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Performance Study On Solar Receiver by Experimental and CFD Analysis through Concentrated Solar Energy System

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***Abstract:* -- The novel design and experimentation on solar collector system which could utilize the direct solar radiations with two different specific heat capacity heat transfer fluids. This economical point focusing reflector and receiver model of dryer and steam generator may be implemented in industries when scaled up. The parabolic reflector with aperture area of 12m2 and multi cavity receiver filled with SiC ceramic beads are fabricated to concentrate and absorb the heat flux from the Direct Normal Irradiation (DNI).Water is circulated by a pump through copper coil around the receive as high specific heat capacity HTF, Whereas Air is the another working fluid of low specific heat capacity, which is sucked from the atmosphere through the drilled holes of the receiver by a induced draft fan. The heat transfer parameters of both working fluids were experimented for five days, while both fluids are flowing in same time and also while flowing separately with same period of time and almost for the same concentrated solar power. The experimental results on the efficiency of the receiver have no major variations, which reveal the possibilities of applications of air drier and steam generator with the same reflector and receiver areas by two different HTFs of varying specific heat capacities. The receiver thermal efficiencies are maintained in between 72.76% to 74.56% for both the heat transfer fluids with uniform heat flux distribution and heat transfer.**

***Keywords*-- Direct Normal Irradiation, absorber, heat transfer fluids.**

Acronyms			
		A_a	Aperture area of Absorber
CSP	Concentrated Solar Power	A_R	Reflector Area
HTF	Heat Transfer Fluid	ηAb	Absorber efficiency
DNI	Direct Normal Irradiation	C	Concentration ratio
PV	Photo voltaic panel	σ	Stefan Boltzmann constant in radiative heat transfer
CFD	Computational Fluid Dynamics	T_{ab}	Absorber Temperature
		T_∞	Ambient Temperature
		ε	Emissivity of the Absorber

I. INTRODUCTION

Concentrated Solar Power (CSP) from point focusing parabolic reflector with multi cavity receiver (collector) through exact tracking will reflect the incident DNI to the focal point which generates heat flux on the cavity absorber plate of the receiver. This economical multi cavity receiver design with two heat transfer fluids in one (single) receiver focused by a reflector can be applied as drier and steam generator. It is made possible from the following referred works on receiver configurations, materials, working fluids and heat transfer models. A.CAROTENOTO et al.(1) studied the thermal behaviour of a multi cavity volumetric solar receiver by minimizing the convective and radiative losses and maximized the radiative absorption through multi channelled Silicon infiltrated silicon carbide material (SiSiC). Janna Martinek and Alan W.Weimer (2) compared and proved the absorbing cavity design is better than the reflective cavity design. Whereas the reflective cavity design was proved better with special tube positioning, but the absorbing cavity design contains three to five large tube arranged in a semicircle around the back cavity wall and high external surface area. An experimental work by Mathew Neber and Hohyun Lee (3) square duct geometry of circulating tube with absorber plate made out of SiC material, achieved the out let temperature of 1248K and effectiveness of 0.82 through a residential CSP model of point focusing parabolic collector**.**

M.A.Gomez et al (4) simulated a solar radiation absorber with CFD by fixed porous beds for a heat transfer model to study the temperature profile inside the bed and the energy balance was compared with the existing experimental data. Thermal performance of solar receivers based on geometrical parameters of different inlet and outlet were studied by M.O.Wang and Kamran Siddigui (5) through a dish type concentrated collector and also compared with the experimental data, which has shown better thermal

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performance for the argon gas entering tangentially from top and leaving out through the bottom configuration. Thomas Fend e al (6) developed a compact heat exchanger model with sintered Silicon Carbide (SiC) material channels shown higher reliability at 950°C with effective performance of 65%, which is more suitable model for point focussing and tower type CSP technologies in small to large scale applications. Two novel high porosity materials of double layer SiC foam, screen printed porous Sic material and also with the channel shaped SiC material were compared with respect to their thermal performance to suit CSP applications by Thomas Fend et al (7). Christos C.Agafiotis et al (8) experimentally investigated porous structure and thermo mechanical properties with SiC porous monolithic multi-channelled honeycomb design under concentrated solar thermal power applications with good compressive and bending strength. Zhiyong Wu et al. (9) investigated experimentally and validated numerically about the pressure drops and penetrability of heat transfer fluid in ceramic foams, which has been overcome by drilled holes in the foams. Carlo Renno and Fabio Petito (10) theoretically modelled to evaluate a concentrating photovoltaic thermal system for the dometic application, which conists of parabolic concentrator of point focusing type with triple junction PV cells and compared it with the traditional PV system. This experimental work on receiver model of multi cavity absorber with ceramic beads inside increases the absorptivity and minimizes the emissivity with maximized conductive, convective as well as the radiative modes of heat transfer.

