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Calculation method for collector performance and available usable temperature in feasibility studies

Summary

In feasibility studies for solar thermal energy systems it is common practice to apply the collector efficiency curve according to EN 12975, where $\eta_{Col} = \eta_0 - a_1/q_{gt} \cdot (t_{col} - t_{amb}) - a_2/q_{gt} \cdot (t_{col} - t_{amb})^2$. To determine the average collector temperature t_{col}, fixed values for the inlet and outlet temperatures $t_{col,in}$ and $t_{col,out}$ are often specified (although these depend on the current operating conditions and are therefore usually unknown). This is problematic, because once they are fixed, also the collector capacity $\dot{Q}_{col}$ is already determined independent of η_{Col} via the energy balance $\dot{Q}_{col} = \dot{W}_{col} \cdot (t_{col,out} - t_{col,in})$ with the heat capacity flow rate $\dot{W}_{col}$ that was used under test conditions to determine a_1 and a_2. This paper shows how the unknown collector outlet temperature as well as the usable temperature behind a solar heat exchanger can be calculated by using reasonable flow rates. A difference in the achievable solar contribution of up to 30 % as compared to the conventional calculation method can arise, if e.g. minimum feed in temperatures to a DHN return line of e.g. 50°C are required.

Keywords: collector efficiency, district heating, variable flow rate

Field of application for the findings: feasibility studies, sustainable and efficient districts, collector calculations

Addressed audience: Engineers, Planers, Software developers

1. Introduction

In feasibility studies, the available solar heat from a collector area A_{col} is typically determined using the following equation.

$$\dot{Q}_{col} = A_{col} \cdot \eta_{col} \cdot q_{gt} \tag{1}$$

with the global irradiation on the tilted collector surface, q_{gt}, and the efficiency, η_{col}, of the collector, which is calculated according to EN 12975 as follows:

$$\eta_{Col} = \eta_0 - a_1 \cdot \frac{(t_{col} - t_{amb})}{q_{gt}} - a_2 \cdot \frac{(t_{col} - t_{amb})^2}{q_{gt}} \tag{2}$$

With the collector efficiency η_{Col} and the parameters contained therein, η_0 , a_1, and a_2, equation (1) describes, in a highly simplified way, the energy conversion of solar radiation into thermal energy as well as the transport of the thermal energy to the heat-transfer medium. Therefore, equation (1) can also be understood as the heat transfer equation of the collector.

In the full paper a more precise description of the parameters η_{Col}, η_0, a_1 and a_2 will be included with relevant references. Here we focus on their flow rate dependency. Razika et al. (2014) derived a linear dependency of the collector efficiency from their measurements of a horizontally oriented flat plate collector with specific flow rates between 19 and 78 l/(m²·h) (Fig. 1, left). Chen et al. (2012) compared two flat plate collectors (one with an ETFE foil between absorber and cover glass and the other one without, see solid and dotted lines in Fig. 1, right). They derived performance curves according to eq. (2) for three different flow rates of 24, 48 and 119 l/(m²h). In combination with collector simulations they provided a nonlinear (i.e. cubic) efficiency curve as function of flow rate.

