Internal thermal coupling in vacuum tube collectors with coaxial absorber pipes

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Abstract

ISFH investigated the impact of the internal coupling in vacuum tube collectors with coaxial absorber pipes. Measurements show an efficiency reduction of 10% if reducing the flow rate from 78 kg/m^{2}h to 31 kg/m^{2}h for a collector group with 60 parallel coaxial vacuum tubes at one-sided connection. For a more detailed investigation a simulation model of a vacuum tube collector was developed. The simulations show non-linear temperature profiles along the inner and outer tubes with the maximum temperature not at the fluid outlet but inside the outer pipe. This non-linearity increases with decreasing flow rates. Significantly higher temperatures if compared to the standard flow direction are observed if the fluid is directed from the outer to the inner pipe.

The model was extended to simulate a complete collector group with 60 vacuum tubes connected in parallel, whereat the tubes are operated with an experimentally determined flow distribution. The simulation results confirm the measured efficiency decrease at low flow rates. It was found, that the main reason for this is the coupling effect in the vacuum tubes, which is more pronounced at unequal flow distribution. Internal coupling in the header increases the efficiency reduction just slightly if not connected one-sided. As a consequence, low flow rates should be avoided for coaxial tube collectors, thus restricting the possible operation conditions.

1. Introduction

Metal-in-glass direct-flow vacuum tube collectors are typically designed with coaxial absorber pipes. This design needs only one intersection between metal tube and vacuum glass envelope if compared to the alternative U-Pipe configuration, resulting in one metal-glass-joint. However, the coaxial design leads to a direct heat exchange between inlet and outlet flow like in a counter flow heat exchanger. In [1] it has been shown that this heat exchange leads to a non-linear temperature profile inside the tubes resulting in higher temperatures in the outer pipe compared to a non-coaxial design. This way the efficiency is reduced significantly at low mass flow rates. In addition, the risk of locally exceeding the boiling temperature rises since the highest temperatures do not appear at the tube outlet but somewhere within the outer pipe.

Former papers as published in [1] left open questions, since the simulation model used in [1] had the following restrictions. The flow direction in the tubes was only possible from inner to outer pipe. Furthermore the model contained no appropriate calculation of the heat fluxes in the header, especially in case of a coaxial header. Therefore the existing model has been enhanced to overcome these restrictions. The new model now allows a comprehensive investigation, whose results are presented in the following. The work concentrates on how the header construction and the flow directions in header and tubes influence the temperature and efficiency effects of the internal coupling.

2. Theoretical Model

A model is developed and programmed in Visual Basic (vb.net®) in order to describe the temperature distribution of a collector with a user-defined number of direct-flow vacuum tubes. The model takes into account several possible operating conditions such as the flow direction and if internal coupling takes place – both might be different for the tubes and the header. Furthermore the collector connection can be varied from one-sided (OSC) to reverse-return connection (RRC) thus defining the mass flow distribution and the type of the internal heat exchange in the header (coflow at RRC and counterflow at OSC). Table 1 gives an overview of all the possible variations.

For the calculation the model divides the header into elements in flow direction. Fig. 1 gives an overview of the model in case of a coaxial header with tubes which show a flow direction from the inner to the outer pipe.

