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Thermal Performance of a Solar Concentrating Photovoltaic Module with Spiral Mini Channel Heat Sink

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Abstract:

Concentrating Photovoltaic (CPV) power generation is one of the attractive choices for efficient utilization of solar energy due to its high cogeneration efficiency. The increase in temperature of solar CPV cell significantly reduces the performance. The efficiency of a CPV system can be improved by introducing effective thermal management or cooling system. In this paper, a new spiral mini channel heat sink with rectangular cross section is developed and its performance is numerically analysed using commercial CFD software ANSYS 14. The mini-channels provided high heat transfer over cell surface area and resulted in lower pressure drop. The coolant outlet temperature rise across the mini-channel is estimated as 343K in CPV module of 300 X 300 mm^2 and with a pressure drop of 8.043 k Pa at a flow rate of 0.16 liter/s. Based on numerical simulations, it is found that the optimum configuration of micro-channel with 4mm width and height of 20mm, having higher figure of merit.

Keywords: Solar Energy, Concentrating Photovoltaic, Spiral mini-channel, Numerical Analysis

Introduction

The methods for solar energy conversion mainly include solar hydrogen production, solar thermal power generation, and photovoltaic (PV) power generation. Since the PV power generation converts directly the solar radiation into electrical energy it has advantage over other techniques that its generating efficiency is not restrained by the Carnot cycle. In spite of its low conversion efficiency, the cost required for installation of large scale application using conventional PV cells is significantly higher. A relatively cheap concentrator to replace part of the solar cells could be used. The Concentrating photovoltaic (CPV) system uses highly efficient solar cells with low-cost concentration technology by which the incident light intensity unit area of the cell increases thereby reduce the cell area required for the given generated power. CPV offer several advantages over flat plate photovoltaic (PV) systems, including lower levelised cost of energy through the replacement of costly solar cells with inexpensive optics and tracking systems. Large ground-mounted utility-scale power generation systems use expensive, specialist solar cells placed under high concentration ratios of up to 1000X [1]. The incident photon from the sunlight reaches the PV cell should be converted into electric energy only. But if incident photon energy is more than the band gap of the semiconducting material, the extra energy not only cannot be converted into electric energy will accumulate as wasted heat severely affecting the photoelectric conversion efficiency. The CPV system provides both electricity and usable heat which can be recovered from an active cooling heat sink thus enhancing the total efficiency of the system with the same cell area. The photovoltaic cell efficiency decreases with increase in temperature and the non-uniform temperature across the cell in an array limits the efficiency of the whole string due to the current mismatch. The cells will also exhibit long-term degradation if the temperature exceeds a certain limit. Based on the concentrator type and geometry, the type of cooling method for photovoltaic cells differs for single-cell arrangements, linear concentrators, and densely packed cells Royneet. al. [2]. Since minimum thermal resistance is required for efficient operation of densely packed cells with high concentration ratio, active cooling is the only viable solution as the geometry of the cells limits the heat removal surface area. Various active cooling methods used in densely packed systems have been studied. Lasich [3] has patented cooling circuit where water flowing through small, parallel channels extracts up to 500kW/m^2 from densely packed solar cells under high concentration maintaining the cell temperature around 40°C for normal operating conditions. Vincenzi et al. [4] have used micro-machined silicon heat sinks in their photovoltaic receiver of 30x30 cm^2 operating at a concentration 120 suns and reported thermal resistance of 4x10^{-5}Km^2/W that is comparable to other micro-channel systems.

Conventional linear CPV systems are generally dense array demanding for quite significant cooling power, very rigid structural support and minimum tracking tolerance to provide the required focal performance. Since the large open primary concentrator mirror areas are exposed to rain, dust, and wind loading, there is always chance for optical errors, reducing the optical efficiency. Many dense array systems need to be manufactured to high tolerances in order to ensure flux uniformity on the receiver in the presence of distortion by gravitational loading, wind loading, and thermal expansion. Leo et. al. [5] developed a new CPV assembly design made of multi-junction photovoltaic cells capable of producing 1.5 kW$_e$ power and generates a maximum of 4.6 kW$_{th}$ of heat energy. This new design reduces significantly the need for perfect optics, accurate tracking, tracking power and maintenance in comparison to high concentration systems. Since the cells are semi densely packed to accommodate the secondary receiver like compound parabolic collector (CPC) the heat flux due to incident irradiation will be at equal discrete points. This allows more space for cooling reducing the flux level. Reddy et. Al. [6] presented the design and numerical analysis of a heat sink with array of micro-channels by combining the merits of both the high heat removal effectiveness of micro/mini-channels with low pressure drops in conventional straight channels and found that the optimum configuration of micro-channel with 0.5mm width and aspect ratio of 8. The reported temperature rise across the micro-channel is 10K with a pressure drop of 8.5 kPa along a single channel with six such channels in each modules at a flow rate of 0.105 liter/s.