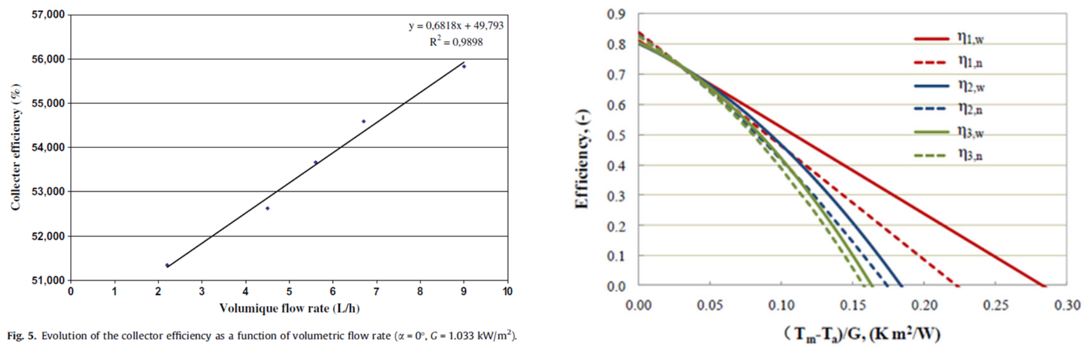

Fig. 1: Left - Collector efficiency as function of flow rate, adopted from Razika et al. (2014)
Right: Collector efficiency of two different collectors (index w and n)
for three flow rates (index 1, 2, 3) adopted from Chen et al. (2012)

2. Method

According to equation (1) and (2) the useful heat output, $\dot{Q}_{col}$ of a collector can be derived from a quadratic function of the temperature difference, Δt_m.

$$\dot{Q}_{col} = A_{col} \cdot q_{gt} \cdot \eta_0 - A_{col} \cdot a_1 \cdot \Delta t_m - A_{col} \cdot a_2 \cdot (\Delta t_m)^2 \tag{3}$$

This temperature difference is calculated from the arithmetic mean of the inlet and outlet temperatures of the collector and the ambient temperature.

$$\Delta t_m = t_{col} - t_{amb} = \frac{(t_{col,in} + t_{col,out})}{2} - t_{amb} \tag{4}$$

To determine the mean collector temperature t_{col}, fixed values for the inlet and outlet temperatures are often assumed (although they depend on operating conditions and are thus usually unknown). This is problematic, because by fixing $t_{col,in}$ and $t_{col,out}$, the collector capacity $\dot{Q}_{col}$ is effectively over-determined because simultaneously to the heat transfer equation (1) the energy balance must apply,

$$\dot{Q}_{col} = \dot{W}_{col} \cdot (t_{col,out} - t_{col,in}) \tag{5}$$

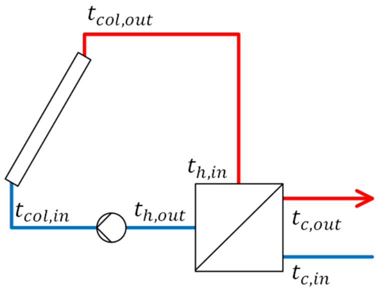

Fig. 2: Nomenclature in collector circuit.

where the heat capacity flow rate $\dot{W}_{col} = \dot{V}_{col} \cdot c_{p,col} \cdot \rho_{col}$ must match the value used during the collector test to determine the values of η_0, a_1 and a_2 for applying equation (2). However, with $\dot{W}_{col}$ the unknown outlet temperature in the mean temperature t_{col} of equation (2) can be replaced, since $t_{col,out} = t_{col,in} + \dot{Q}_{col}/\dot{W}_{col}$.

By inserting $t_{col,out}$ into eq. (4) and using the resulting mean temperature difference

$$\Delta t_m = \frac{\dot{Q}_{col}}{2 \cdot \dot{W}_{col}} + t_{col,in} - t_{amb} = \frac{\dot{Q}_{col}}{2 \cdot \dot{W}_{col}} + \Delta t_i \tag{6}$$

in eq. (3) a quadratic equation for the collector capacity is derived as function of $\Delta t_i = t_{col,in} - t_{amb}$. After solving for $\dot{Q}_{col}$, it turned out that only the positive square root produces technically meaningful results.

$$\dot{Q}_{col} = -\frac{p_i}{2} + \sqrt{\frac{p_i^2}{4} - q_i} \tag{7}$$

With

$$p_i = (2 \cdot \dot{W}_{col})^2 \cdot \frac{1000}{A_{col} \cdot a_2} + 2 \cdot \dot{W}_{col} \cdot \left(2 \cdot \Delta t_i + \frac{a_1}{a_2}\right) \tag{8}$$

$$q_i = (2 \cdot \dot{W}_{col})^2 \cdot \left(\Delta t_i^2 + \frac{a_1}{a_2} \cdot \Delta t_i - q_{gt} \cdot \frac{\eta_0}{a_2}\right) \tag{9}$$

and the same technical parameters of the collector (i.e., η_0 , a_1, a_2, and the corresponding heat capacity flow rate $\dot{W}_{col}$ under test conditions), eq. (7) provides the same collector capacity, $\dot{Q}_{col}$ as described by eq. (1) and (3). However, $\dot{Q}_{col}$ can be calculated solely from the operating conditions at the collector inlet, without assuming an outlet temperature, because instead of Δt_m, the known temperature difference $\Delta t_i = t_{col,in} - t_{amb}$ is used.

