Heat Loss from Cavity Receiver for Solar Micro-Concentrating Collector

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ABSTRACT

In the past decade there has been a significant increase in the use of linear concentrating Fresnel collectors for large scale steam production. This paper describes a micro-concentrating Fresnel collector for use on building rooftops. The modules of this collector system are approximately 3 meters long by 1 meter wide and 0.3 meters high. Applications include domestic hot water, industrial process heat, and solar air conditioning. The absorber is contained in a sealed glass envelop to minimise convective losses. The main heat losses are due to natural convection inside the enclosure and radiation heat transfer from the absorber tube.

In this paper, a two-dimensional computational fluid dynamics model for combined natural convection and surface radiation is developed for the micro-concentrator cavity receiver. The influence of operating temperature, emissivity of the surface, orientation and the geometry on the total heat loss from the receiver is investigated. The objective of the investigation is to optimize the design to maximise the overall thermal efficiency of a prototype micro-concentrating collector.

Keywords - Cavity receiver, Computational fluid dynamics (CFD), Linear fresnel micro-concentrating collector, Natural convection, Solar energy.

INTRODUCTION

Linear concentrating solar thermal technologies offer a promising method for large scale solar energy collection. In these technologies, the ratio of thermal energy loss to total solar radiation on the receiver decreases significantly; hence the collector has higher efficiency at high temperatures than non concentrating collectors, and can be used for solar thermal power generation or solar cooling (Zhai *et al*. 2010). Linear Fresnel solar concentrator can also be used for medium temperature (80^{o}C-250^{o}C) applications (Singh *et al.* 2010).

Many researchers have investigated concentrating solar collector systems of different sizes and application types. These systems are able to achieve high outlet temperature at low cost. It is possible to use them in thermal-power plants, hot water production for heating, and also solar air conditioning (Petrakis *et al*. 2009). Until now, the only commercially available high temperature solar thermal technologies, such as parabolic trough and linear Fresnel, have not integrated well on rooftops, as they have been complex, cumbersome, have high wind loads and are difficult to maintain.

In this research, a new low-cost micro-concentrator (MCT) has been studied, which is designed to operate at temperatures up to 220°C, and be seamlessly integrated into the architecture of buildings. The application of this system ranges from domestic hot water and industrial process heat to solar air conditioning for commercial, industrial and institutional buildings. Rooftop solar cooling technologies need to be very space efficient. Since lower temperatures can only drive single effect chillers, traditional flat panel collectors need more than twice the roof area to produce sufficient cooling for a low rise building. High temperature systems, such as parabolic trough collectors, require more space on the rooftop to avoid shading as they track the sun. In this regard the MCT is considered more efficient compared to both low temperature collectors and more complex high temperature systems. The MCT system module is approximately 3.2 meters long by 1.2 meters wide and 0.3 meters high (Figure 1).

Fig. 1: A solar micro-concentrator system (source: Chromasun Inc.)

This paper focuses on the MCT absorber and cavity arrangement, and presents the results of a computational investigation of the thermal performance of the cavity receiver. The absorber of a solar concentrating device plays an important role in the collection of solar energy. To achieve high efficiency in a concentrating solar collector, there should be minimum thermal losses from the absorber. Figure 2 shows a schematic of the cavity along with the internal modes of heat transfer. During operation, the absorber tube heats up due to the incident concentrated solar radiation, resulting in emission of long-wavelength radiation into the cavity. This radiation represents a heat loss from the absorber, and thus results in a decrease in collector thermal efficiency. In addition, the emitted radiation is absorbed by the cavity windows and bottom wall, which in turn heat up. This promotes buoyancy-driven flows within the cavity, resulting in convection losses and a further reduction in thermal efficiency. In some systems conduction of heat away from the absorber tube represents a third mode of heat loss (Reynolds *et al.* 2004).

