FLUID FLOW INVESTIGATIONS OF BIONIC ABSORBERS MADE FROM ALUMINIUM AND STEEL

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Abstract

Challenges of future solar collector development are cost reduction, industrial production methods as well as flexibility with respect to different designs. In contrast to conventional sheet-and-tube constructions, metal forming processes offer flexible, hydraulically and thermally optimized designs without additional costs. Among those processes aluminium roll-bonding as well as partial roll cladding in combination with hydroforming of steel are promising technologies. Solar collectors containing absorbers with a bionic FracTherm® channel design are currently being developed within the European project BIONICOL (aluminium roll-bond) and a German research project (partially roll cladded and hydroformed steel absorbers with a multi-layer configuration). This paper focuses on fluid flow investigations considering the special shape of FracTherm® channel designs which can be produced using the mentioned production technologies (among others). CFD simulations were carried out in order to learn more about three-dimensional flow phenomena and to calculate pressure drop and flow distribution. Moreover, a fluid dynamics test facility for both flow visualization and measurements was developed. Pressure drop measurements and visualizations of the flow distribution in large absorbers were carried out.

1. FracTherm® absorber designs

FracTherm® absorber designs consist of a multiply branched, fractal-like arrangement of channels, similar to natural ones. The aim of this “bionic” approach is to obtain a uniform flow distribution and a low pressure drop [1]. FracTherm® absorber designs need appropriate production methods for complex structures as well as fluid flow investigations in order to learn more about detailed flow phenomena.

2. Projects on the development of aluminium and steel absorbers

2.1. BIONICOL project

The aim of the European project BIONICOL, which is carried out by Fraunhofer ISE together with four companies, is to develop typically sized solar collectors (about 1 m x 2 m) with aluminium roll-bond absorbers containing a FracTherm® channel design (Fig. 1). Apart from corrosion investigations done by project partners, which are one of the core tasks of the project, Fraunhofer ISE carried out fluid flow simulations using CFD (Computational Fluid Dynamics) in order to better understand the hydraulic behavior of FracTherm® channel designs and thus be able to develop appropriate hydraulic models which can serve as a basis for optimization. Moreover, a fluid dynamics test facility was developed in order to have the possibility to validate numerical and analytical calculations.

Fig. 1: FracTherm® absorber produced during BIONICOL project

2.2. Steel absorber project

A German steel absorber project, which is led by Technische Universitaet Dortmund and carried out together with Fraunhofer ISE and a number of companies, follows a concept similar to roll-bond technology. It is based on partially roll cladded metal sheets in combination with hydroforming (Fig. 2 and Fig. 3). However, in this case steel is used instead of aluminium, corrosion resistance is realized by additional layers e. g. from copper or stainless steel and dies containing the channel shape are used for hydroforming (roll-bonding does not use dies). Since steel can be deformed much more than aluminium and dies are used, the possible channel geometries (including header channels) are very different from roll-bond channels. This also has an influence on the FracTherm® designs to be investigated, both with respect to production and to fluid flow.

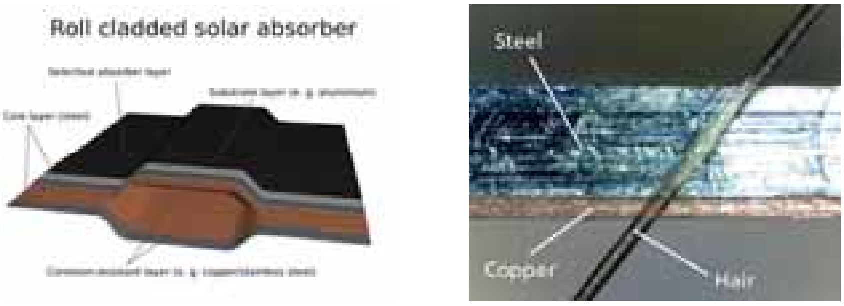

Fig. 2: Scheme of a possible multi-layer configuration of a partially roll cladded, hydroformed solar absorber (left) and microscopic picture of a roll-cladded steel-copper sample (right)

