A STUDY ON HEAT TRANSFER AND FLUID FLOW ANALYSIS OF POROUS MEDIUM SOLAR THERMOCHEMICAL REACTOR

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ABSTRACT

Utilization of solar thermal power for high temperature fuel production has the potential to significantly reduce the fossil fuel dependence of our current economy. Over the past two decades, remarkable progress has been made in the development of solar driven thermochemical reactors for the production of hydrogen and syngas as they are promising energy carriers for transportation, domestic and industrial applications. Porous media solar thermochemical reactor, thermal transport and fluid flow characteristics have significant impacts on hydrogen production efficiency. These issues could be achieved more efficiently and at a lower cost by applying computational fluid dynamics (CFD). This research will be working on thermal analysis performance of thermochemical reactor system. Different cases of porosity, inlet velocity of fluid medium and intensity of solar irradiance will be considered during the analysis. The result outcomes will be optimized further by applying Taguchi L9 orthogonal technique in order to identify the optimum configuration for porosity, inlet velocity and solar irradiance for the complete reactor system.

Keywords: Porous Medium, Thermochemical Reactor, Fluid Flow, CFD, Heat Transfer etc.

INTRODUCTION

Currently, heat transfer analysis of solar thermochemicalreactor using concentrated solar energy as a heat source todrive high-temperature chemical reaction is an attractingresearch area in the general context of solar fuels andspecifically for syngas production(Xing *et al.*, 2017)The technology ofthermochemical solar energy-to-fuel conversion usingconcentrated solar energy is mostly considered as aninteresting option for CO2 depletion which promotescarbon recycling, thereby decreasing the dependenceextent on fossil fuels(Rupesh, Muraleedharan and Arun, 2016). However, the thermalperformance of solar thermochemical reactor decreasesthe syngas yield and the syngas efficiency.

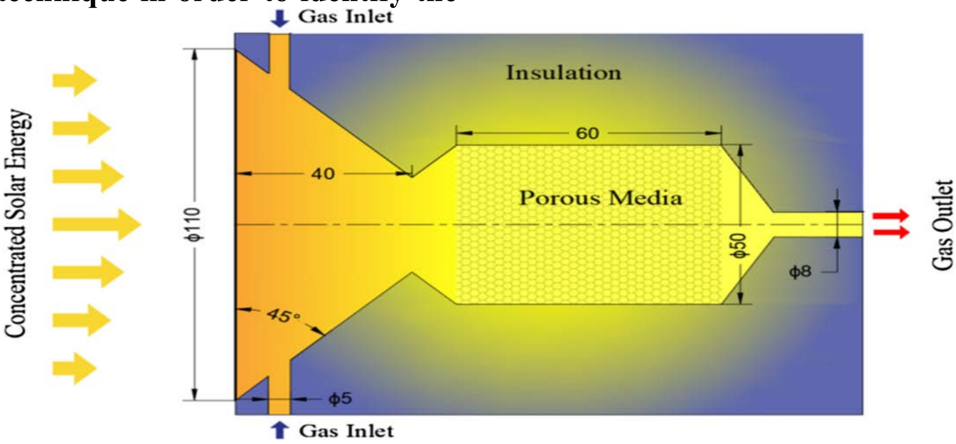


Fig. 1 Thermochemical Reactor Used in Industry

Thermochemical systems are a good alternative to current technologies for long-term heat storage, since theenergy is stored as a chemical potential and there is no heat loss during the storage phase. A large number ofstudies have now been conducted on the development of integrated thermochemical reactors, but fewer studieshave investigated separate reactor technologies. The latter present the advantage of dissociating the thermalpower and storage capacity of the system, which also increases the energy storage density of the process.(Farcot *et al.*, 2018)

The solar concentrating systems described have beenproven to be technically feasible in large-scaleexperimental demonstrations aimed mainly at theproduction of solar thermal electricity in which aworking fluid (typically air, water, helium, sodium,or molten salt) is solar-heated and further used intraditional Rankine, Brayton, and Stirling cycles(Geyer *et al.*, 2001)Solar thermochemicalapplications, although not developed as far as solarthermal electricity generation, will make use of thesame solar concentrating technology.Because thermodynamics is the science thatdescribes the conversion of one form of energy intoanother form, it is germane to the field of SolarThermochemistry. Solar thermochemical processesconvert radiant energy into chemical energy. Thetwo fundamental thermodynamic laws that givepractical information with regard to any solarthermochemical process are the 1st and 2nd laws.Using the 1st law, one establishes the minimumamount of solar energy required to produce aparticular fuel or chemical species. The 2nd lawindicates, among other things, whether or not thechosen path for producing the fuel is physicallypossible. Both types of information are required for aprocess designer.(Meyers Ed, Steinfeld and Palumbo, 2001)