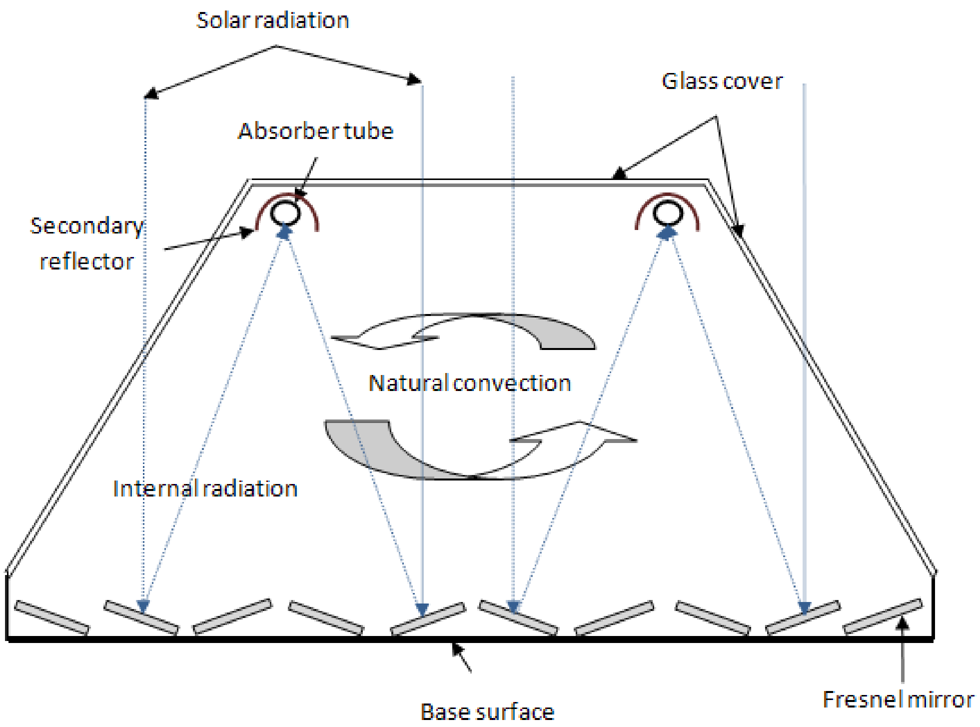

Fig. 2: Cross-section of the receiver cavity of micro-concentrating collector

Considerable research effort has gone into understanding the collection of solar radiation and heat loss paths from the absorber of a concentrating thermal receiver (Reynolds *et al*. 2004). Recently, Facao & Oliveira (2009) studied the overall heat loss coefficient of a trapezoidal cavity for a linear Fresnel receiver using computational fluid dynamics. They analysed two geometrical parameters: receiver depth and insulation thickness. Singh *et al.* (2010) studied the overall heat loss coefficient of a trapezoidal cavity absorber with a rectangular pipe and round pipe with ordinary black coating and selective surface coatings at different absorber temperatures (up to 175^{o}C) and developed correlations for the heat loss coefficient. Recently different groups have intensified their work on prototypes and industrial size line focussing Fresnel collectors. The Belgium Company Solarmundo attracted attention with their concept of a Fresnel collector, having built a 2500 m^2 prototype in Liege, Belgium (Haberle, A. *et al.* 2001, 2002 and 2006). Nevertheless until now, no work has been carried out on compact small scale Fresnel concentrating systems.

The current study investigates the role of radiation and natural convection heat transfer inside the cavity, along with heat transfer at the boundaries in order to fully understand the heat loss mechanisms.

COMPUTATIONAL MODEL

A computational model for the prototype absorber has been developed using ANSYS-CFX (ANSYS 12.1), a commercial computational fluid dynamics software package. For simplicity, a two dimensional geometry with a symmetry plane is created (Figure 3).

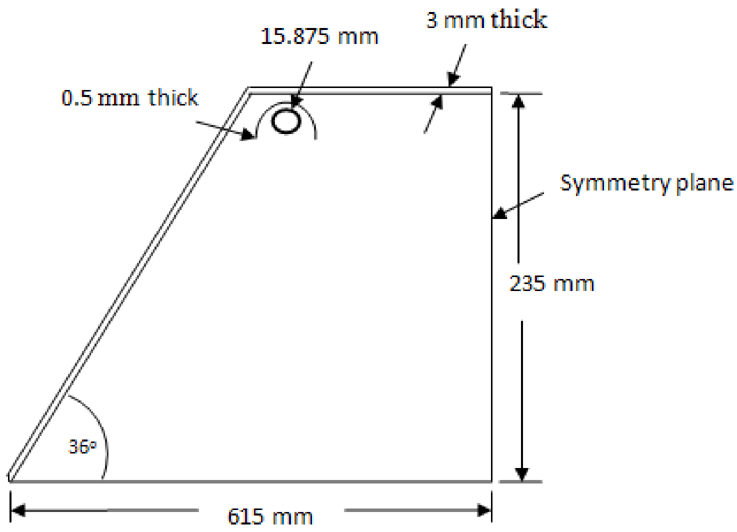

Fig. 3: Cavity geometry

Tab. 1: Boundary conditions for the computational model

Property	Unit	Boundary conditions	
		Absorber tube	Glass cover
Temperature	^{o}C	150 to 300	
Convection co-efficient	W/m^2K		10
Ambient temperature	^{o}C		20
Long wavelength emissivity		0.05	0.9

