldistribution on the thermal performance of a single collector with parallel channels was investigated by Chiou (1982). He presents a method to determine how much the collector efficiency is penalized by the flow maldistribution. Wang and Wu (1990) developed a numerical model to predict the flow distribution in collector arrays with vertical pipes, both in U-type and Z-type configuration. Compared to the Z-type configuration, the U-type presents a higher maldistribution, with the flow rates in the absorber pipes decreasing monotonically with the distance from the array inlet. The same trend is found by Jones and Lior (1994), who considered a single collector with vertical pipes, instead of an entire array. Weitbrecht et al. (2002) present both an experimental and analytical study on the flow distribution in a Z-type collector in isothermal conditions, verifying the results from Wang and Wu (1990) and Jones and Lior (1994). They conclude that a more uniform flow distribution is

* Corresponding author.
E-mail address: febav@byg.dtu.dk (F. Bava).

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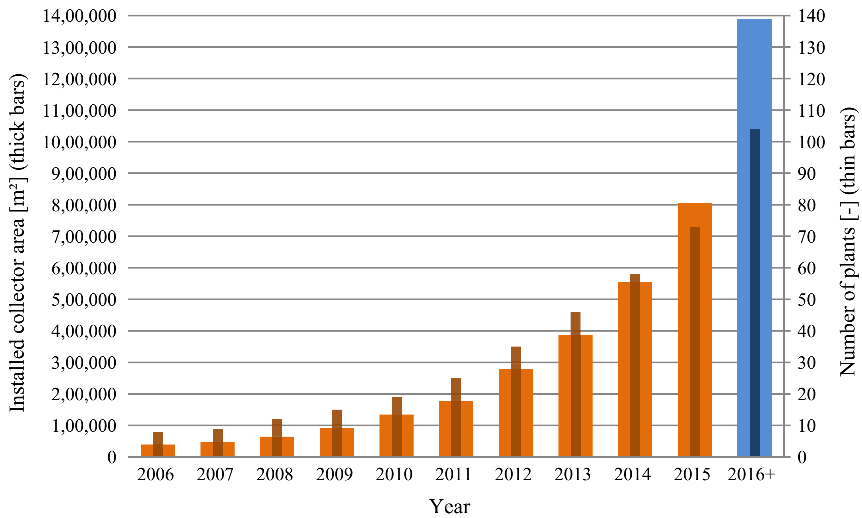

Fig. 1. Historical development of solar collector fields for DH applications in Denmark: installed collector area and number of operating (orange) and upcoming (blue) plants at the end of 2015 (Trier, 2016).

achieved when the pressure losses in the absorber pipes are much higher than in the manifolds. Fan et al. (2007) studied the flow and temperature distribution in a solar collector for large collector fields applications. Calculations with a CFD model and experimental measurements are compared. The authors conclude that the flow distribution is determined by friction (and hence buoyancy can be neglected), if the velocity in the collector pipes is high compared to the temperature rise across the collector. Bava and Furbo (2016) propose a numerical model to evaluate the pressure drop and flow distribution in a collector with horizontal U-connected pipes. Based on the findings of Fan et al. (2007), the authors argue that in large collector fields for DH applications the relation between the fluid velocity in the absorber pipes and the temperature rise across the collector is such that buoyancy can be neglected. The model was validated against measurements carried out on a collector for solar assisted DH plants.

Uniform flow distribution is of great importance also for the efficient operation of the entire collector field, but it is often overlooked (Dorantes et al., 2014). Ideally, the layout of a collector array should keep the pipe lengths as short and the flow distribution as uniform as possible. Shorter pipe lengths entail lower material and installation costs, lower thermal losses from the distribution lines, reduced pressure drop and consequently lower pumping power. Since reduction in pipe length and uniform flow distribution cannot be optimized simultaneously, a compromise between the two needs to be found. Rohde and Knoll (1976) investigate different hydraulic solutions for minimizing the flow maldistribution in a collector field of 12 collector rows connected in parallel. These solutions include various size manifolds, orifices and balancing valves. The last two are proposed as the best solutions, both in terms of performance and cost. It is noted that a configuration of valve settings maintains the desired flow distribution only at a certain flow rate. Finally, laminar flow produces less uniform flow distribution than turbulent flow. Also Knabl et al. (2014) present different solutions to achieve uniform flow distribution. A solution consists of maintaining a constant pipe diameter in the supply and return pipe. An example is represented by the first large collector fields built in Sweden, such as Falkenberg (1989) and Nykvarn II (1991). Another possibility is to adopt a Z-configuration (or reverse return). Though, both these solutions entail higher costs due to the additional material. Balancing valves can be installed in each row, but these increase the investment cost, installation time and maintenance (in case of defective valves). Installing pipes with different diameters within each collector row is a cheaper solution, but must be calculated in advance exactly, as a later adjustment would be very expensive.

1.3. Solar collector fields for DH applications

In Denmark the majority of large collector fields are installed next to a heating plant supplying a DH network. The inlet temperature to the collector field is determined by the return temperature from the DH network. Typical return temperatures are in the interval 35–45 °C (Windeleff and Nielsen, 2014). The control strategy of the collector field aims at reaching a constant outlet temperature, by continuously regulating the total flow rate based on the solar irradiance (Heller, 2000). The desired outlet temperature is the DH supply temperature. Typical supply temperatures are in the interval 70–85 °C (Windeleff and Nielsen, 2014). The temperature drop across the heat exchanger should be considered. When sufficiently high temperatures cannot be reached, for example in periods with low solar irradiance, the additional energy is provided by an auxiliary energy source.

Most of the Danish collector fields are made of 12–14 m^2 flat plate harp collectors (Windeleff and Nielsen, 2014). The diameter of the supply and return pipes to and from the collectors is progressively decreased as the fluid is diverted to the collector rows. A uniform flow distribution across the collector field is achieved by installing balancing valves at the inlet of each collector row. Unlike orifices, the setting of these valves can be changed if needed, so providing a higher flexibility. Additionally, if coupled with an on/off valve at the row outlet, balancing valves can be used for maintenance purposes. For example, in case of leakage in a row, this can be isolated, while the rest of the collector field continues its normal operation. The setting of the valves is usually chosen in such a way that the desired flow distribution is achieved in nominal operating conditions, i.e. high solar irradiance, high flow rate, nominal inlet and outlet temperatures. As found by Rohde and Knoll (1976), these valve settings provide a perfectly uniform flow distribution only in a specific operating condition, while deviations can be expected in other conditions.

Being able to evaluate these deviations is of great interest, as it allows understanding how the collector field performance is affected by off-design conditions. Additionally, it is of particular importance with respect to critical conditions such as incipient stagnation and anti-freezing mode. A collector row supplied with