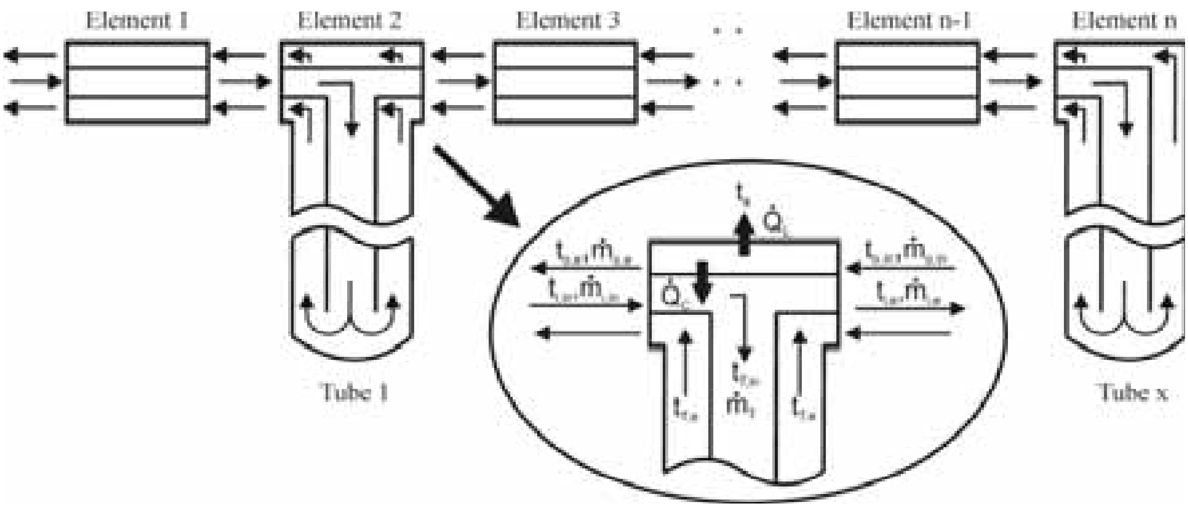

Fig. 1. Example scheme of the collector model and one T-piece element with the following variables: t_a: Ambient temperature, $t_{y,z}$: Fluid temperature of inner (y = i) or outer (y = o) header pipe or of the collector tube (y = T), at inlet (z = in) or exit (z = e), $\dot{Q}_L$: Heat loss, $\dot{Q}_C$: Coupling heat flux [2]

The header model is based on energy balances for the inner and outer pipe in each element, which in case of the example of Fig. 1 are expressed as follows.

Outer pipe: $\dot{m}_{o,e} \cdot c_p \cdot t_{o,e} - \dot{m}_{o,in} \cdot c_p \cdot t_{o,in} = \dot{m}_T \cdot c_p \cdot t_{T,e} - \dot{Q}_C - \dot{Q}_L$ (1)

Inner pipe: $\dot{m}_{i,e} \cdot c_p \cdot t_{i,e} - \dot{m}_{i,in} \cdot c_p \cdot t_{i,in} = \dot{Q}_C - \dot{m}_T \cdot c_p \cdot t_{i,m}$ (2)

Using an iterative procedure the heat fluxes and outlet temperatures of each header element may be calculated using the collector inlet temperature, overall mass flow rate and the tube outlet temperatures. For the determination of the collector tube outlet temperatures a model of a collector tube is used which divides the tube into a specified number of elements in flow direction. Here too, the energy balance equations for the absorber and the inner and the outer pipe in each element are solved iteratively.

Detailed descriptions of the models are given for the tubes in [1] and for the header in [2]. The mass flow distribution through the tubes is an input into the header and tube model. It has been determined using further experimental and/or theoretical methods (see [3]).

The following analysis is made with a group of two collectors. Each collector consists of two header tubes (one dividing and one combining) and 30 tubes with coaxial pipes, i.e. 60 tubes in total. The pipes are made of copper with a length of 1.7 m and inner and outer pipe diameters of 5.3 mm and 10.4 mm with wall thicknesses of 0.7 mm and 1.6 mm, respectively. The group may be connected from one or both sides (latter for reversed return connection). The model uses a measured flow distribution (i.e. percentage of total collector mass flow rate passing through one specific collector tube) for one-sided collector connection (OSC) and a calculated one for the reverse-return connection (RRC).

3. Results and Discussion

Efficiency Measurements and simulations

Measurements are carried out using a group of two direct-flow coaxial vacuum tube collectors (as described in Section 2, but with separate distributing and collecting manifold tubes instead of a coaxial version of the header design). The group is installed on an outdoor test roof at a horizontal collector slope. An efficiency curve is obtained at high flow conditions with a mass flow rate of 500 kg/h (78 kg/m^{2}h). The measured data shows a very good agreement with former test data with a slightly increase in measurement uncertainty. The efficiency measurements are repeated with a lower mass flow rate of 200 kg/h (31 kg/m^{2}h).