The absorber tube is modelled as an isothermal surface. The convective flow and resulting temperature distribution between the absorber tube and the secondary reflector and glass cover are studied for various absorber temperatures, from 150°C to 300°C. The absorber tube is coated with a selective surface and the long wavelength emissivity is taken as 0.05. The cover glass at the top and sides of the cavity are modelled as convection boundaries with external heat loss coefficients of 10 W/m^2K, exchanging heat with an ambient temperature of 20°C, with internal emissivity of 0.9. The base reflector surface is modelled as an adiabatic surface.

The air flow in the cavity is modelled as laminar as the Rayleigh number is in the range of 1.8×10^4 - 2.7×10^7. Radiation is modelled using the Monte Carlo simulation method (Wang *et al.* 2010). All discretization is carried out using second order schemes. Air properties are modelled as an ideal gas. Minimum convergence criteria were set at 10^{-3} for continuity and velocity, and 10^{-6} for energy. A hybrid mesh is used with structured quadrilateral elements forming the wall zones and unstructured triangular elements used in the central zones of the collector cavities. The resulting mesh size is approximately 2 mm, with 97788 mesh points in total. A grid dependency study has been undertaken to ensure the adequacy of this mesh density.

RESULTS AND DISCUSSION

The natural convection and surface radiation heat losses from the cavity receiver are determined for different absorber temperatures. The air flow patterns in the receiver cavity of the collector are shown in Figures 4 & 5. These figures demonstrated that radiation heat exchange plays an important role in the convection in the cavity receiver. The process of internal heat transfer is dominated by radiation effects. This is because the absorber temperature is much higher than that of the other surfaces in the cavity.

Locations where fluid motion is fastest are down along the glass side walls, then along the base surface. The next fastest fluid motion is a layer along the upper glass cover, with the fluid dropping down into the cavity from the glass at the symmetry plane. Heating of the base of the cavity by the long wave radiation from the absorber drives convection cells in the bottom with a rising plume up the symmetry plane. Although the bottom convective cells cover most of the cavity they do not significantly effect convection around the absorber. For the boundary conditions specified in Table 1; the results show significant thermal gradients in the cavity only around the absorber and secondary reflector. Fluid flow around the absorber tube is entrapped by the secondary reflector which minimises the convective heat loss from the absorber tube to the cavity (Figures 8 & 9).

Due to the mixing caused by the bottom convection cell there is a relatively constant temperature in the cavity below the level of the absorber tube and a higher temperature convection cell under the top glass surface as shown in Figures 12 & 13. In this study the secondary reflector around the absorber tube was considered to be a thin aluminium sheet. It may be possible to reduce the strength of the upper convection cell by using an insulated reflector.

Heat loss results are shown in Tables 2 & 3 for cases with and without radiation heat loss effects. The long wavelength emissivity of the absorber selective coating is taken as 0.05 (Chromasun Inc.). Due to the low emissivity of the selective coating the radiation heat loss is only 15% to 20% of the convective heat loss. The total heat loss at 220°C is approximately 50W per meter length of tube compared to an expected solar input of approximately 300W to 400W per meter length. At this stage of the project conduction heat loss through supporting structure for the absorber has not been included.

In order to validate the heat loss result it is necessary to perform a systematic comparison of CFD simulation results with experimental data. The geometries considered in the present study are relatively new and no experimental data is currently available for this or a similar geometry. Therefore, validation has not been carried out at the time of writing this paper however an extensive program of experimental measurement is planned.

