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Design and Efficiency Estimation of Solar Volumetric Air Receiver Using Cfd Technique

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ABSTRACT

concentrated solar energy harvesting is used in high temperature applications. Volumetric Air Receiver (VAR) is used as a receiver for transferring heat energy to the air from the energy incident on it using large number of heliostats. Present study provides the receiver design with primary air flow within it and critically examines the efficiency of heat extraction and maximum obtainable air temperature for further use. Design is performed to optimise the heat extraction for the purpose of moderate temperature rise of inlet fluid to be used for further applications. Computational Fluid Dynamics (CFD) is used for all the simulation purpose.

KEYWORDS VAR, Solar energy, CFD, moderate temperature

Introduction:
Consumption of energy may be considered as an index of growth of any country [7]. The race of being counted in the list of developed country many nations now have their focus on energy based development results the demand of energy increasing with high frequency. Due to unbalanced system of demand and supply of energy the globe is reported to be facing problem of energy crisis. This reason leads the community to look up the various opportunities to utilize the renewable sources of energy in an efficient way. Among various forms of renewable sources solar energy is primary source of renewable energy, most abundantly available on earth [8]. The enhance application of it may help to reduce pollution, at lower cost of fuels, saving to fossil fuel storage , control on global warming and the reduction of greenhouse gas emissions[1]. However practicing the same may require considerable changes in technological aspect of material, process and application.

The current technologies for harnessing the solar energy can be classified as line and point focusing techniques. Solar thermal concentrating technology is still striving for its cost competitive application and efficient working. Concentrated solar power (CSP) technologies uses selective surface-based collectors have poor efficiency of energy conversion due to emissive losses at high temperatures. VAR are an innovative technology may play a significant role in improving the performance of CSP plants [11, 17]. It has a long history research and development [9, 10]. The further research on it may provide extended contribution in twenty first century.

Craig et.al (2014) shows CFD based results on Pressurized Air Receiver (HPAR) in which cavity receiver geometry is used as design variable and the parameter then used to model and optimize targeted solar irradiation on it. It has been done in combination with conjugate heat transfer problem [12]. Hischier (2011) presented a novel design of indirect receiver consisting reticulate porous ceramic absorber for power generation via solar driven gas turbine [13]. Hoffschmidt et.al (2001) provided a detailed development study report on development of VAR and their feasibility to produce sufficiently high temperature air [15]. M.I. Roldán et.al (2014) presented thermal evaluation of different absorber configurations for a VAR designed for a solar furnace has been carried out by means of 2D numerical model. The study results compare air velocity and thermal profiles at the absorber outlet propose a gradual-porosity configuration as an alternative to a previous design of a porous silicon-carbide honeycomb to heat an air stream to high-temperature industrial processes [19].

The research paper aims to present critical simulation based results volumetric air receiver (VAR) design with primary flow to identify heat extraction and other optimum parameter for efficient use of the same. The Computational Fluid Dynamics (CFD) technique of simulation is utilized for all study addressed in this paper.

Materials and Methodology:
The volumetric receiver made of a metal with good thermal conductivity properties to allow the heliostats to absorb at a larger depth. Basically VAR is structured body of porous interlocking shapes of foam, foils or wires allow the concentrated solar radiation to pass through it.[14] The absorbed radiation helps to heat the ambient air through surface convection when it passes through VAR [2,3,4]. This effect causes one of the biggest advantages of volumetric solar receivers namely the increase of the heat transfer area and the consequent reduction of local flux density at the absorber surface. Due to simple design of pressurized quartz window, less sensitive to thermal shock, Flexibility in the use of heat transfer fluid specially air, Flexibility in the solar field expansion, open type VAR is considered for this study. However closed type of receiver is also available. The VAR operating at ambient pressure are usually called open volumetric receivers and ones operating at elevated pressure levels closed (or pressurized) volumetric receivers [14].

Thermo-physical requirements of a volumetric receiver includes good absorption, volumetric optical extinction, heat transfer surface, high fluxes, radial heat transport , permeability which can be find in the dark material with high porosity, high cell density, temperature resistance thermal conductivity, 3D-Structure[16]

The efficiency of the VAR depends on the geometric parameters, optical properties, and thermo-physical properties of the porous material and on the heat transfer fluid [2, 5].

In present study we have used digital VAR system created in Ansys commercial software as shown in figure 1.

