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Use of CFD modelling for transpired solar collectors and associated characterization of multi-scale airflow and heat transfer mechanisms

Sadjad Tajdaran[a]*, Fabrizio Bonatesta[a], Raymond Ogden[a], Christopher Kendrick[a]

[a] *Oxford Brookes University, Gipsy Lane, Oxford OX3 0BP, UK*

Abstract

Transpired Solar Collectors (TSCs) are façade-integrated solar air-heating systems which comprise perforated wall-mounted cladding or over-cladding panels. The thermal performance of TSCs can be modeled, however current approaches tend to rely on non-realistic assumptions and simplifications, casting doubts over the resulting accuracy. The aim of this research has been to provide a comprehensive numerical model for TSCs using Computational Fluid Dynamics (CFD) able to take full account of factors such as: solar radiation, wind direction, non-uniform flows (particularly around the perforated plate), and the various types of heat transfer that occur. Many of these are not easily modeled using conventional CFD based approaches used for smaller or more easily predictable technologies.

The model comprises a full size section of a typical TSC that can be easily morphed. A multi-block meshing approach was used to reduce grid size and to capture jet flows taking place in the plenum region through the perforations. When compared to experimental data over a wide range of climatic conditions, the modeled values of outlet temperatures at the absorber plate and plenum demonstrated a high level of accuracy, giving assurance regarding the validity of the approach. To the authors' best knowledge, the model represents the most comprehensive TSC simulation tool so far developed.

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Keywords: Transpired solar collectors; Computational Fluid Dynamics; Heat Transfer

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1. Introduction

Many developed and developing countries are adopting targets for carbon reduction. The UK for example intends to reduce carbon emissions by 80% in comparison to 1990 levels by 2050 [1]. Buildings in the UK are responsible for 40% of energy use and 36% of greenhouse gas emissions; figures which are relatively typical of

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* Corresponding author. Tel.:+44-1865-484086.
E-mail address: stajdaran@brookes.ac.uk

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many EU, North American and other geographic areas.

Reducing dependence on conventional hydrocarbon heating technologies requires the development and optimisation of viable alternative systems which can replace or be used in conjunction with conventional building heating systems. Within the range of novel heat generation technologies, Transpired Solar Collectors (TSCs), originally developed for crop drying and industrial applications, have been shown to be an effective and sustainable method of preheating supply air to buildings [2].

TSCs are building cladding systems that can generate heat by collecting solar radiation. The system normally comprises a wall mounted perforated sheet that acts as an absorber plate for solar radiation. Solar radiation heats the absorber plate which then transfers heat to the air flowing in the proximity of its surface. The air is drawn through the perforations into a plenum behind the absorber plate, before being ducted into the building using low-consumption fans as part of the ventilation requirement (Fig. 1). A number of geometrical characteristics and climatic variables affect the efficiency of TSCs, hence knowledge of their influence is essential for system optimisation.

Experimental research carried out on small-scale physical TSC prototypes [3, 4] tend to be inherently non-realistic as real size and climatic variables are difficult and expensive to reproduce. Conversely, numerical approaches are cost-effective and more flexible [5, 6]. In particular, Computational Fluid Dynamics (CFD) modelling potentially offers a more realistic insight into the details of heat transfer and fluid flow for TSC systems.

In order to properly model TSCs using CFD, various factors need be taken into account including variable flow regimes and flow non-uniformities, jets through perforations, complex boundary layer development along the absorber plate, and the varied forms of heat transfer that occur. Models must also take into account variable atmospheric conditions at the external boundaries, and specific flow conditions at the interface between free stream air flow and solid surfaces. Fluid velocity plays a characteristic role in the interaction between free stream air flow and solid surface. Velocity is commonly assumed to be zero at the fluid-solid (plate) interface and this leads to the establishment of a boundary layer adjacent to the solid. Based on Schlichting's homogenous suction theory [7], when the flow is laminar and the Reynolds number is below 70,000, an asymptotic boundary layer establishes over the perforated flat plate after a specific starting length. The minimum suction velocity that maintains the stability of the asymptotic boundary layer is given as $V_s = 1.24 \times 10^{-4} U_\infty$.