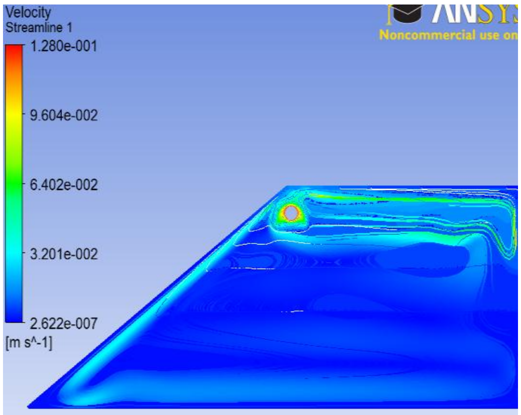

Fig. 4: Velocity streamlines in the cavity receiver (without radiation heat loss, absorber tube temperature 200°C)

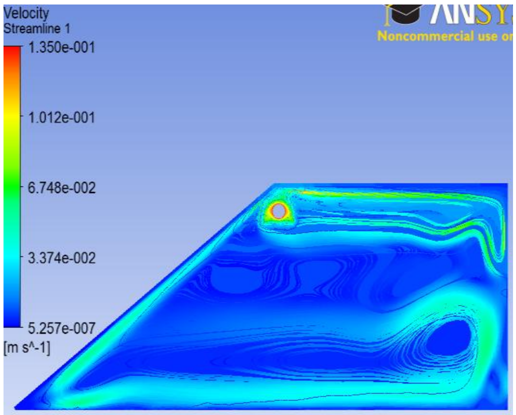

Fig. 5: Velocity streamlines in the cavity receiver (with radiation heat loss, absorber tube temperature 200°C)

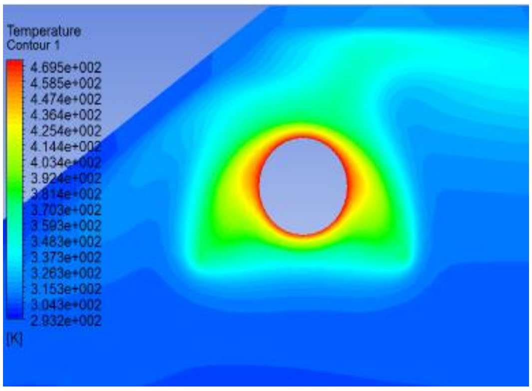

Fig. 6: Temperature contours in the cavity receiver (without radiation heat loss, absorber tube temperature 200°C)

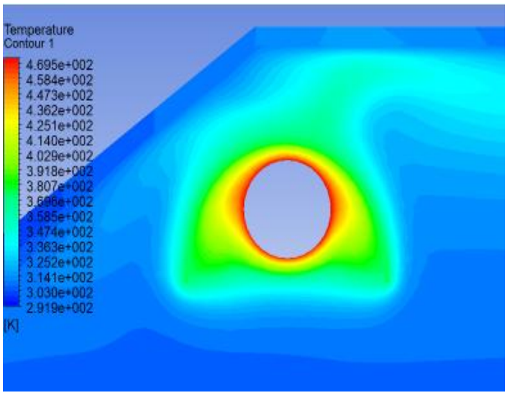

Fig. 7: Temperature contours in the cavity receiver (with radiation heat loss, absorber tube temperature 200°C)

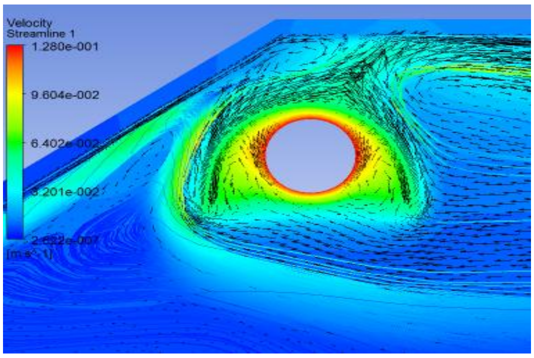

Fig. 8: Velocity magnitude contours and vectors in the cavity receiver (without radiation heat loss, absorber tube temperature 200°C)

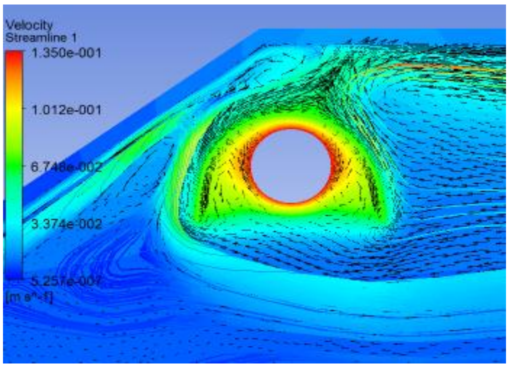

Fig. 9: Velocity magnitude contours and vectors in the cavity receiver (with radiation heat loss, absorber tube temperature 200°C)