In this paper a new spiral mini channel heat sink with rectangular cross section is developed and its performance is numerically investigated using commercial CFD software ANSYS 14. To maintain the efficient working of CPV system, the heat should be removed effectively, uniformly and continuously from the CPV cells. The effects of geometric parameters like heat sink channel height and width are analysed and results in terms of heat transfer coefficient, pressure drop and figure of merit are presented.

Design and Development of Spiral Heat Sink for CPV Cooling

The CPV system is developed as part of the Bio-CPV project [7] with the objective to generate 4 (no of CPV dish) x 2.5kW$_e$ (electricity generated per dish) to cater the daily electricity demand for the village. The CPV cells used is GaInP/GaAs/Ge cell, which has an efficiency of 37.2% and a maximum power of 18.6 W at 500x concentration [8]. If concentration ratio is increased the efficiency of the cell decreases slowly to 600X, then decreases drastically. The CPV module is mounted on the focus of parabolic dish reflector having overall geometric concentration ratio of 500X and an aperture area of $9m^2$. The primary concentrator has concentration ratio (CR) of 125 suns and 12 x 12 array of three-dimensional compound parabolic concentrators (CPCs) (L_{cell} = 10mm, L_{cpc}=20mm, h_{hom}=10mm, h_{cpc}=20mm) with optical homogenizer forms secondary concentrator with CR of 4 suns. The CPV module consists of a secondary reflector with homogenizer, CPV cell assembly mounted on active spiral mini channel heat sink. The overall dimension of the cooling module is 270 x 270mm integrated with cover and mounting arrangement will have dimensions of 300mm x 300mm as shown in Fig.1.