Hydrogen is the simplest and most abundant element onearth. Hydrogen combines readily with other chemical elements,and it is always found as part of another substance,such as water, hydrocarbon, or alcohol. Hydrogen is alsofound in natural biomass, which includes plants and animals.For this reason, it is considered as an energy carrier and notas an energy source.(Kalamaras and Efstathiou, 2013)

Hydrogen can be produced using diverse, domesticresources, including nuclear, natural gas and coal, biomass,and other renewable sources. The latter include solar, wind,hydroelectric, or geothermal energy.This diversity of domesticenergy sources makes hydrogen a promising energycarrier and important for energy security. It is desirable thathydrogen be produced using a variety of resources and processtechnologies or pathways. The production of hydrogencan be achieved via various process technologies, includingthermal (natural gas reforming, renewable liquid and bio-oilprocessing, biomass, and coal gasification), electrolytic (watersplitting using a variety of energy resources), and photolytic(splitting of water using sunlight through biological andelectrochemical materials).(Kalamaras and Efstathiou, 2013)

LITERATURE REVIEW

(Zhang *et al.*, 2018) Worked on thermal transport and fluid flow in high-temperatureporous media solar thermochemical reactor were investigated by considering different thermo physical models. The numerical simulation was performed using FLUENT software with user-defined functions. Moreover, different cases, including LTNE model, radiation model, momentum source term model, heat transfer model, and the effect of porous media were investigated and compared. Then, the application range, result deviation and variation tendency of different models under different conditions were indicated in detail.

Quentin Bellouard et al. (2018)in his study aimed at demonstrating the feasibility of syngas production in this reactor concept and to prove the reliability of continuous biomass gasification processing using solar energy. The study first consisted of a parametric study of the gasification conditions to obtain an optimal gas yield. The influence of temperature, oxidizing agent (H2O or CO2) or type of biomass feedstock on the product gas composition was investigated. The study then focused on solar gasification during continuous biomass particle injection for demonstrating the feasibility of a continuous process.

(Huang *et al.*, 2018)explained thatMethane-to-syngas conversion plays an important role in industrial gas-to-liquid technologies, which is commercially fulfilled by energy-intensive reforming methods. Here we present a highly selective and durable iron-based La0.6Sr0.4Fe0.8Al0.2O3-δ oxygen carrier for syngas production via a solar-driven thermochemical process. The oxide shell, acting like a micro-membrane, avoids direct contact between methane and fresh iron, and prevents coke deposition.

(Gorensek *et al.*, 2018)stated thatkey element of this vision is the need to generate CO 2-neutral hydrogen efficiently and at a large scale. 1,2 Potential processes to do this can be broken out into four categories: 1) electrolytic processes; 2) biological processes, e.g., microbial biomass conversion, photo biological; 3) direct solar water-splitting processes, e.g., photo electrochemical; and 4) thermochemical processes, e.g., hydrocarbon reforming and coal or biomass gasification with carbon capture, water-splitting cycles.

(Villafán-Vidales *et al.*, 2017)explained thathydrogen is a promising energy carrier for transportation, domestic and industrial applications. Nowadays hydrogen is consumed basically by the chemical industry, but in long term its demand is expected to grow significantly due to emerging markets. Hence production of hydrogen with sustainable methods is a relevant issue. This work presents a review of the different CSP- aided thermochemical processes for hydrogen and syngas production. For each process, some relevant solar-tested reactor prototypes are described.

Although some of these reviews present and comment on the different configurations and prototypes used for thermal transport and fluid flow in high-temperature porous media solar thermochemical reactor, none of them has provided a detailed assessment of porosity parameter and thermal analysis of high working temperature thermochemical reacting system. Also negligible work has been done on different cases of porosity, fluid inlet velocity and effect of solar irradiance. Therefore, keeping in mind the gap from the literature; the aim of this new review is in evaluating the reactor concepts, and highlighting their performance of thermal analysis of thermochemical reacting system based on multiple cases of porosity, air inlet velocity and solar irradiance. Further, the results will be optimized in order to get the optimum configuration for the reactor system.