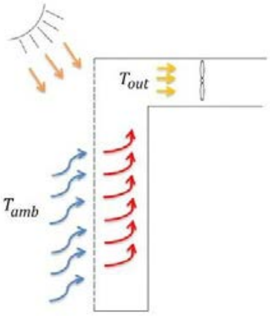

Fig. 1. Schematic diagram of the thermal field in TSCs.

Kutcher [4] developed an empirical correlation for flat TSCs heat loss by applying Schlichtings's theory. The asymptotic boundary layer is reached when there is no energy and momentum transfer into the boundary layer [4, 8]. The theory and the underlying assumption may not be representative of real applications where suction through the perforations is non homogenous and where the approaching flow is not laminar and uniform [6]. Because of the homogenous flow assumption, which causes a repeating flow behaviour after the starting length, some experimental studies did not identify the necessity to extend the size of the system investigated (less than 0.5 m^2 in size) to larger more realistic systems as being used in buildings [9, 10]. These important physical constraints can be overcome using 3D numerical modelling and the availability of appropriate computing resources.

Wind speed (U_∞) and suction velocity (V_s) have been considered as crucial variables that characterise the fluid flow and heat transfer in TSCs [11, 12]. It has been noted that if the suction velocity is relatively large, the boundary layer doesn't grow to turbulent flow and the thickness of the boundary layer remains constant. Depending on the suction rate, surface porosity and upstream flow type, the asymptotic region can be either laminar or turbulent [13]. Moffat and Kays [14] highlighted that a turbulent boundary layer travels to asymptotic laminar boundary layer for a homogenous suction ratio $V_s/U_\infty > 0.004$.

Numerical approaches to model full-scale TSC systems are challenging because of the demanding computational requirements. As a consequence, a range of simplifications concerning the underlying physics, system sizes and geometries and boundary conditions, are routinely adopted. For example, some models are based on periodic behaviour of flow over the absorber plate [15, 16, 17, and 4] and include either just one perforation for flat plates or one corrugation for profiled plates. Li et al. [6, 18] investigated flow structure and convective heat transfer for a full scale experimental apparatus modelled in 3D using CFD tools. A full-size section of the experimental device was used as computational domain and the results were validated with the measurements. However, radiation was excluded from the simulation and the approaching flow was set to be parallel to the absorber plate.

This research investigates a section of a full-scale TSC, taking account of wind direction and a solar model which simulates solar radiation on the external side of the absorber plate. The study is based on the geometry of a system installed on the south-faced façade of an unoccupied residential tower at the Wheatley Campus, Oxford Brookes University (latitude 51.75°, longitude -1.13°). The paper discusses the initial phase of a research project aimed at developing a comprehensive CFD model which will enable accurate understanding of the underlying thermal and dynamic mechanisms.

2. Methodology

A high resolution computational domain has been created to reproduce the physical TSC system, so as to capture the multi-scale fluid flow behaviour which establishes over the perforated plate and within the perforations, and the jet flows that emerge from them. The existence of very small circular perforations ($D = 1.5 \times 10^{-3}\ m$) over a relatively large surface area ($2.73\ m \times 1.74\ m$) of the flat absorber plate leads to a multi-scale geometry. Affordable computational costs were achieved by considering a representative section of the full geometry featuring fewer perforations. Experimental data from previous work were used for model validation as well as boundary and initial conditions for the simulations [19].

Steady state, three-dimensional, conservation equations of mass, momentum and energy have been solved within the commercial CFD software STAR-CCM+. The Reynolds-Averaged Navier-Stokes (RANS) Realizable $k - \varepsilon$ turbulence closure model has been utilised for the solution. The interaction between boundary layer and solid surfaces has been captured via the 'Two-Layer All y+ Wall Treatment' [20]. All heat transfer modes were taken into account, with solar radiation modelled through the 'Solar loads' model which utilises specified time, date and sun direction (Azimuth and Altitude). Actual solar radiation intensity data was also available from measurements [19].

A 'Conformal Trimmer' meshing model has been utilised to produce a refined, fully connected, adaptive, hexahedral grid [20], with typical cell size of $0.2\ mm$ around the perforations, and of $10\ mm$ away from the absorber plate (Fig. 2). The total number of computational cells was 11M. The simulations have been performed on a High Performance Computing Cluster available at Oxford Brookes University.