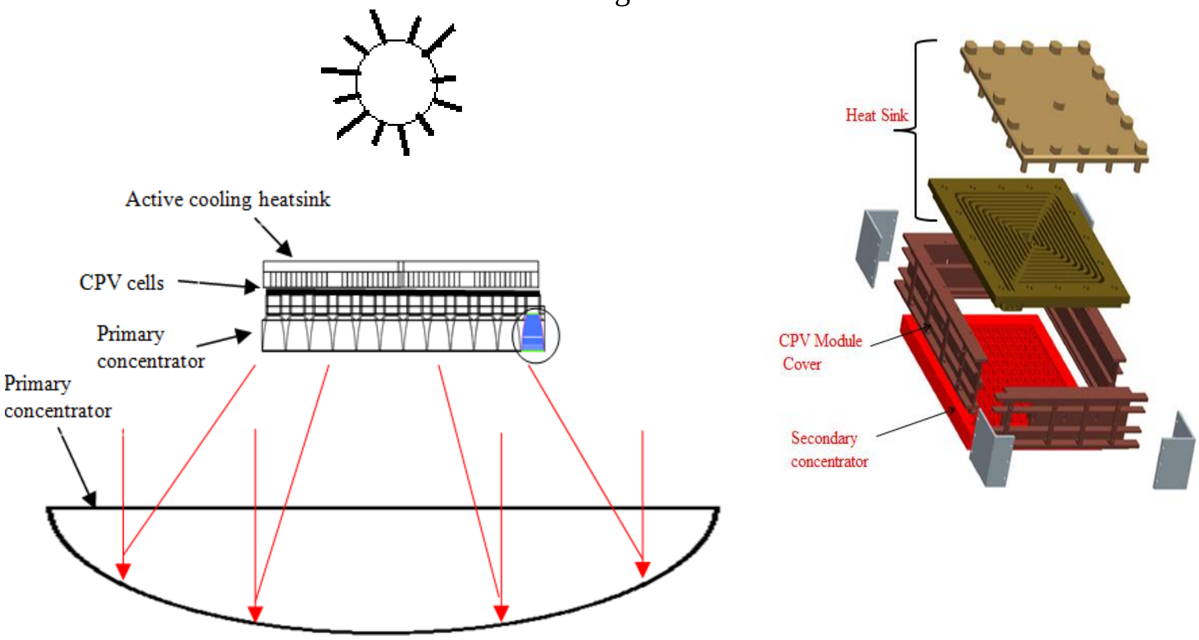

Fig. 1 Parabolic dish with spiral mini channel heat sink

Totally 144 solar cells are used in a 12x12 array mounted on IMS (Insulating Metal substrate) and the back side an active cooling heat sink made of aluminium with Spiral cooling mini channel with rectangular cross section is mounted. The solar cells should be maintained at safer temperatures by the mini-channel heat sink for efficient operation of the CPV module. The parallel micro-channel heat sink has been investigated to determine the optimal design under uniform power density applied over the CPV cells from the bottom of the heat sink. The cooling system consists of cooling block made of Aluminum with spiral flow mini channels with rectangular cross section where separate inflow and outflow paths with inlet and outlet ports were grooved. The base of the heat sink receives heat flux from the bottom surface and the heat is transferred directly to the coolant by convection from the base and indirectly through the dividing wall. The coolant enters the inlet port at ambient temperature and takes up the heat all the way through the flow path grooved in heat sink flowing clockwise towards the centre. The fluid flows anticlockwise through outflow channels located adjacent to the inflow channel. The base of the heat sink receives heat flux from the bottom surface and the heat flux is transferred directly to the coolant by convection from the base and indirectly through the dividing wall. The large surface area of micro channel enables the coolant to take away large amounts of heat per unit time per unit area while maintaining a considerably low device temperature. so, high heat fluxes can be dissipated at relatively low surface temperatures. Also it should guarantee a uniform cooling over the surface and to the required pumping power should be to a minimum. The solar radiation (550 W/m^2) is concentrated on secondary reflector (CPC) which in turn concentrates onto the bottom surface of the mini-channel spiral cooled receiver holding a dense array of efficient triple junction PV cells. The cells are able to convert ~30% of the incoming energy into electricity while collecting 50% in the form of heat.

Numerical Simulation

The numerical simulation has been carried out under steady, incompressible, turbulent flow in the micro-channels for different Widths (4, 5, 6 mm), height (10, 15, 20) and Reynolds number (20,000). The flow and heat transfer simulations are based on the simultaneous solution of governing conservation of mass, momentum and energy equations represented [9] as

Continuity equation

$$\frac{\partial m}{\partial t} = \sum_{in} \dot{m} - \sum_{out} \dot{m} \tag{1}$$

Momentum equation

$$\frac{\partial}{\partial t}\left(mV_n\right) = \sum F_n + \sum_{in} \dot{m}V_n - \sum_{out} \dot{m}V_n \tag{2}$$

Energy equation

$$\frac{\partial}{\partial t}\left(me\right) = \sum_{in} \dot{m}e - \sum_{out} \dot{m}e + \sum_{i} q_i - \sum_{j} w_j \tag{3}$$

The analysis was carried out using CFD software ANSYS Fluent 14. The numerical solution was considered to be converged when the residual became smaller than 1 x 10^{-4} for the continuity and momentum equations and the energy equation. The material properties used for simulations are listed in Table 2. Since the IMS substrate is thin (3mm) and made of three layer (Aluminum- Dielectric- Copper) of materials, the equivalent properties are calculated and used. The SIMPLE algorithm for velocity-pressure coupling and associated hydrodynamic and thermal boundary conditions are given below.

The cooling fluid velocity corresponding to the Reynolds number of 20,000 was imposed at the inlet for all cases, while a constant pressure was imposed at the outlet. No-slip boundary conditions were assumed at the walls. The k-epsilon turbulence model with standard wall function is used. For the thermal problem, the flux distribution on the receiver of the dish is simulated using ray tracing code ASAP assuming the reflectivity of dish and CPC to be 90% and 80% respectively. As shown in Fig. 2, a constant irradiation flux was assumed on the boundary corresponding to the solar cells. The average flux intensity over the cell will vary depending on the position of the cell in the array. A constant fluid temperature of 40°C was assumed for the incoming fluid, purely convective outflow was imposed at the outlet. All the remaining boundaries were insulated.