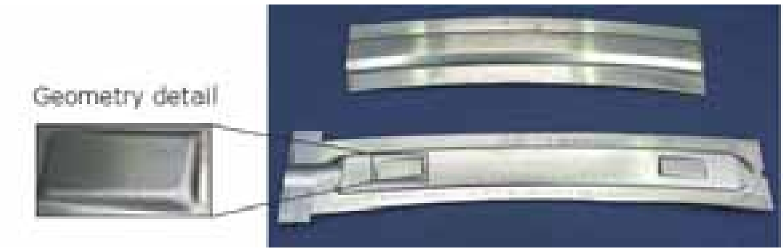

Fig. 3: Sample of a non-solar roll cladded, hydroformed technical component [2]

3. Fluid flow investigations

The geometry of FracTherm® bifurcations is very different from classical Y- or T-shaped tube bifurcations. While for the latter ones ζ values for analytical pressure drop calculations can be found in the literature (e. g. [3]), there are no ζ values available for FracTherm® bifurcations. Therefore CFD simulations were carried out at Fraunhofer ISE in order to both understand the basic influences on the pressure drop as well as volume flow distribution and determine ζ values in FracTherm® hydraulic networks for analytical calculations [4]. In order to simplify the discretization effort for the CFD simulations, the cross-sections of the roll-bond channels were idealized as being rectangular. It could be shown that the resulting error is to be expected in the range of 3-6 %. The width of FracTherm® channels is usually reduced from iteration to iteration, which leads to a change in cross-sectional area and thus in flow speed. Assuming rectangular cross sections with constant channel height h it can be shown that the relation between the widths w_i and w_{i+1} of two consecutive channels would need to be $w_{i+1} = 0.5 \cdot (w_i - h)$ in order to reach the same REYNOLDS number in all channels. However, this would lead to extreme, unrealistic changes in width. With realistic widths the REYNOLDS numbers are high in the first iterations and decrease continuously in the following iterations (Fig. 4). It can be seen that in most cases the flow is laminar, even in the first iterations. Many of the CFD calculations were carried out for different REYNOLDS numbers: Re=300, Re=900 and Re=1500.

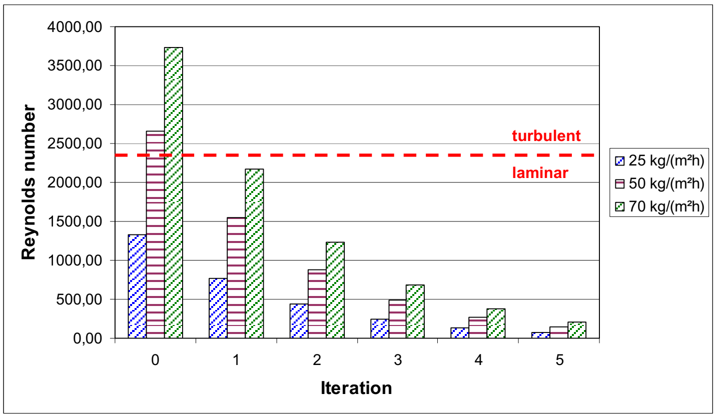

Fig. 4: REYNOLDS numbers in a FracTherm® absorber (2 m²) at different mass flow rates

The most important flow phenomena which could be observed are secondary flows (DEAN vortices) occurring in curved channels as well as flow separation. Regarding the streamlines in the asymmetric bifurcation in Fig. 5 (left) it can be seen that part of the fluid (center, high speed) tends to keep its direction and flows into the right branch, whereas another part of the fluid (bottom and top, low speed) moves to the left and thus enters the left branch. This is due to the curvature of the channel in front of the bifurcation. Therefore the existence of DEAN vortices in some cases might lead to a more uniform flow distribution in the following bifurcation. These secondary flows can also occur in symmetric bifurcations due to the s-shaped curvature of the flow path. The resulting vortex pairs – in this case after the bifurcation – can be seen in the right picture in Fig. 5.