Additionally simulations are made with the same inlet conditions as in the measurements using the flow distribution for OSC and considering no internal coupling in the header (as in the measured collector). Fig. 2 shows the measured and simulated results considering the internal heat exchange in the tubes.

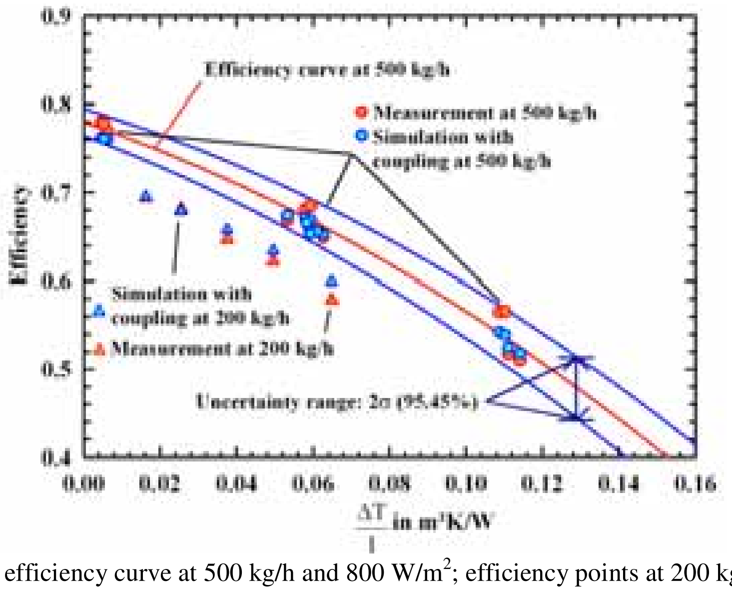

Fig. 2. Measured efficiency curve at 500 kg/h and 800 W/m^2; efficiency points at 200 kg/h and 500 kg/h altogether with simulation assuming non-uniform one-sided flow distribution

The measured efficiency points at 500 kg/h are within the uncertainty range of the fitted efficiency curve. The efficiency at 200 kg/h is significantly lower. The efficiency decreases from 8% (relative deviation) at $\Delta T/G = 0.015$ to 11% at $\Delta T/G = 0.07$ if compared to the efficiency curve at 500 kg/h. For differing irradiance levels the measured discrepancies have the same size. The investigated collector group thus shows a considerable dependency on the mass flow rate in the measurements, which may not be explained with reduced heat transfer coefficients. The simulations both at 500 kg/h and 200 kg/h are in good agreement with the measurement (maximum deviation 4%), thus validating the model and confirming the efficiency drop due to the internal coupling.

Temperature Profiles in a coaxial vacuum tubes

The tube model allows investigating the temperature profile in a coaxial vacuum tube. Simulations were made with a tube specified with the data of the measured collector. As input conditions the irradiance is set to 1000 W/m^2, the ambient air temperature to 20°C and the fluid inlet temperature to 80°C. Two different total mass flows are selected representing high (80 kg/m^{2}h) and low flow conditions (20 kg/m^{2}h). The simulations are carried out with both possible flow directions within the tubes.

Fig. 5 presents the temperature profiles versus the specific path length x, which is the ratio of the distance from in- or outlet to the overall tube length. In addition, two methods to average the fluid temperature are applied: The first method is the arithmetic mean temperature between inlet and outlet temperature ($t_{m,arith}$), which is the conventional method used in standard collector tests. The second method is the temperature averaged over the length of the outer pipe ($t_{m,real}$). It represents that temperature, which is responsible for the heat losses to the ambient resulting from the heat transfer between absorber and ambient air. Fig. 3 shows the results for the flow direction from the inner to the outer pipe (left) and vice versa (right).