Table 1 properties used for mini channel heat sink simulations.

Parameters	**Values**	**Parameter**	**values**
Properties of heatsink (Aluminum)		Properties of IMS (substrate)	
Density	2719 kg/m^3	Density	723 kg/m^3
Specific heat $C_{p,S}$	871 J/kg K	Specific heat $C_{p,S}$	484 J/kg K
Thermal conductivity K_p	202.4 W/m K	Thermal conductivity K_w	249 W/m K

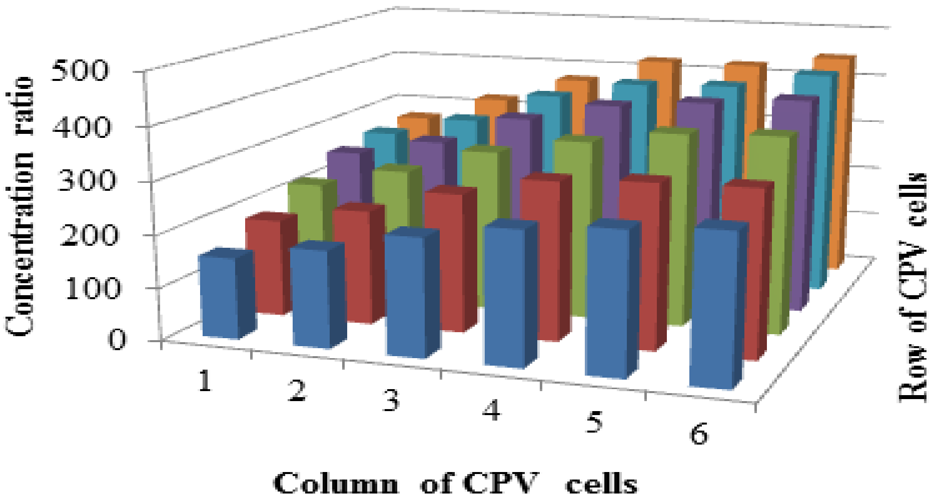

Fig. 2 Solar flux Boundary condition

The optimal design is determined by minimizing and comparing the following five parameters: Pressure drop between the inlet and outlet of the mini channel heat sink, Average temperature of the substrate calculated by equation (4), Temperature uniformity calculated by (5), cell (bottom surface of heat sink) surface temperature and figure of merit. The equation (6) and (7) are used to find the heat transferred from heat sink to fluid and the corresponding pumping power.

Average temperature of the IMS substrate defined as,

$$T_{avg} = \frac{\int_V T dv}{\int_v dv} \quad (4)$$

Temperature uniformity index U_T, defined as,

$$\frac{\int_V |T - T_{avg}| dv}{\int_v dv} \quad (5)$$

The total heat rate and figure of merit are defined as

$$\dot{Q}t_{otal} = \dot{m}C_p \left(T_{mean,L} - T_{mean,0}\right) \quad (6)$$

$$F_{merit} = \frac{\dot{Q}t_{otal}}{\Delta P} \quad (7)$$

Results and Discussion

The flow and heat transfer characteristics have been investigated in the spiral mini channel heat sink. The CPV coolant outlet temperature requirement should be in the range of 320 – 370K, to use it for hot water, single effect absorption and desalination purposes [10]. The coolant outlet temperature decreases with the increase in mass flow rate. To predict the performance the Reynolds number is maintained as 20,000 which correspond to mass flow rate of about 0.1 kg/s maintaining the outlet temperature within above said limits in in all cases. The effect of aspect ratio of mini channel heat sink on the surface temperature of cell (T_s), average temperature (T_{avg}) and temperature uniformity index (U_T) of the cell surface for W=6mm were given in Fig. 3 a. Since T_s , T_{avg} and Temperature uniformity index U_T of bottom surface increases with decrease in the aspect ratio, for minimum ΔT and lower T_{avg} for cell surface aspect ratio should be reduced which results in better performance.