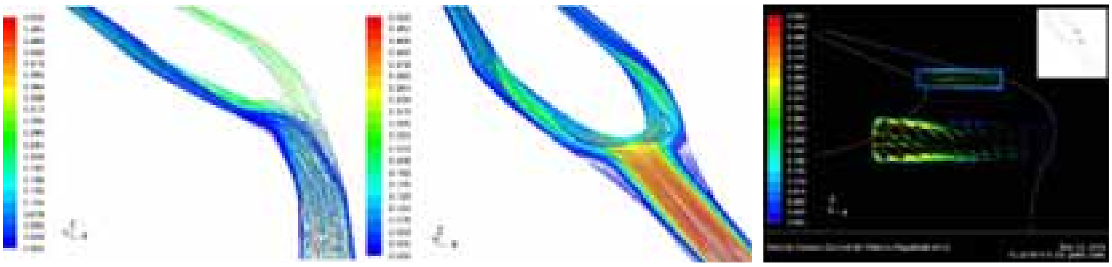

Fig. 5: Streamlines of different bifurcations (left), Dean vortices after bifurcation (right)

Flow separation is also a phenomenon appearing in the bifurcation region. Its intensity increases with the Reynolds number. Fig. 6 (left) shows flow separation on both sides of a symmetrical bifurcation. Since flow separation can lead to a higher pressure drop, it was tried exemplarily to reduce its intensity by adjusting the geometry to the velocity distribution calculated by the CFD simulations (Fig. 6, right). However, no pressure drop reduction could be detected in this trimmed bifurcation.

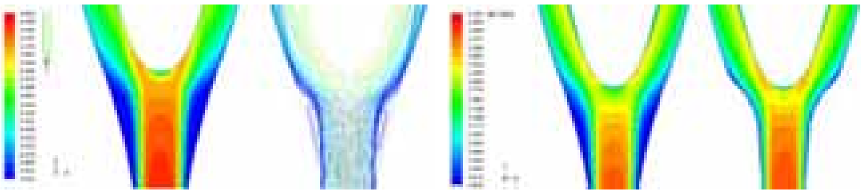

Fig. 6: Velocity magnitude and streamlines of a symmetrical bifurcation (left), bifurcation before and after trimming (right)

In real FracTherm® structures bifurcations follow each other often with very short distances. Therefore it can be expected that the flow profile entering the bifurcation area is not symmetric. In order to investigate this effect, three inlet profiles – "left-distorted", symmetric and "right-distorted" (Fig. 7, left) – were generated from output profiles of curved channels. Afterwards CFD simulations were carried out using these different inlet profiles (Fig. 7, right). Depending on the geometry the effect can be positive or negative with respect to the aim of an equal mass flow distribution. A general conclusion on this matter is difficult, but it can be stated that e. g. a left-distorted profile (resulting from a former right curvature) can improve the uniformity of the mass flow distribution in a bifurcation with a left curvature. Therefore a sequel of opposite curvatures (left-right or right-left) might be beneficial. This assumption still has to be investigated.

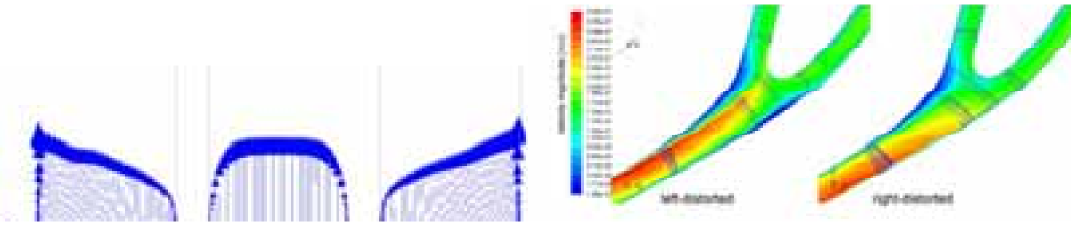

Fig. 7: Distorted inlet profiles (left), resulting flow profiles in midplane (right)

Some simulations were also used in order to determine ζ values for analytical pressure drop calculations. However, more work is needed in order to receive a comprehensive database covering a wide range of possible bifurcation geometries.

Apart from simulations of individual bifurcations some CFD simulations were also carried out with a model of a small, but complete solar absorber with an iteration depth of three (leading to eight channels in the third iteration). This absorber as well as the nomenclature of its branches can be seen in Fig. 8. Carrying out simulations with this absorber it was possible to calculate the total pressure along each possible path in the absorber. Fig. 9 shows the results: it is very remarkable that no sudden pressure drop can be observed in the bifurcation regions (dashed vertical lines) as would be expected in conventional T- or Y-pieces. This can be seen as an indication that FracTherm® channel structures indeed can lead to lower pressure drops.