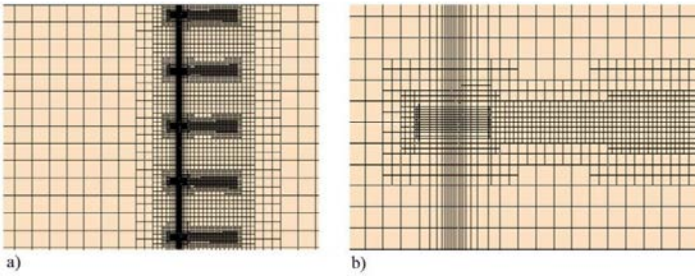

Fig. 2. a) Hexahedral Mesh created around the plate and in the free-stream region; b) Details of the conical grid scheme to capture the jet flow.

CFD model configuration, geometry and boundary details are given in Fig. 3. Based on the prototype cassette-panel TSC, the model comprises circular perforations with 20 mm pitch distance and square layout. The suction velocity (V_s) varied from 3 to 4 m/s with typical suction ratios (V_s/U_∞), adopted from the measurements, highly over 0.004 m/s. This suggests that asymptotic boundary layer is expected to develop over the perforated plate in the stream-wise direction. Extended surfaces both sides of the perforated plate have been created to ensure the boundary layer growth over the perforated plate in the horizontal direction. The frontal boundary parallel to the absorber plate has been taken to be far enough not to affect layer growth and to enable the simulation of a free stream around the system. The absorber panel has been modelled in its full size in the vertical direction. The plenum is also modelled in its full size, enabling a realistic representation of the bulk flow establishing inside. For brevity, the details of the boundary conditions, which were consistent with the typical wind direction data, are given in Fig. 3.

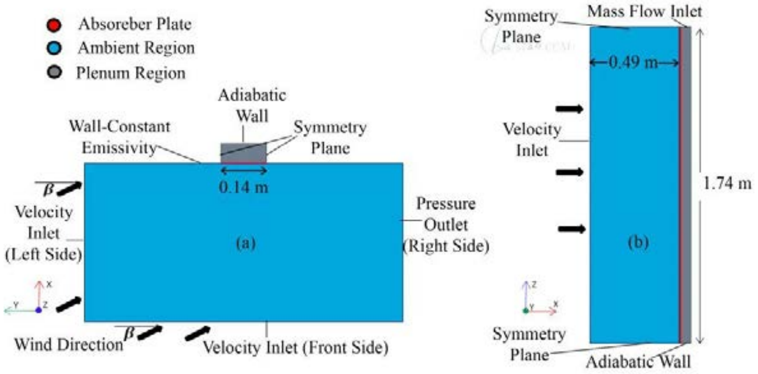

Fig. 3. Computational domain and boundary conditions details; a) Top view, b) Side view.

3. Results and discussion

The present section summarises essential CFD results, including validation against available measurements and thermal performance results as a function of wind direction for two cases featuring different suction ratio.

The test conditions used for validation are summarised in Table 1. The temperature of the absorber plate (T_s) is believed to reflect the effects of the variables that change both in the plenum and the in the ambient region. Hence, the plate temperature was chosen as a validation criterion to assess the reliability of the model. The other validation criterion was plenum outlet temperature(T_{out}), as this is the temperature of the air ducted into the building.

Table 1. Details of the cases used for validation.

Case Number	Ambient Air Temperature (°C)	Wind Speed (m/s)	Wind Direction (°) β	Suction ratio V_s/U_∞	Vertical Solar Radiation (w/m^2)
1	4.33	2.77	24.67	0.01	425.09
2	5.13	2.83	37.67	1.25	585.99
3	6.27	5.60	12.33	0.61	646.90
4	7.33	2.80	12.33	0.01	277.80
5	8.40	4.97	-1.33	0.00	570.08
6	9.27	6.90	4.67	0.00	101.04
7	10.57	3.63	14.33	0.01	621.92
8	11.53	3.60	-0.33	0.01	735.64
9	12.07	2.93	16.00	0.01	388.86
10	12.10	3.23	1.33	1.47	546.72

Fig. 4 shows modelled data against experimental validation criteria. All temperature data were predicted with 15% accuracy, with 90% of the cases showing accuracy in excess of 10%. A literature survey shows that due to model complexity and computing restrictions, parameters such as wind direction, solar load and radiative heat transfer have not routinely been taken into account in numerical investigations. The initial validation results presented here, however, show that sophisticated CFD models are able to return realistic predictions of the quantities which are essential for the assessment and optimisation of TSC systems.