The difference between Average temperature of the substrate and cell surface temperature is almost same for the channel with AR 0.6 and 0.3, less than 1 for channel with AR 0.3. Since the CPV cell size is 5x5 mm^2 a channel of width more than 5mm will directly dissipate the heat from the cell before heat spreading. On the other hand the cooling channel having width of 4 mm will dissipate the heat after spreading through the IMS substrate, which is evidenced by the surface and average temperature difference in Fig. 3 b. Also the slope of the Temperature non-uniformity in both cases varies by 0.01. Due to effective heat dissipation form the cell, the predicted maximum temperature for 6mm and 4mm width channel heat sinks are 323K and 343K respectively.

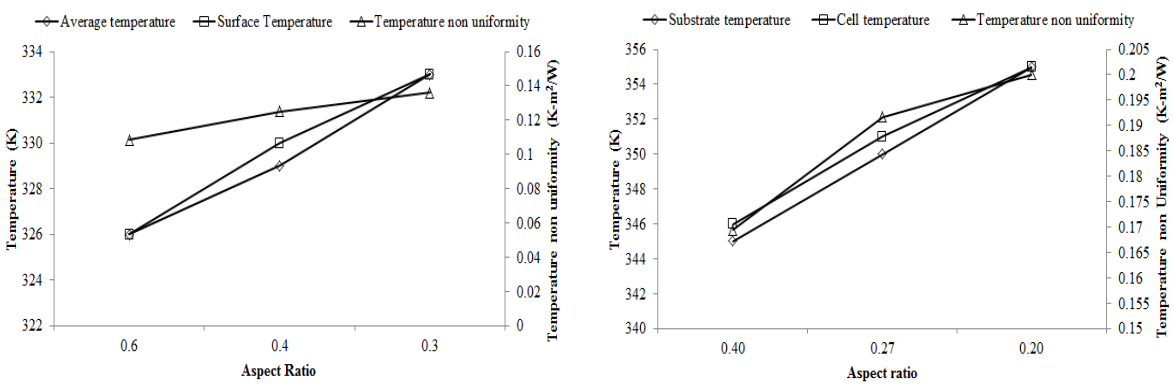

Fig. 3 Effect of Aspect ratio of mini channel on T_s, T_{avg} and U_T for a) W=6mm, H=10mm and b) W=4mm, H=10mm

In order to improve the temperature uniformity, the flow pattern in the module should ideally in the form of a spiral. The variation of surface temperature (T_s), average temperature (T_{avg}) and temperature uniformity index (U_T) of the bottom surface with respect to width of the channel is shown in Fig. 4 a. The T_s, T_{avg} and U_T decreases sharply with increase in the channel width. The T_s for 10mm channel is 345K lower than 350K, 355K for channel with 15 and 20mm height respectively. But if the channel width is increased from 4mm to 6mm, both T_{avg} and T_s will be almost equal (333K) to the channel with 3mm width and 10mm height with more temperature uniformity (0.13 instead of 0.169) and less pressure drop of 6.4 kPa.

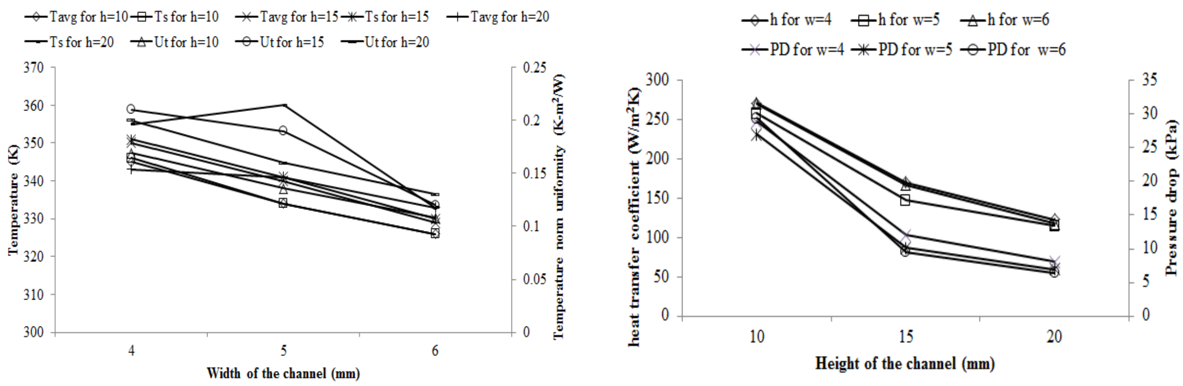

Fig. 4 a) Effect of Channel width of mini channel on T_s, T_{avg} and U_T and b) Effect of channel height of mini channel on heat transfer coefficient and pressure drop