Fig. 8: Part of small absorber (left), nomenclature of branches (right)

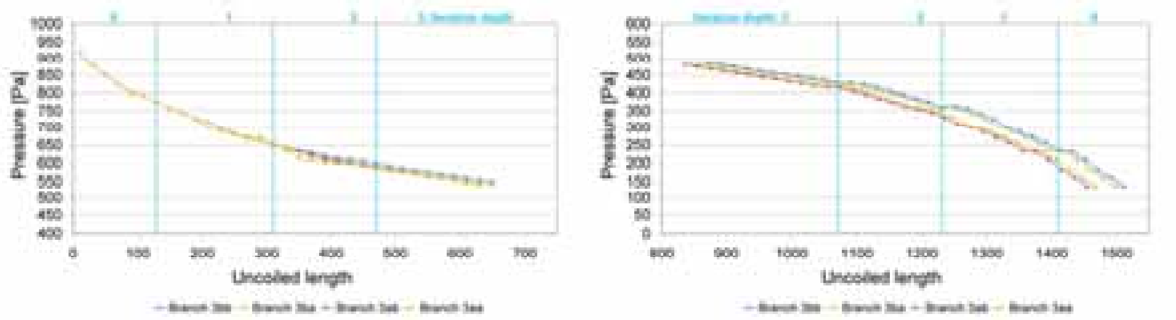

Fig. 9: Total pressure in small absorber; left: diverging bifurcations, right: converging bifurcations

4. Fluid dynamics test facility

One problem with CFD simulations apart from numerical errors is the correct definition of all boundary conditions such as exact geometry, fluid data, surface roughness and others. Therefore it is necessary to be able to validate the calculated data. This is to be done with a fluid dynamics test facility which is being developed at Fraunhofer ISE [5]. The aim of this test facility is to be able to both measure and visualize flow phenomena – especially of FracTherm® bifurcations – in real absorbers as well as in scaled models. Apart from pressure drop and volume flow measurements it is intended to install visualization technologies such as thermography, ink or tracer particle injection and hydrogen bubbles method (for scaled, transparent models). The test facility is still under construction, but almost finished. As soon as it is fully in operation, it will be possible to observe real flow phenomena which so far had only been investigated using simulations.

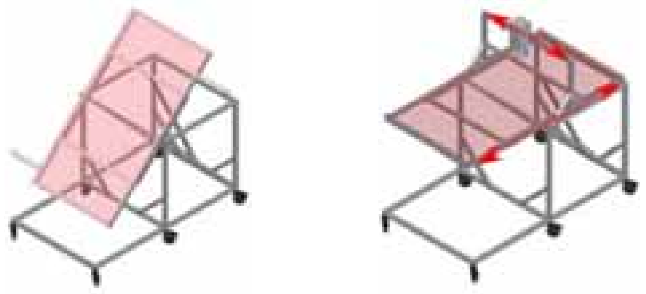

Fig. 10: Rack of fluid dynamics test facility: tiltable table (left), movable camera (right)

5. Pressure drop measurements

The pressure drop of a FracTherm® absorber with dimensions of 1060 mm x 1820 mm was measured for different volume flow rates. Fig. 11 shows the result in comparison with the curve of another roll-bond absorber with similar dimensions designed by Treikauskas [6]. This absorber follows a different design concept and was hydraulically optimized. Since in this case both inlet and outlet are positioned at the top, whereas in the FracTherm® absorber the inlet is in the bottom left corner and the outlet in the top right corner, the additional pressure drop in the inlet channels leading from the top to the bottom of the absorber according to Treikauskas was estimated by analytical calculations and subtracted from the curve taken from [6]. It can be seen that the pressure drop curve of the FracTherm® absorber – which is not yet hydraulically optimized – is lower. However, after the pressure drop measurements it was detected that some of the channels in the first iterations had been deformed due to too high internal pressure (Fig. 12). Therefore more measurements without deformation will have to be carried out in order to be able to estimate the influence of these widened channels on the pressure drop.