In the full paper additional equations will be derived, which use the inlet temperature on the cold side of the heat exchanger in Fig. 2 (which might correspond to the temperature in a DHN return line) to calculate $\dot{Q}_{col}$ and the available usable temperature, $t_{c,out}$.

3. Results

Fig. 1 shows the impact of the improved calculation method for a typical summer day in Germany with a maximum ambient temperature $t_{amb} \approx 24$ °C and a maximum global horizontal irradiation $q_{gt} \approx 900$ W/m². For a fixed inlet temperature $t_{col,in} = 50$ °C the performance of a collector with $\eta_0 = 0.779$, $a_1 = 1.070$ W/(m²K), $a_2 = 0.014$ W/(m²K²) and $\dot{W}_{col} = 0.11$ kW/K was calculated for two cases. In the first case a fixed outlet temperature $t_{col,out}^{fix} = 60$ °C was used (instead of $\dot{W}_{col}$) to calculate Δt_m and q_{col}^{fix} (established method). In the second case $\dot{W}_{col}$ was used to calculate q_{col}^{min} and the outlet temperature $t_{col,out}^{min}$ (improved method). In addition, it was assumed that $t_{col,out}^{min}$ has to exceed $t_{feed-in}^{min} = 60$ °C before solar energy can be used e.g. as feed-in to the return line of a district heating network. When $t_{col,out}^{min} < t_{feed-in}^{min}$ the solar gain q_{col}^{min} was set to zero. The comparison of q_{col}^{fix} (closed symbols) and q_{col}^{min} (open symbols) makes it clear that both values are nearly identical when $t_{col,out}^{min} > t_{feed-in}^{min}$ (i.e. between hour 9 and 15). The small differences result from small differences in Δt_m due to different outlet temperatures $t_{col,out}^{fix} = 60$ °C and $t_{col,out}^{min} > 60$ °C, respectively. Thus, q_{col}^{min} is a bit smaller as q_{col}^{fix}. However, the main difference occurs when $t_{feed-in}^{min}$ cannot be reached. On that specific day the daily sum of q_{col}^{min} is 22 % lower than q_{col}^{fix}. On a yearly basis the difference might increase to 30 or even 40 % depending on the threshold $t_{feed-in}^{min}$ and the available usable temperature, which can now be calculated. In the full paper a more detailed discussion will be implemented in combination with an application example of a feasibility study for a sustainable district.

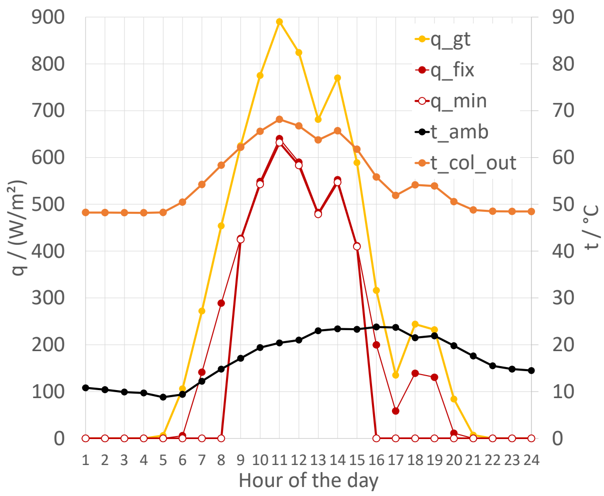

Fig. 3: Comparison of established and new method.

4. References

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