The change in convective heat transfer coefficient and pressure drop (ΔP) with respect to Reynolds number is shown in Fig. 4 b. The maximum predicted heat transfer coefficient is 271 W/m^2K, for channel width of 4mm and height of 10mm. It drastically reduces from 271 W/m^2K to 123 W/m^2K with increases in height from 10 mm to 20mm. Similar trend is found for the other channel widths. The increase is due to decrease in fluid velocity for increased height and width. The pressure drop (ΔP) reduces with increase in channel height. The maximum pressure drop is 2.88 kPa for channel width of 4mm and height of 10mm, and minimum is 6.48 kPa for channel width of 6mm and height 120mm. Both heat transfer coefficient and pressure drop follow similar profile with channel dimensions. ΔP decreases by three times when width is doubled.

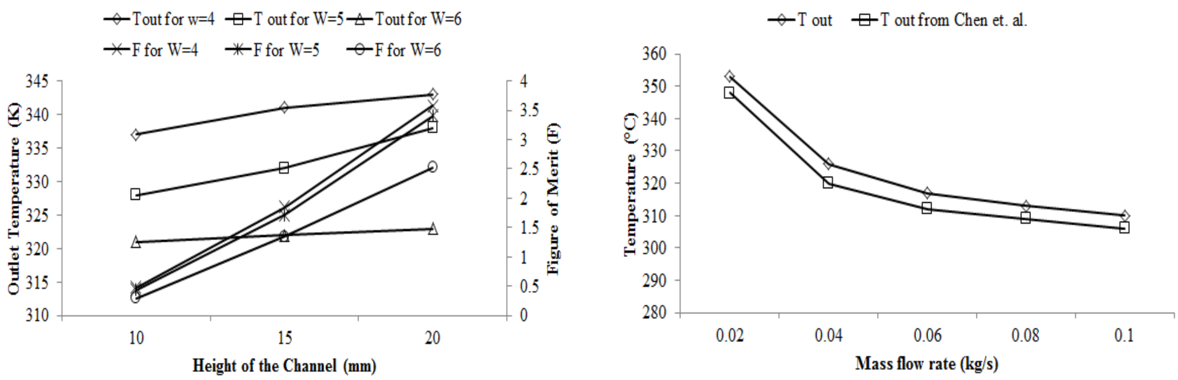

Fig. 5 a) Effect of channel height of mini channel on outlet temperature and Figure of merit b) The variation of coolant outlet temperature with mass flow rate for optimized heat sink

The effect of channel height on water outlet temperature and Figure of Merit is given in Fig. 5 a. For the given constant channel width the maximum outlet temperature is 343K for channel height of 4mm, which is more than 323K, the outlet temperature for 6mm channel height. The outlet temperature increases with increase in channel height due to more cross sectional area resulting in higher flow rates. In order to compare the heat transfer performance of spiral heat sinks, the results were given in terms of figure of merit. It is defined as the ratio of heat transferred from the wall to the fluid per unit pumping power supplied. The results show that maximum Figure of Merit is 3.58 for channel with 4mm width and 20mm height and minimum is 0.29 for channel with 5mm width and 10mm height. The coolant outlet temperature is for the present study is compared with the results from Chen et. al. [11]. It is evident from the Fig. 5 b that both have similar profile. The maximum outlet temperature is 353K at 0.02 kg/s reducing to 310K at 0.1kg/s.