II. EXPERIMENTAL SETUP

2.1 Ray Tracing Optimization Method Tonatiuh

Ray tracing simulations are very effective for design and optimization of parameters in parabolic dish collector. In this work the diameter is subjected from 1 meter to 20 meters , is used to simulate the sun radiation in the parabolic reflector. The focal length is measured by fraction of the dish diameter as shown in the Fig1. After setting the necessary parameters like dish diameter, rim angle Direct Normal Irradiation (DNI), the ray tracing is executed for the incident flux at the receiver is mapped by two dimension coordinates mapping. A geometric optics formulation is used in the present analysis over the projected areas of both the sun and the concentrator. The reflection from each concentrator the diameter is subjected from 1 meter to 20 meters ment is mapped analytically onto the surface of the cylindrical receiver. In the following analysis, concentration on the receiver surface is first calculated under the idealized conditions of collimated solar incidence, aligned with the axis of a perfect-surface concentrator. An arbitrary incidence angle is then used to derive a general mapping of the solar radiation.

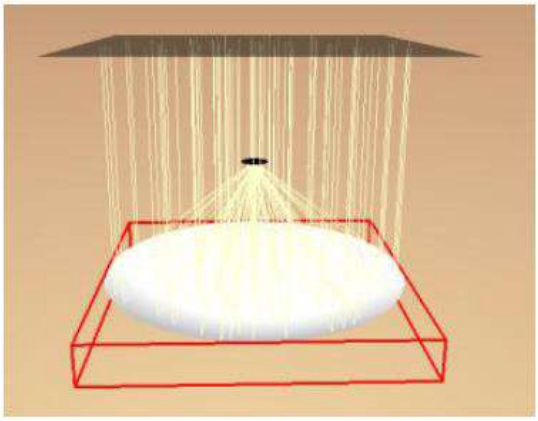

Fig.1 Sun Rays Through Parabolic Surface

Fig. 2 Reflector and Receiver

The optimized dish type point focusing reflectorfig2. constructed with 12 square meter effective area of focal length 2.16 m and rim angle of 45º. The reflector has been positioned 12° 30' N latitude and 79° 56' E longitude at melmaruvathur nearby city of Chennai in India. The word **collector** is applied to the total system including the receiver and the concentrator. The receiver is that element of the system where the radiation is absorbed and converted in to heat energy form. The concentrator is the part of the collector that directs and focuses the DNI radiations on the absorber plate of the receiver. Applications of concentrating collectors are mandatory in medium or high temperature energy

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conversions in solar thermal power generation. This work is proposed to process industries, where the requirement of heat at small-medium range of temperatures from 100°c – 300°c, or even higher for drying and steam generation

Fig. 3 receiver with multi cavity absorber plate.

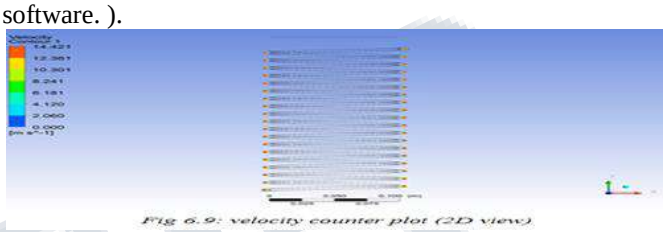
Fig.4 SiC Ceramic beads

2.2. Experimental Work

Air from the atmosphere through the multi cavity drilled holes is sucked by a 12 V induced draft fan through the ceramic beads of the receiver with he optimized flow rate of 0.04kg/sec in open loop. The data acquisition were made and tabulated for the input and output parameters through solar power meter to measure the DNI, . Water has been circulated through a copper coiled tube of internal and external diameters of 5.9mm an6.4mm respectively by a pump which could deliver 1000 litres/hour at maximum height of 1.8m has been used to circulate the water with the optimized flow rated of 0.5 litre per minute. The flow of water was measured by a rota meter of range 0-2 lpm, an anemometer to measure the velocities of air and K type thermocouples to measure the receiver, air and water temperatures. The temperatures of absorber, air and water are measured and tabulated at beginning (T1) and end of each hour (T2) from 9.00 hours to 15 hours for five days. The receiver has been insulated with glass wool for 19.5mm, which was wrapped by aluminium foil sheet over the cover of the receiver to minimize the losses.