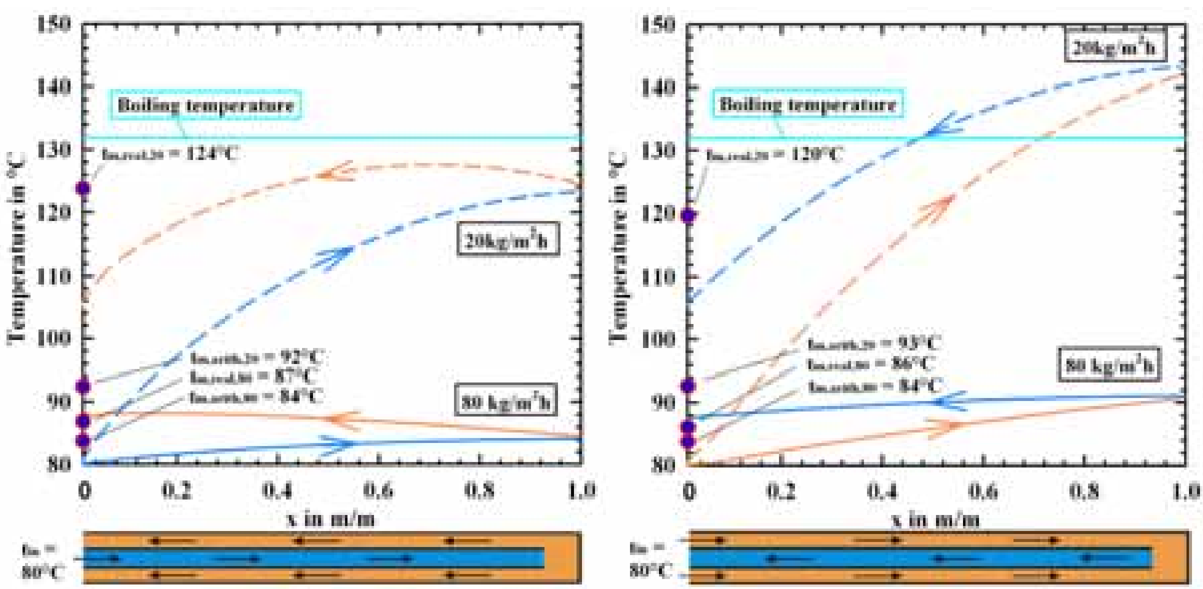

Fig. 3. Example for calculated temperature profiles in a coaxial vacuum tube at 80 kg/m^{2}h and 20 kg/m^{2}h with flow direction from inner to outer (left) and from outer to inner pipe (right), blue graphs represent the inner pipe temperatures, orange graphs the outer pipe temperatures. Furthermore, the boiling temperature of the fluid (water glycol mixture 60%/40%) at 2.6 bars abs. is indicated. Below: scheme of the collector tube with flow direction

The temperature profiles in the coaxial tube show non-linear characteristics. With the inlet at the inner pipe (Fig. 3 left) the temperature rises in the inner pipe due to the internal heat exchange. The increase is inversely proportional to the mass flow rate. After the redirection point the temperature still rises until the maximum temperature is reached inside the outer pipe, and then it decreases towards the tube outlet temperature. The location x of the maximum and the difference between maximum and outlet temperature increases with decreasing flow rate. At a mass flow of 80 kg/m^2h the maximum temperature is 88°C at x = 0.15 and at 20 kg/m^2h 129°C at 0.7. While the arithmetic mean temperature $t_{m,arith}$ differ just slightly (84/92°C), the real mean temperatures $t_{m,real}$ rise from 87°C (80 kg/m^2h) to 124°C (20 kg/m^2h).

With the inlet at the outer pipe (Fig. 3 right) the temperature rises in the outer pipe due to both the internal heat flow and the incoming solar irradiance. The maximum temperature is at the end of the outer pipe. After the redirection the temperature decreases in the inner pipe due to the heat flow to the outer pipe. The real mean temperature increases from 86°C at 80 kg/m^2h to 120°C at 20 kg/m^2h. They are slightly lower than in the reverse flow direction (Fig. 3 left). Therefore a slightly higher efficiency is gained resulting in a higher outlet temperature. Apart from that this flow direction leads to higher maximum temperatures with temperature 90°C at 80 kg/m^2h and 140°C at 20 kg/m^2h. The latter exceeds the boiling temperature of 132°C. This is consistent to a pressure of 2.6 bars absolute. Locally lower pressure levels caused by a hydraulic pressure drop over the collector are not considered, as this effect is negligible. Thus the fluid starts to evaporate although the outlet temperature is far below the boiling point.