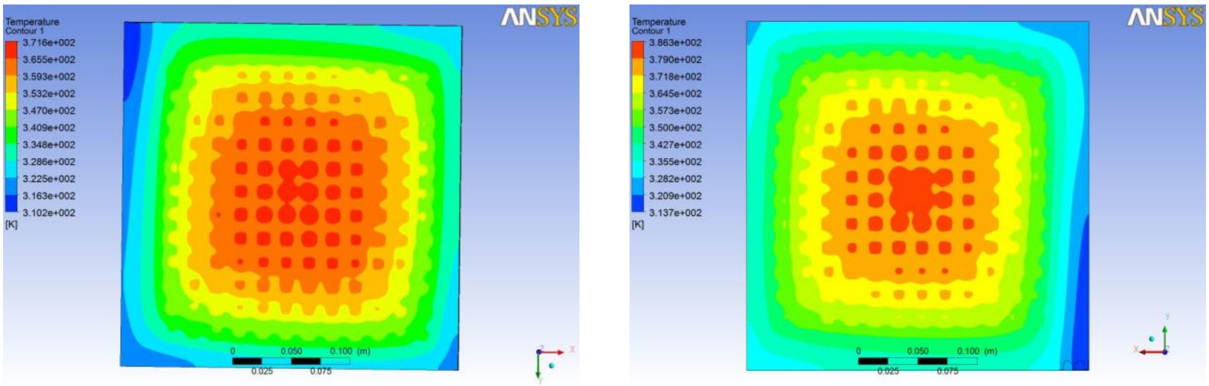

Fig. 6 Temperature contour in cell surface of heat sink for W=4mm and a) h=10mm and b) h=20mm

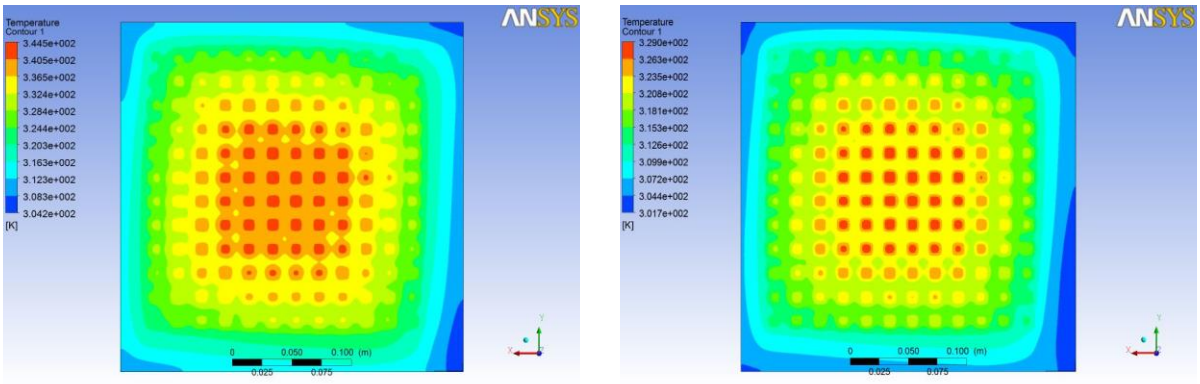

Fig. 7 Temperature contour in cell surface of heat sink for W= 6mm and a) h=10mm and b) h=20mm

The spatial temperature variation on the bottom surface (cell surface) of heat sink due to the flow direction for 4mm and 6mm width channels are shown in Fig. 6 and Fig. 7 respectively. The reason for less temperature contour near the edge is due to the fact that maximum temperature difference occurs near the inlet located at the lower right corner of the heat sink. As discussed in results it is evident from the temperature contours the heat dissipation is more in case of higher channel width and height for the same flow conditions.

Conclusions

The spiral mini channel heat sink is investigated numerically by varying the width and height of the channel for effective cooling of CPV module. It was found that mini channels with lower widths and higher height results in a low temperature rise of bottom surface and high figure of merit. The optimized geometry of mini channel for the CPV receiver was found to be W=4 mm, Length = 20mm. The final results predicts the Surface temperature is 355 K of CPV module of dimensions 300 x 300 mm^2, with a pressure drop of 8.0 kPa along the length of the channel at a flow rate of 0.16 lit/s.

Acknowledgments

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Nomenclature

H	height of channel (mm)	v	y-direction velocity of liquid (m/s)
W	width of channel (mm)	w	z-direction velocity of liquid (m/s)
t	Time (sec)	U_T	Temperature uniformity index (K)
v	Volume flow rate (m^3/s)	P	Pressure (Pa)
AR	Aspect ratio	e	Internal energy (J/kg)
Q	Heat rate (W)		**Subscripts**
C_p	Specific heat (J/kg K)	avg	average
Re	Reynolds number	n	normal
F	Surface Force (N)	max	maximum
$\dot{m}$	Mass flow rate (kg/s)	min	minimum
q	Heat flux (W/m^2)	w	work transfer
T	Temperature (° C)	in	inlet
V	Velocity (m/s)	out	outlet
u	x-direction velocity of liquid (m/s)		

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