2.3 Computational Fluid Dynamics Analysis for Water and Air

The CFD analysis has been done on the solar receiver to study the temperature distribution, heat transfer rate the flow parameters like pressure and velocity. The receiver model is created by AUTODESK INVENTER software (fig 1) then discretised with hexahedral elements of 1326803 numbers through 807093 nodes by HYPERMEXH software.).



Fi g5. Velocity vector plot for Water

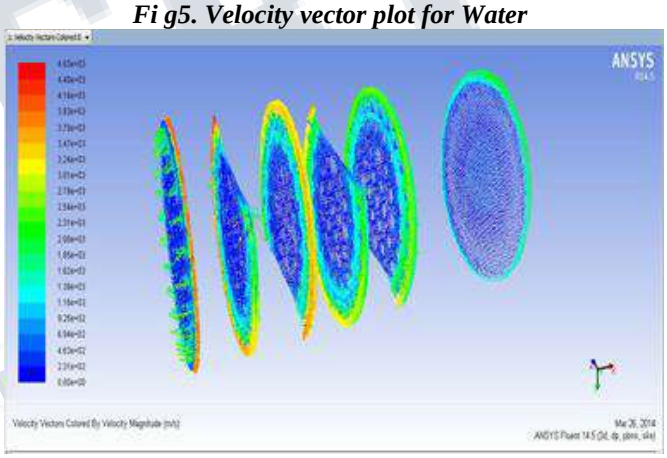


Fig 6. Velocity vectors plot for Air

The analysis is done by the ANSYS-CFX software (fig 5& 6) with the boundary conditions for the solid domain (absorber of Cu and SiC materials) flow boundary condition for fluid domain (water) of at 1 atmospheric pressure through a pump of discharge capacity 1000 litres per hour. The inlet temperature of water is 20℃ with the mass flow rate of 0.205kg/sec. The total area of water inlet is .7156e-05 m2 and there are totally 18.5 turns, the water flows from top to bottom.. The output parameters like pressure, velocity, static temperature across the receiver for the inputs of solar energy, viscous- K-Epsilon, density, specific heat capacity, for solid and fluid medium (aluminium & air)..The solution method applied is pressure velocity coupled in which momentum and turbulent kinetic energy were considered as second order upwind. The two zones are given in the cell zone condition another one is the fluid zone and another one is solid zone for

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a fluid zone the material is selected as air and the rotational axis direction is given as (x=0, y=0, z=1). Momentum: Wall motion – stationary wall, Shear condition – no slip, Thermal condition – heat flux, – coupled. The solution method is taken as pressure velocity coupling method in which the momentum and turbulent kinetic energy was taken as second order upwind

III. RESULTS AND DISCUSSIONS;

The multi cavity copper ceramic receiver assumed as defuse surface with drilled holes of inner core. This multi cavity holes with ceramic beads are considered as a grey surface for defining the reflectivity in terms of absorber emissivity(∈) with radiosity and irradiation(DNI) Mathew Naper in his design of high temperature residential scale solar receiver considering the above parameters to select the following equations to find the energy (qA) entering the absorber. through the aperture area (AA). The same eq uations are opted to calculate the absorber efficiency (ηAb) based on the concentration factor, which is the ratio of reflector area (AR) and absorber area.

QAb =$\in A(C\ q - \sigma TAb4 + \sigma T\infty 4$) (1)
Q gain = mcav (Tout - Tin) (2)
Qloss=ULAR(Tave-Tamb) (3) ηth.R= $mcave(Tout - Tin)$ $(ndAapG)$ (4)

The conducive and convective losses in the large scale applications at high temperatures are negligible very small compare to radiative losses, but considering the small scale level it is important to minimize all the losses. The radiative losses are depends on the mass, circumferential area and specific heat of the material (copper and ceramic beads) used for the receiver. The maximum achieved absorber temperature was 492K, for that the heat losses due to radiation was approximated as 13.6%,it is 61.99 +10- W, which is due to the radiative losses are 4 th power of temperature. While for conduction and convection losses are 7.6%, it is 37.79 with variation of 12W. This reflector and multi cavity receiver with manual tracking shown less variations in the receiver efficiencies for the three different modes of applications of HTFs., which have been explained through tabulations and plots as follows. The calculations have been done with the average data from five days of data accusation for both working fluids and separately for the two working fluids.