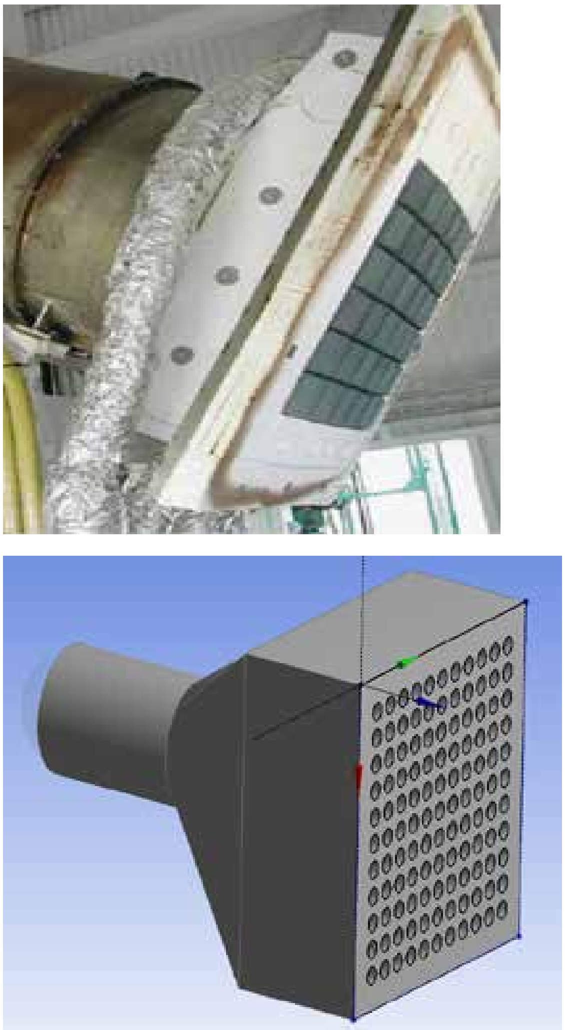

Fig1. Physical equipment developed by Agrafiotis, C.C[3] And digital drawing in Ansys developed in this study

Since the increase in surface area increases heat transfer rate due to convection which is also clear from Equation 3. In order to increase surface area we have used porous plate's arrangement with staggered alignment among plate number 1, 2 and 3 as shown in Figure 2.

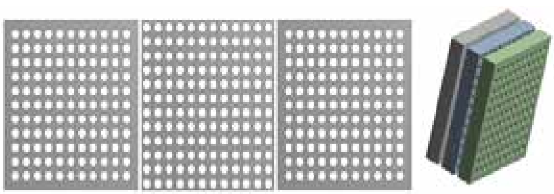

Fig2. Staggered Plate arrangement within the volumetric air receiver

To define the efficiency of porous structure surface to volume ratio (SR= 0.238) is calculated according to equation 1 for plate 1 and 3. Dimensional details for plate are shown in Figure 3.

$$SR = (2*L*L-121*Pi*d^2/4+Pi*d*w)/(L*L*w- 121*Pi*w*d^2/4) \quad (1)$$

Where, L and w are the length and width of plate and d is diameter of holes. Values of L, d and p are 76 mm, 4 mm and 6 mm respectively taken keeping in mind the manufacturing limitation of preparing such plate with holes by conventional machines so as to minimise the cost of product. Distance between plates has been fixed at 3 mm for effective utilisation of staggered geometry because of changing the path of fluid in a small length travel induces turbulence within the region creating better extraction of energy at the cross sectional area of plates. It should be noted that creation of turbulence being attained at the expense of pressure drop between inlet and outlet which may require higher pumping work.