It must be noted that the model cannot simulate the process of evaporation, therefore the profiles shown neglect additional evaporation relevant energetic effects. The experimental investigation in [3] shows that the evaporation during operation (so-called partial stagnation) can lead to an efficiency reduction in direct-flow vacuum tube collectors depending on the collector slope. Vapour generation in an operating collector array (pump is on) leads in any case to more unstable conditions, in extreme cases resulting in a collapse of the collector flow. Boiling should therefore be avoided to guarantee a safe operation. For this reason the flow direction from outer to inner pipe might not be the better option although it leads to a slightly higher efficiency especially at low mass flow rates.

Simulation of different collector configurations

The following examination intends to determine the proportion of the flow distribution effect and the internal coupling effect in the header influencing the efficiency reduction and the maximum temperature increase. Therefore simulations are made with 1000 W/m^2 incident irradiance, 20°C ambient and 40°C fluid inlet temperature and flow rates from 15 kg/m^2h to 80 kg/m^2h. As a reference the simulation is made for a collector group without internal coupling both in the tubes and the header (which is nearly independent of the collector connection).

The simulation is repeated considering internal coupling in the tubes and with reverse-return (RRC) and one-sided (OSC) collector connection with or without internal coupling in the header. The configuration firstly assumes a flow direction from inner to outer pipe in the tubes and in the header. Fig. 4 compares the efficiency reduction with respect to the reference case and the maximum temperature in the complete collector group of the four variants. At OSC the temperatures in the tubes are partially higher than 180°C at 15 kg/m^2h.

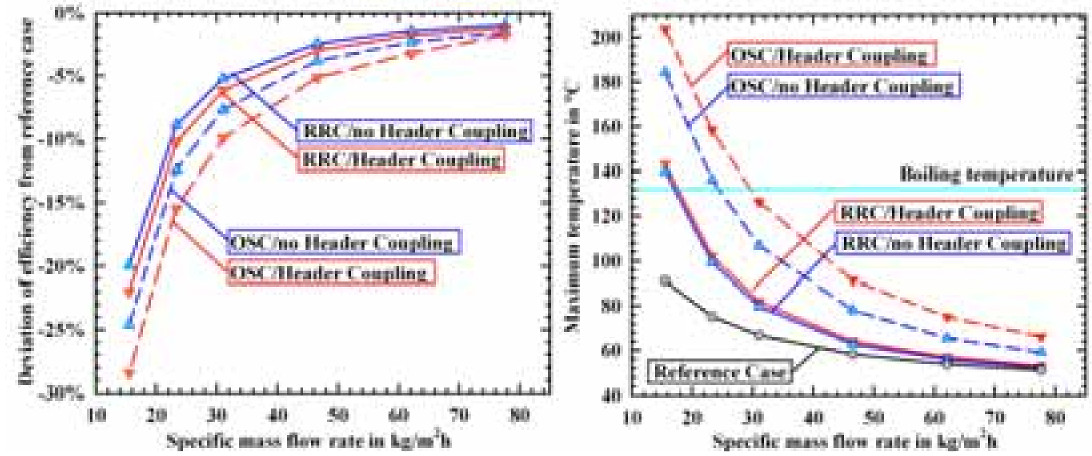

Fig. 4. Efficiency reduction and maximum temperatures for header with and without internal coupling

The efficiencies at 80 kg/m^{2}h differ approximately 2% from the reference case and show only small variations for the different design variants. At lower mass flow rates the efficiency reduction compared with the reference case and the differences between the variants increase significantly (9% to 16% at 20 kg/m^{2}h). The maximum temperatures at OSC are considerably higher if compared to RRC. Below 30 kg/m^{2}h the maximum temperature exceeds the boiling point (considering a pressure of 2.6 bars absolute) and evaporation occurs in the collector. In summary RRC shows higher efficiencies and lower maximum temperatures and should be the preferred collector connection design. At RRC the differences with or without coupling in the header are low. Therefore it might be reasonable to replace a two-pipe with a coaxial header if this is constructional advantageous. However, the internal coupling affects the efficiency and temperatures for all investigated variants at low flow rates.