Table;1 Water and Air as HTFs

Time	DAY 1					DAY 2					DAY 3					DAY 4					DAY 5				
9.00 To 10.00	990	115	28	43	29	34	950	118	27	42	29	42	910	120	25	45	29	42	930	140	29	42	29	43	28
10.00 To 11.00	998	137	28	54	30	42	968	137	29	45	29	46	940	145	29	53	29	42	998	136	28	55	31	51	31
11.00 To 12.00	1140	178	30	67	31	51	1013	160	30	59	30	63	1130	152	30	64	31	57	1190	182	29	71	32	74	30
12.00 To 13.00	1170	185	29	67	31	72	950	178	29	72	31	74	1250	182	29	69	32	75	1290	208	30	80	33	94	30
13.00 To 14.00	1250	208	30	81	34	78	1180	188	30	84	33	77	1080	198	30	80	33	78	1130	218	31	102	34	88	34
14.00 To 15.00	980	187	30	85	34	74	970	188	30	87	33	72	940	187	30	82	33	73	1030	211	31	86	34	78	34

Table 2; Air as HTF

	Day1				Day2				Day3				Day4			
9.00 To 10.00	950	148	28	48	920	147	28	49	880	155	28	40	850	155	28	42
10.00 To 11.00	1132	171	30	56	1180	174	30	59	980	176	28	55	990	180	28	54
11.00 To 12.00	1260	187	32	70	1270	189	31	77	1120	176	31	65	1130	178	30	69
12.00 To 13.00	1292	190	33	84	1290	201	33	88	1280	196	33	82	1252	195	32	80
13.00 To 14.00	1315	206	34	97	1320	218	35	97	1302	185	35	97	1280	212	34	97
14.00 To 15.00	1220	204	34	95	1200	207	35	94	1020	190	35	97	1180	203	34	93

Table 3; Water as HTF

	Day1				Day2				Day3				Day4			
9.00 To 10.00	990	117	28	49	910	113	27	45	650	104	27	38	680	106	28	40
10.00 To 11.00	1073	140	29	56	1160	139	28	59	900	128	27	48	948	131	27	55.5
11.00 To 12.00	1084	162	30	70	1280	165	28	61	915	147	28	45.5	1152	148	28	77
12.00 To 13.00	1164	178	30	82	1286	180	28	84.5	940	160	28	80	1247	159	29	89
13.00 To 14.00	1297	189	31	98	1305	192	30	107	1105	174	30	88	1092	178	30	105
14.00 To 15.00	1150	174	31	90	1200	185	30	105	1020	167	30	88	1000	167	30	105

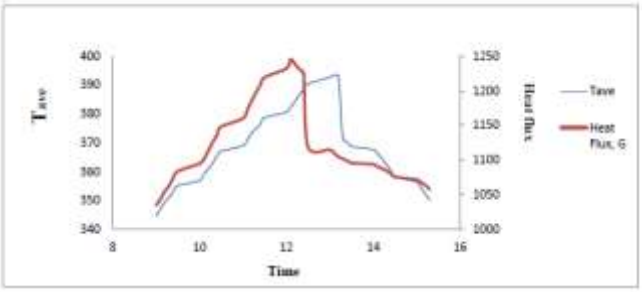

Fig 7. Temperatures Vs Time from 8.00 to16 hrs

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Table .4 Efficiencies of Air, Water &Both

Water & Air	Air	Water
0.736573	0.734289	0.73939
0.735009	0.734094	0.74469
0.743331	0.736897	0.745644
0.742712	0.735189	0.743218
0.741762	0.733515	0.741384
0.727586	0.729553	0.73885

The table 4 and the fig 8 show the efficiencies of the absorber (receiver) with respect to time from 9.00 to 15.00 hours for HTFs of water and Air, only for Air and only for water. The efficiencies are maintained in between 72.76% to 74.56% with uniform heat flux distribution and heat transfer through the multi cavity volumetric receiver made from ceramic beads filled alluminium receiver. The SiC ceramic which has the black body characteristic of emissivity and absorptivity as 1 (one) with better thermal conductivity 490 W/mK at 27°C acts as better absorber, heat storage and transfer solid medium. In this work based on the quality of SiC beads it has been considered as a grey body of emissivity of 0.8