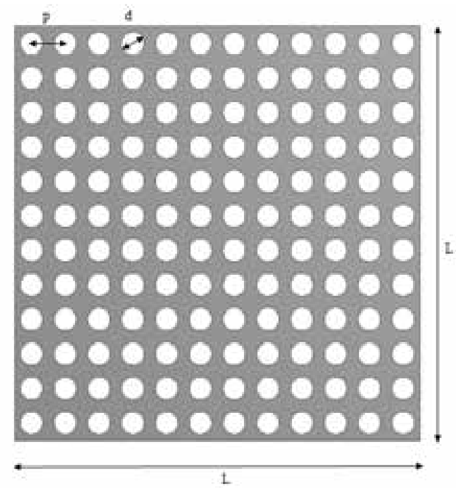

Fig3. Details of single plate dimensions

Simulation Setup: Commercial software Ansys is used as a simulation tool. Cut section of the geometry used for simulation is shown in figure 4 with all the boundary conditions as applied to it. Heat flux of 25 kW/m^2 is applied at Heat Absorbing surface which can be obtain by heliostat field. Number of heliostat required of same size as of VAR receiver area will be around 100 assuming 25% efficiency of field [20]. Material used for simulation is created as copper because of good conductivity. Fluid in this case is taken as air but it can be replaced by other fluid such as heat transfer fluid (HTF) used in solar power plant. Inlet velocity is used as 2m/s for the proper functioning of duct system (for small flow rate of 300 m^3/h) [21]. Boundary condition as a "wall" is used as an adiabatic wall which can be obtained physically by insulating the system by glass wool or Plaster of Paris (POP) type material. Flow is assumed to be laminar within the system.

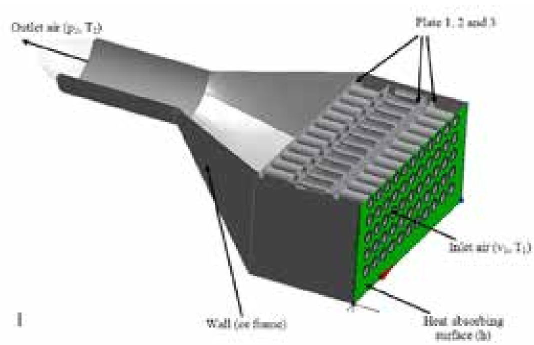

Fig4. Cut section view and Boundary condition applied to VAR

Once the geometry is created, Fluid area is extracted from the geometry in order to get the mesh zone for fluid. For meshing we have used triangulated meshing at surface and tetrahedral volume elements within internal volume. Contact region is established between fluid zone and solid geometry zone as shown in Figure 5(a) coloured in dark grey region. Maximum meshing element size kept at 16.85 mm which gives the total number of nodes after meshing are 1075456. Meshed zone is shown in Figure 5(b). For simulation purpose HP workstation with 8 core is used which takes around 4 hour to complete single case run.

Fig5. (a) Contact region between air and frame+plate arrangement is shown in dark grey and (b) corresponding meshed body (Part of body is shown here)

Mathematical Formulation:
Once the reflected irradiation in the form of heat flux is absorbed at the receiving surface of VAR, It is absorbed at the surface. Absorbed energy transferred throughout the plate and frame material by conduction as well as there is an exchange of heat at the contact surface of plate and frame surface with fluid region by convection. Since we are developing VAR for moderate temperature rise application, heat transfer through radiation can be neglected. Development of governing equation can be developed for mass, momentum and energy equation as described by Vyas A. (2014, 2016) [22] [23]. Equation 2(a), 2(b) and 2(c) is solved for fluid region while for solid material only equation 2(c) is required to be solved.

Continuity equation:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho\, U) = 0 \qquad 2(a)$$

X- direction momentum equation:

$$\rho\frac{Du}{Dt} = -\frac{\partial p u}{\partial t} + \nabla.(\rho U) \qquad 2(b)$$

Energy equation:

$$\rho\frac{De}{Dt} = \frac{\partial p e}{\partial t} + \nabla.(\rho E U) \qquad 2(c)$$

At the contact region heat is transferred from solid wall to fluid by conduction and then within the fluid by convection. At steady state energy balance at contact surface is given by equation 3.

$$-kA\frac{\partial (T-Ts)|_{y=0}}{\partial y} = hA\,(T_s - T_\infty) \qquad (3)$$

Using Equation 3 Nusselt number can be derived in equation 4(a) which is used for the determination of heat transfer coefficient (h) along with Prandtl number (Pr) and Reynolds number (Re) in Equation 4(b) and 4(c) respectively.

$$Nu = \frac{h_{av} L_c}{k} \qquad 4(a)$$

$$R_e = \rho v D/\mu \qquad 4(b)$$

$$Pr = \frac{\mu\, C_p}{K} \qquad 4(c)$$

Where L_c(Characteristic Length) = 4*A/P = d = 0.072 m, A = Cross Sectional Area, P = Perimeter and K = Thermal conductivity of air.

For air: μ = 1.98 X 10^{-5}, C_p = 1 X 10^3, K = 0.024 in SI units.