So far, all the variants discussed consider a flow direction from the inner to the outer pipe both in the tubes and in the header. Further simulations investigate the impact of the flow direction. For this, the simulations are repeated for RRC with different flow direction in the header and in the tubes (from inner to outer pipe (io) or from outer to inner pipe (oi)). Fig. 5 shows the efficiency reduction with regard to the reference case and the maximum temperatures for the four possible variants.

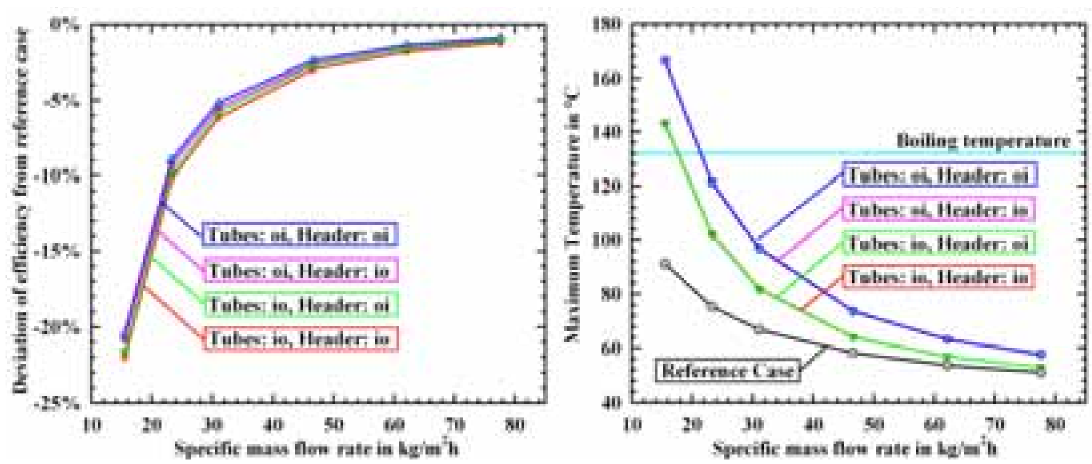

Fig. 5. Efficiency reduction and maximum temperatures for header with internal coupling at RRC and different flow directions in header and tubes

The differences in efficiency between the simulated variants are low. A slightly higher efficiency is achieved if the fluid passes through the tubes from outer to inner pipe. However, this configuration leads to higher maximum temperatures and thus causing an earlier evaporation. Therefore the flow direction in the tubes should be from inner to outer pipe. The flow direction in the header shows nearly no differences in the efficiency and maximum temperature curves.

Finally, the aspect of the starting point for evaporation shall be investigated in detail. Simulations are made at the same operation conditions while varying the mass flow rate. The flow rate is lowered until the highest temperature in the complete collector group exceeds the boiling point of 132°C. This way the simulations lead to the maximum flow rate at which evaporation in the respective configuration may be expected. Fig. 6 shows these flow rates for the following configuration attributes:

- With and without coupling in the collector tubes
- With and without coupling in the header
- Flow distribution caused by one-sided (OSC) or reverse return (RRC) collector connection or uniform flow distribution (U) respectively
- Tube flow direction from inner to outer pipe (Tio) or vice versa (Toi), Header flow direction from inner to outer piper (Hio) or vice versa (Hoi)