The influence of wind direction on thermal performance of TSCs has not been considered so far in relevant literature. Nonetheless, this is essential because wind direction can change the air flow in the vicinity of the perforated plate, causing variability in the heat gain of the system and consequent temperature rise.

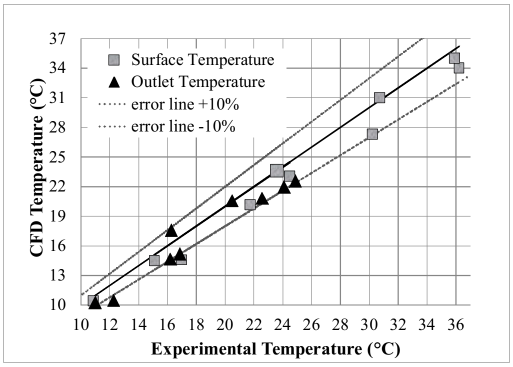

Fig. 4. Comparison between the CFD results and the experimental data for absorber surface and plenum outlet temperature.

Temperature rise refers to the difference between the outlet temperature and the ambient temperature (T_{amb}). It implies the ability of the system to raise the ambient temperature to a higher, more practical level. Simulations have been performed to illustrate these effects and a summary of the conditions investigated is given in Table 2.

Table 2. Details of the case studied for Wind direction effect

Case No.	Amb. Temp (°C)	Wind speed (m/s)	Wind Direction (°)	Suction ratio	Solar Radiation (w/m2)
1	10	3	0 10 30 50	0.011	600
2	10	3	0 10 30 50	0.00625	600

Figure 5 shows temperature rise and absorber surface temperature as a function of wind direction, for two cases featuring different suction ratio. Both cases show similar trends for surface temperature and temperature rise. Surface temperature decreases of about 0.25 degree Celsius per 10 degree variation in wind direction, indicating that an angle between free stream flow and parallel boundary layer would increase the level of turbulence around the plate, leading to a reduction in the absorber surface temperature.

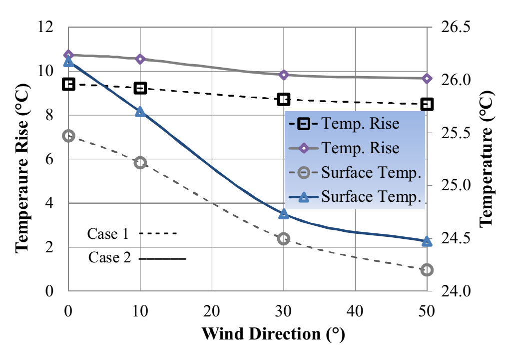

Fig. 5. Impact of wind direction on temperature rise and absorber surface temperature.

Consistently, due to higher turbulence and lower temperature of the air passing through the perforations, the TSC experiences a decrease in ‘Temperature Rise’. On average, the temperature rise decreases of about 1.6 degree Celsius per 10 degree increase in wind direction; the variation is nevertheless steeper between 0 and 30 degree wind direction indicating a greater sensitivity in that region.

A comparison between case 1 and 2 shows that lower suction ratio results both in higher temperature rise and higher surface temperature; this is in agreement with relevant literature [11, 12]. Higher the suction ratio implies higher air flow velocity in the vicinity of the perforations, leading to lower temperature of absorber surface.

4. Conclusion

A high-resolution, 3-dimensional, steady, RANS CFD approach has been developed to model TSC systems. Multi-block meshing has been utilised to capture the multi-scale air flow behaviour which establishes in the various regions of the physical system. The following can be concluded from the investigations carried out thus far:

- The validation results for the CFD simulations indicate the model is able to return realistic values of absorber surface and plenum outlet temperatures.
- The model is comprehensive in nature, and can flexibly account for variables which are essential for system performance evaluation and system optimisation. These include wind direction, non-uniform suction through the perforations, and solar load.
- The investigation of the influence of wind direction shows that greater wind angle leads to lower levels of surface temperature and temperature rise. Surface temperature decreases of 0.25 degree Celsius per 10 degree variation in wind direction; on average, temperature rise decreases of 1.6 degree Celsius over a similar interval.
- Consistently with relevant literature, lower suction ratio leads to higher absorber temperature and higher temperature rise.

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