Dittus-Boelter equation can be used in the cases where temperature difference is not too high for the calculation of heat transfer coefficient (h) using relation given by Equation 5.

$$Nu = 0.023\, Re^{4/5} \times Pr^{0.4} \qquad (5)$$

Values of Nu, Re, Pr and h_{av} come out to be 32.1, 9404.04, 0.825 and 10.13 W/m^2 C respectively. Thus value of heat transfer coefficient (h) for porous media with SR value of .023 can be used in the scale of 10.13 W/m^2 C.

Results and Discussion
Temperature difference at outlet and inlet can be calculated. Outlet temperature profile can be obtained by simulation results at outlet as shown in Figure 6(a). Average temperature can be computed using weighted area method which gives the value of 329.122 ^{0}C. Inlet temperature used as 23 ^{0}C. Once the temperature difference of 29.122 ^{0}C is obtained.

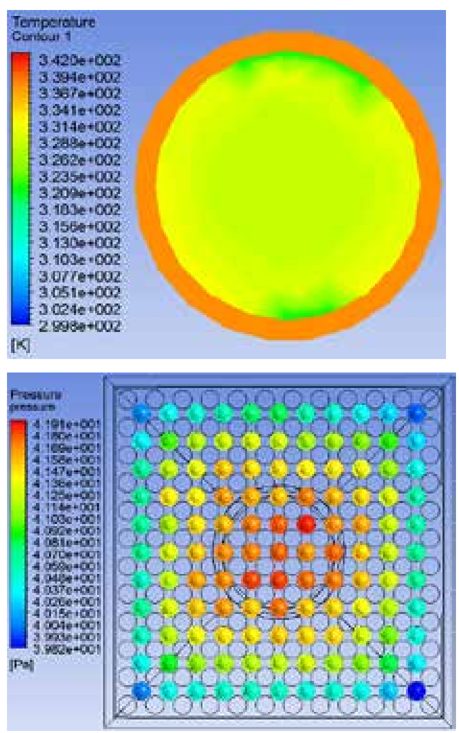

Fig 6(a) Temperature profile at outlet and (b) Pressure profile at inlet

Pressure difference can also be computed at inlet from pressure distribution as shown in Figure 6(b) and pressure drop computed as 41.11 pascals can be used to estimate the pumping power required to maintain fluid circulation at particular mass flow rate and temperature. Vector for flow field at X-Z plane and Temperature distribution inside the VAR can also be obtained as shown in Figure 7(a) and Figure 7(b) respectively to estimate the visual correlation between flow and temperature variation within the VAR.

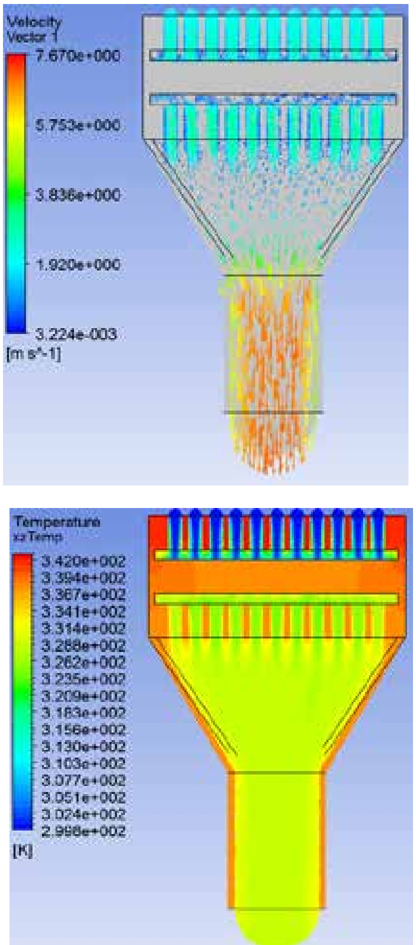

Fig 7(a) Vector field at X-Z plane and (b) corresponding Temperature distribution

Conclusion

(i) Design of low cost VAR is presented and efficiency is estimated for moderate temperature rise of air. Present study can be applied successfully for other fluids like oil where high temperature of fluid is required.

(ii) With the variation of input heat flux using different number of heliostat, fluid velocity and type of fluid one can regulate the working temperature at outlet.

(iii) More robust design and high temperature can be obtained by partly recirculating the fluid as a secondary flow in VAR.

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