Tab. 2: Heat loss flux results without radiation heat loss

Absorber temperature # °C	Heat loss flux (W/m^2) Absorber tube
150	516
200	827
220	953
240	1138
280	1429
300	1542

Tab. 3: Heat loss flux results with radiation heat loss

	Heat loss flux (W/m^2)	Radiative heat loss flux (W/m^2)	Convective heat loss flux (W/m^2)
Absorber temperature # °C	Absorber tube		
150	585	67	518
200	978	117	860
220	1109	144	965
240	1286	172	1114
280	1650	242	1408
300	1802	281	1526

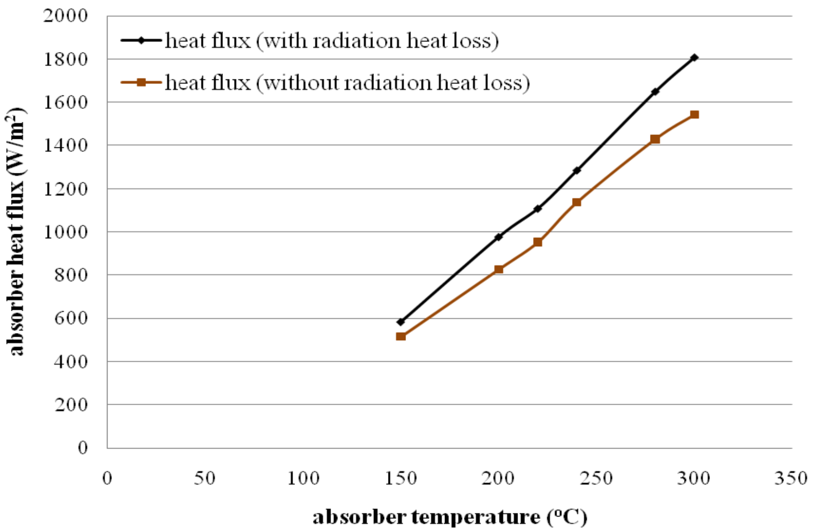

Fig. 10: Absorber heat flux (W/m^2) showing the effect of radiation heat loss

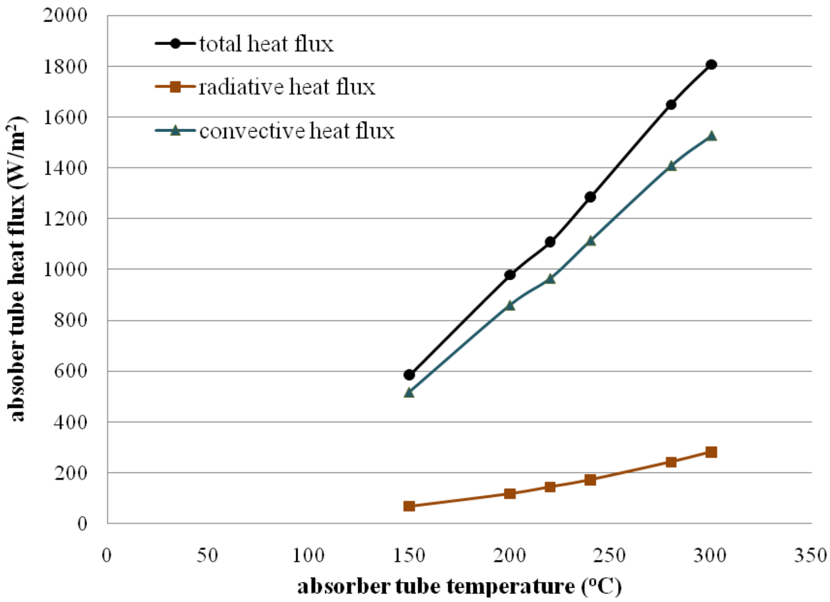

Fig. 11: Absorber heat flux per unit of absorber area (W/m^2) for different absorber temperatures