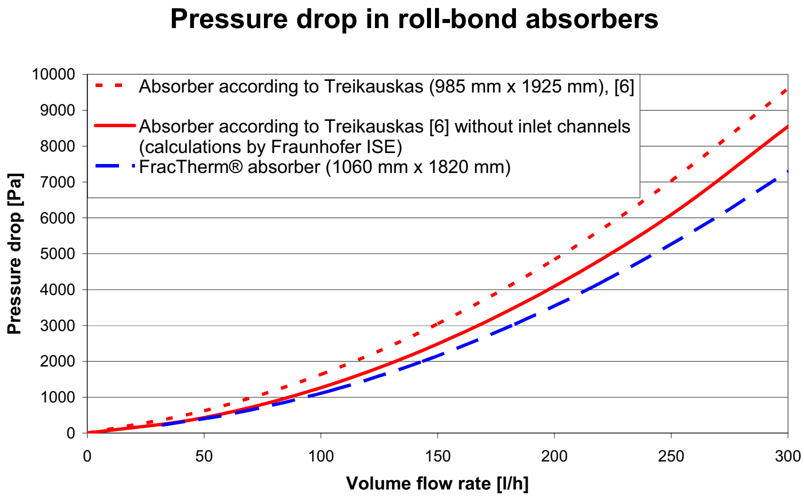

Fig. 11: Pressure drop curves of a not hydraulically optimized FracTherm® absorber in comparison with an optimized absorber of similar dimensions, but different design by Treikauskas [6]

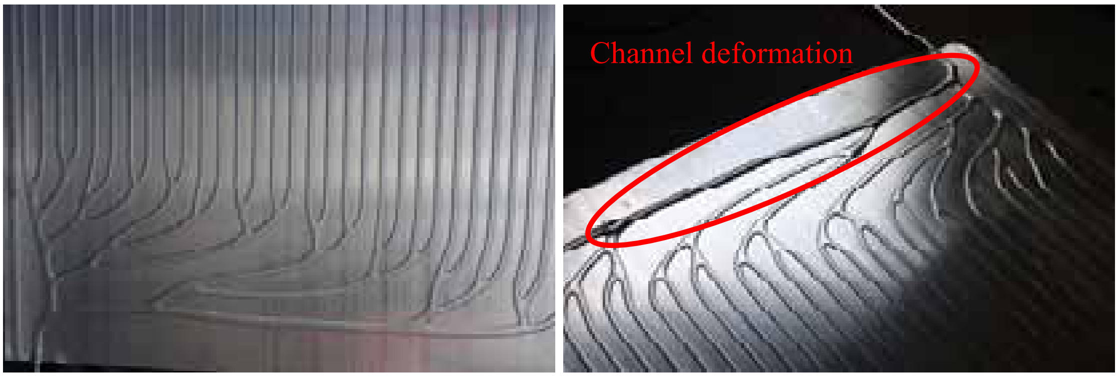

Fig. 12: Part of FracTherm® absorber before (left) and after (right) deformation due to too high pressure

6. Visualization of flow distribution using thermography

In order to investigate the flow distribution in FracTherm® absorbers, they were filled with cold water, and afterwards warm water was introduced. Fig. 13 shows the thermography sequence of the absorber with the deformed channels shown in Fig. 12, right. It is obvious that the fluid flow is not uniform, which can be seen very well in the first three pictures. The widened channels are located on top of the absorber, and this is where the fluid first reaches the outlet. The flow distribution in the absorber without deformed channels (Fig. 14) is much better, but still not perfect. A reason for this can be that the analytical calculations used for a hydraulic adjustment of the channels did not yet consider different ζ values, since a comprehensive ζ value database for a variety of geometries is not yet available. The lower temperature in the upper right part of the absorber in Fig. 14 was caused by a cooling effect due to a fan located near the absorber.