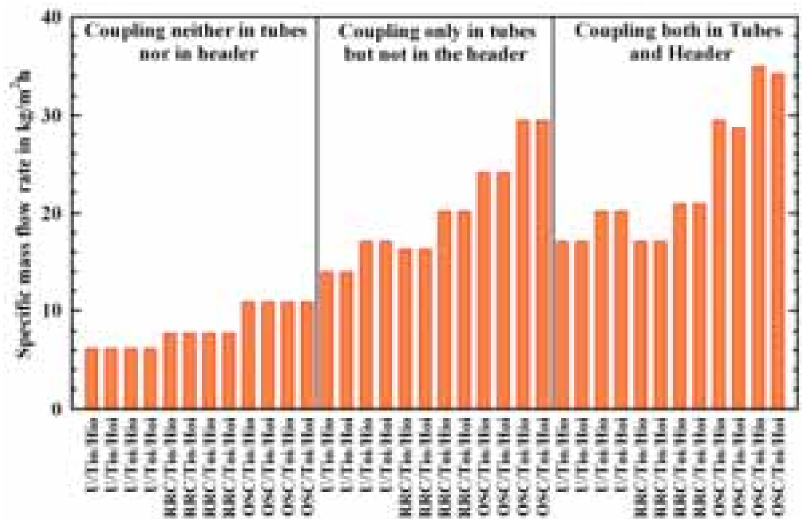

Fig. 6. Maximum mass flow rate when boiling point is exceeded for different configurations

A high mass flow rate indicated in Fig. 6 identifies a higher tendency to vapour generation and thus shows a more critical configuration. From the diagram the following results can be extracted:

- The lowest mass flow rates occur without coaxial collector tubes.
- A more unequal flow distribution leads to earlier evaporation: The lowest uniform flow distribution results in the case OSC, followed by RRC, while U indicates an ideal uniform flow through the tubes.
- Headers with internal coupling lead to significant higher values exclusively in the case of OSC.
- Significantly higher flow rates occur for a tube flow direction from outer to inner pipe.
- The flow direction in the header shows nearly no effect.

4. Conclusion

Coaxial tubes show constructional advantages for vacuum tube collectors if compared to the U-pipe design because only one instead of two vacuum intersections is necessary for each tube. The temperature profile of a coaxial tube shows a non-linear characteristic with the maximum temperature within the outer pipe. The local distance between tube outlet and the point of maximum temperature and the amount of the temperature difference between maximum and outlet increase with decreasing flow rates. Therefore local vapour generation may occur, although the tube outlet temperature is far below the boiling point. This effect is more pronounced at a flow direction from outer to inner pipe since the maximum temperatures are significantly higher compared to the reverse flow direction.

The collector efficiency is highly depending on the flow rate. This is shown with a collector group representing a typical vacuum tube collector design. The extent of the efficiency reduction depends on the tube flow rates. Therefore the flow distribution has to be regarded. Using a reverse-return collector connection is less critical than a one-sided collector connection. But even at an idealistic uniform flow a significant efficiency drop occurs at low flow rates. Internal coupling in the header increases the efficiency reduction just slightly except in case of a one-sided connection. The flow direction in the header and in the tubes does not influence the efficiency significantly. Because of the higher maximum temperatures in the tubes the fluid path should always be from the outer to the inner pipe.

In summary each collector with coaxial tubes shows a significant efficiency reduction at low flow rates independent of header construction and flow direction and just slightly affected by the collector connection. Thus the flow rate of collectors with coaxial vacuum tubes must be kept at a minimum level (e.g. 50 kg/m^{2}h).

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References

[1] J. Glembin, G. Rockendorf, J. Scheuren, Internal thermal coupling in direct-flow coaxial vacuum tube collectors, Solar Energy 84 (2010) 1137-1146.

[2] J. Tang, Modellierung eines direkt durchströmten Vakuumröhrenkollektors mit Kollektorsammler (Modeling of a direct-flow vacuum tube collector with header), Student research project (2010), Leibniz Universität Hannover, Germany.

[3] J. Glembin, D.Eggert, J. Scheuren, G. Rockendorf, Partial stagnation in direct-flow vacuum tube collectors: Conditions for occurrence, risks and consequences, EUROSUN (2010), Graz, Austria.