METHODOLOGY

1. Design and modelling of porous media solar thermochemical reactor in CATIA V5.
2. Further converting the CATIA V5 File in .STEP format for importing it in ANSYS Fluent work bench.
3. Assigning the name selection to the different parts of thermochemical reactor model.
4. Meshing of thermochemical reactor model for performing the simulation process.
5. Providing the suitable boundary conditions according to the selected base paper.
6. Assigning the material properties to the model.
7. Setting the proper setup for CFD analysis procedure.
8. Evaluating the results after the finish of simulation work.
9. **9.** Optimizing the result values using Taguchi L9 method for most optimum result.

For the modelling and CFD analysis CATIA V5 and ANSYS software will be used. CATIA V5 is a well-known modelling software used for modelling in various industries like automotive, aerospace, general engineering etc. Whereas ANSYS is a simulation software used to perform various numerical based analysis on components having applications in automotive, aerospace, general engineering etc. For the optimization process tagauchi optimization method is used.

DESIGN AND ANALYSIS

Modelling

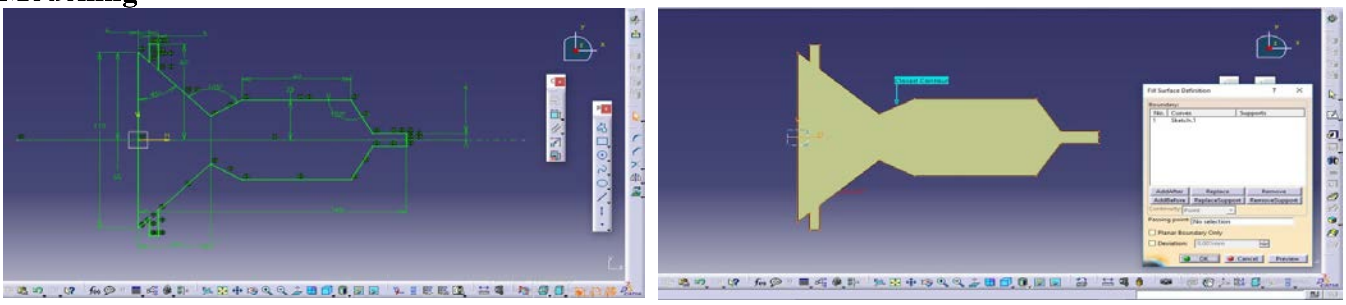


Fig. 2 (a)Sketch of Thermochemical reactor in CATIA V5 (b) Designof Thermochemical reactor in CATIA V5

For the modelling purpose CATIA V5 Software is used In which first the sketch of thermochemical was prepared and afterward it was converted into surface model for analysis procedure.

Meshing

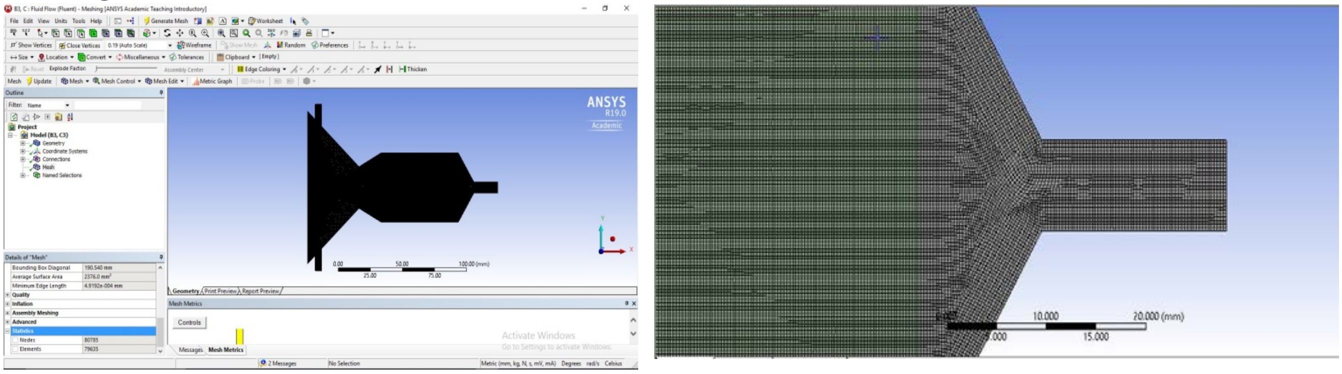


Fig. 2 (a) Meshing of Thermochemical reactor in Ansys Fluent (b)) Enlarged view of Thermochemical reactor meshing

In the Meshing process fine rectangular mesh was obtained containing 80785 Nodes and 79635 Elements. Skewness was maintained below 0.99 so as to have the compatibility for CFD Analysis.