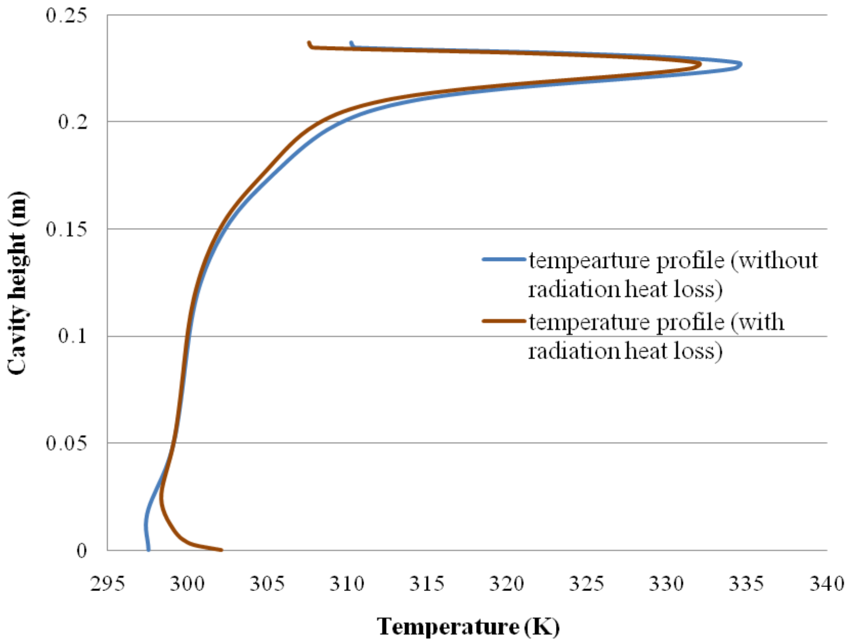

Fig. 12: Temperature profile within the cavity for absorber tube temperature of 200^{o}C (with and without radiation heat loss)

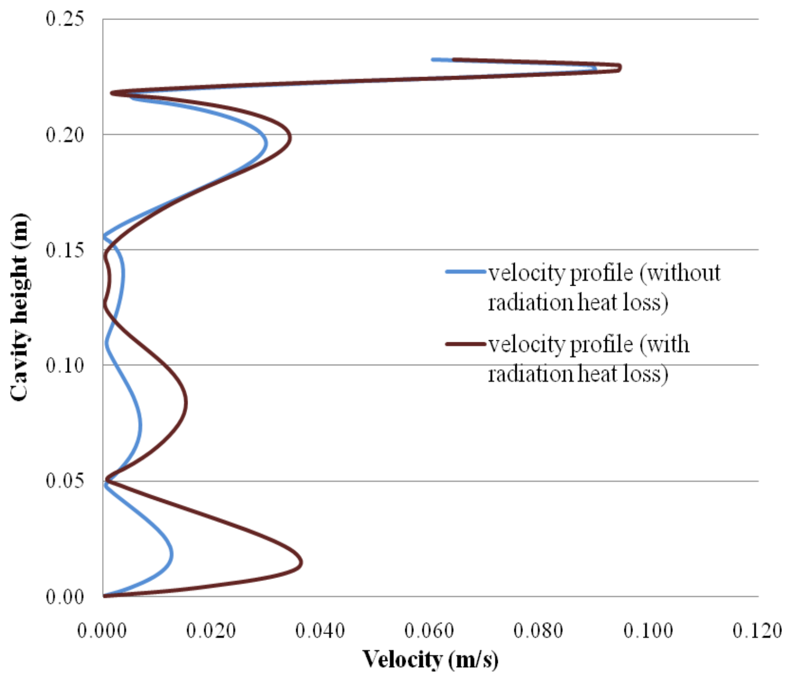

Fig. 13: Velocity profile within the cavity for absorber tube temperature of 200°C (with and without radiation heat loss)

CONCLUSION AND FUTURE WORK

Preliminary results have been obtained for the performance of a new cavity receiver concept for a linear Fresnel micro-concentrator collector. The performance was numerically simulated using computational fluid dynamics package, ANSYS-CFX. To analyse the thermal performance of the collector, a simple 2-D numerical analysis has been carried out with steady-state laminar model and heat loss results are obtained. In future, an experimental investigation of performance will be carried out to assess the validity of the CFD results.

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BIOGRAPHY OF PRESENTER

Ms Tanzeen Sultana, a PhD candidate in the School of Mechanical & Manufacturing Engineering at the University of New South Wales (UNSW), holds an Austrian Postgraduate Award (APA) and an Engineering Research Award (ERA). Currently she also holds an “Associate Lecturer” position in the School of Mechanical & Manufacturing Engineering, UNSW. Her research interest includes: solar thermal design and optimization, engineering heat transfer and renewable energy.