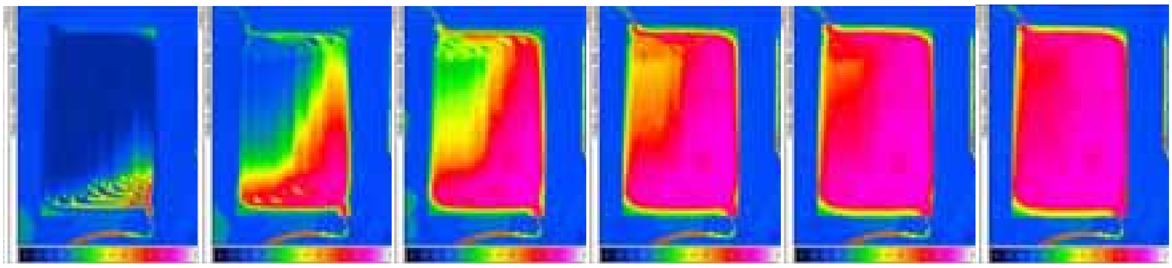

Fig. 13: Thermography sequence of absorber with deformed channels

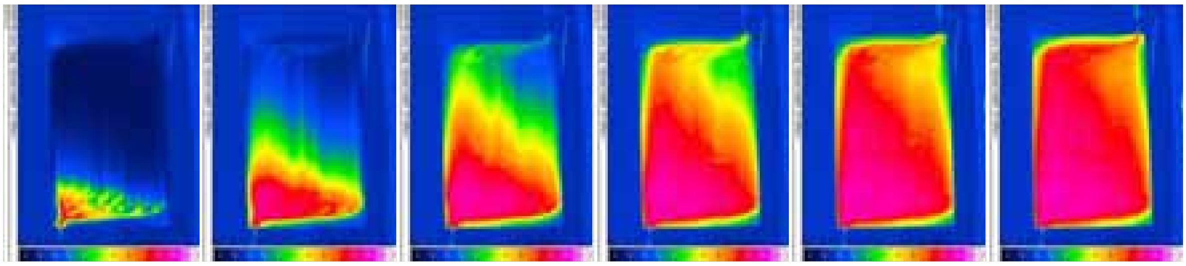

Fig. 14: Thermography sequence of absorber without deformed channels

7. Conclusion and outlook

Various CFD simulations of FracTherm® bifurcations were carried out in order to learn more about basic flow phenomena occurring in these very special geometries and to determine exemplary ζ values for analytical hydraulic calculations. Simulations of a small absorber did not show sudden pressure drops in bifurcation areas as would have been expected for conventional T- or Y-pieces. A fluid dynamics test facility will allow for validating CFD simulations soon. The pressure drop of a large absorber turned out to be lower than in another, optimized roll-bond absorber. However, the influence of some channels deformed due to too high internal pressure could not yet be estimated. The fluid flow distribution of the absorber with deformed channels was much less uniform than that of the absorber without deformed channels. The possibilities of the production method investigated in the steel absorber project will increase the flexibility in design, since larger deformation of the channels is possible an they therefore do not have to be designed flat. This will lead to new challenges especially with respect to three-dimensional bifurcation designs. It is expected that future work comprising CFD simulations, measurements and visualizations as well as analytical calculations will make an optimization of FracTherm® channel structures possible and thus make them attractive as alternative hydraulic designs not only for solar absorbers but for a variety of possible applications.

8. Acknowledgement

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References

[1] Hermann, M., (2005). Bionische Ansaetze zur Entwicklung energieeffzienter Fluidsysteme fuer den Waermetransport, Universitaet Karlsruhe (TH), Doctoral thesis

[2] Kleiner, M. et. al. (2007). Fertigung innovativer IHU-Stahlbauteile auf Basis neuartiger, partiell plattierter Blechhalbzeuge. Abschlussbericht zum FOSTA-Projekt P565, Verlag und Vertriebsgesellschaft mbH, Duesseldorf

[3] Idelchik, I. E., (1994). Handbook of hydraulic resistance. 3. CRC Press, Inc.

[4] Lunz, K., (2009). Stroemungsmechanische Untersuchungen an mehrfach verzweigten Kanalstrukturen am Beispiel eines FracTherm®-Solarabsorbers, University of Erlangen-Nuernberg, Diploma thesis

[5] Keyl, H.-M., (2009). Planung und Konzeption eines Teststandes zur Untersuchung von Stroemungsphaenomenen an Solarabsorbern, Hochschule Ulm, Diploma thesis

[6] Treikauskas F.-D. et al.: Aluminium-Rollbond – die neue/alte Loesung fuer den solar-thermischen Kollektor-Absorber. Tagungsband 19. Symposium „Thermische Solarenergie" OTTI 2009, S. 68-73