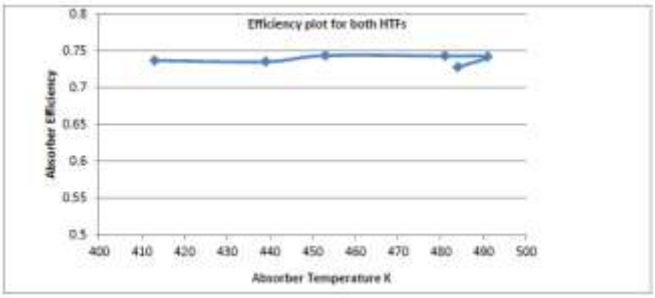

Fig 8 Absorber Efficiency Vs Absorber Temperatures

The plot of both HTFs in the fig 8 shows the average absorber efficiency as 73.78% and also the efficiencies are varying marginally from 72.76% to 74.33%), it means there is no considerable drop in the receiver temperature which is caused by increased radiative and conductive heat **transfer** because of the surfaces and thermal conductivity of the ceramic beads. This generated heat is stored and uniformly distributed throughout the receiver.

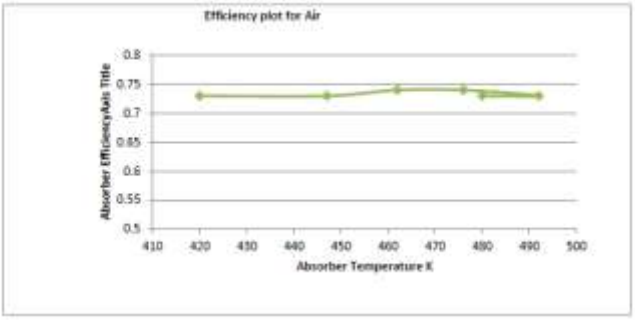

Fig. 9.AbsorberEfficiencyVsAbsorberTemperature

The fig.9 shows the steady absorber efficiency of 72.75% to 74,33% when the air is in application, which also indicates that the receiver temperature also uniform. The efficiency starts decline after 13.00 hrs. to14. The efficiency of the receiver not falls suddenly even after 14.00hrs, which is due to the design geometry of multi cavity absorber plates and rods and also by the SiC beads inside the receiver.

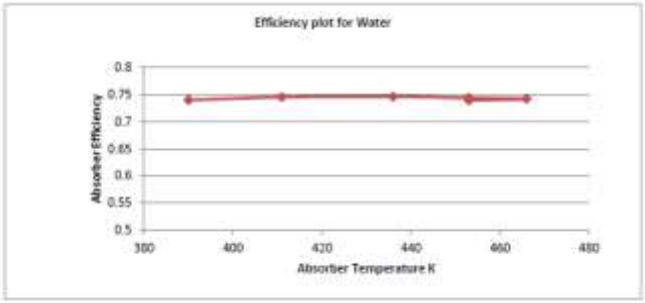

Fig10.AbsorberEfficiency Vs Absorber Temperature

The fig10. shows the steady performance with minimum variations in the receiver efficiency (73.88% to 74.56%) when the water is flowing. Better heat generation and storage in the receiver is made possible by the SiC ceramic material inside and also the efficiency is not dropping as when both fluids are in application during 14-15 hour. . It is also clear from the table 1,2 & 3 and efficiency plots of fig 8.9 &10 the receiver temperature is almost steady for the three experiments of the flow (both HTFs and separately for water & air).

IV CONCLUSION

Considering the consistent receiver efficiencies, it is possible to use two working fluids of low and high specific heat capacities for small scale and residential applications. The absorber temperature has been maintained from the available concentrated DNI, hence the design is economical because the same absorber and reflector areas are used for

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two HTFs. The results of multi cavity receiver design with ceramic beads, showing effective absorptivity with minimized losses, hence enhancing the heat transfer of radiative conductive and convective modes are made possible). The success behind for the consistency is SiC ceramic material which is inside the receiver to store the heat and supply the same for both the heat transfer fluids in consistent manner. The receiver materials used for the receiver with better thermal conductivities (Cu 98W/Mk at 225℃ and SiC 490W/mK at 27℃) with volumetric (3D) flow (zig-zag floe through plates and Sic beads) also improve the storage and heat transfer rate.

Future work; The performance of the collector may be studied by experimenting with copper or SiC material for the whole receiver design with different scale level and heat transfer models to suit for small to medium range of applications like food processing, heat treatment and steam generation.

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