Name Selection

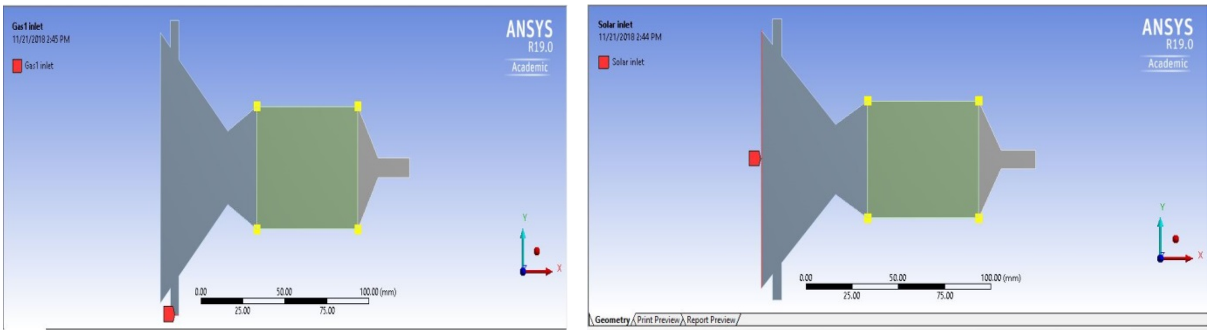


Fig. (a)Gas inlet 1 (b)Solar inlet

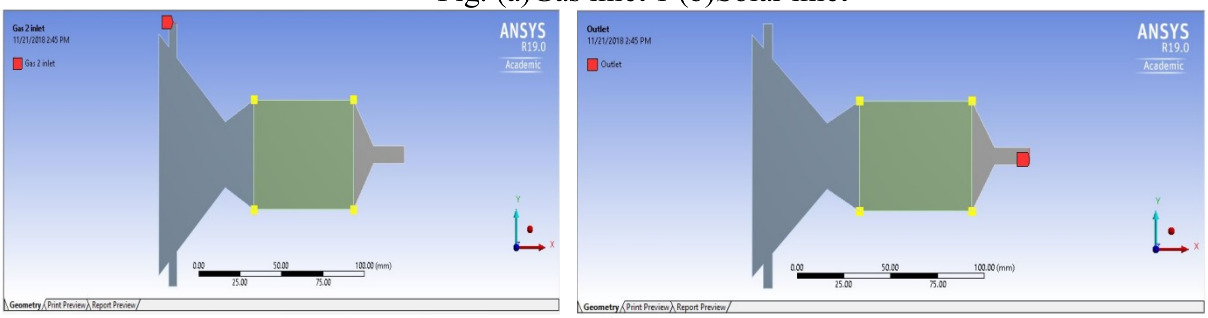


Fig. (a) Gas inlet 2 (b) Solar outlet

Boundary Conditions

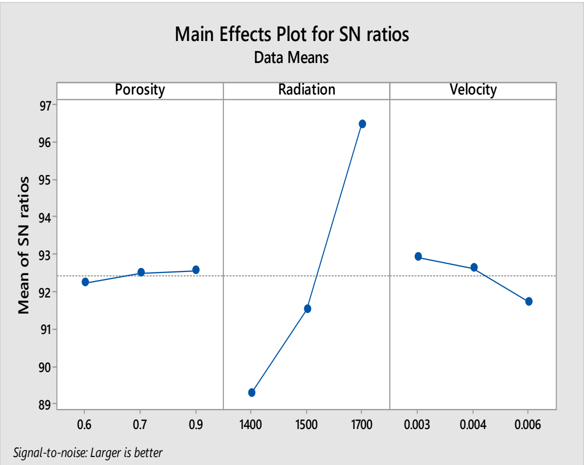
For the analysis procedure Steady state, Viscous – K-epsilon, Standard wall fin Model was selected with energy in on condition, SiC Material from Fluent database and activate porous zone and give 0.6, 0.8 0.9 and 1.0 porosity was selected in material selection.After providing the Material properties in solar thermochemical reactor boundary condition were provided as inlet velocity 0.005m/s and inlet solar temperature as 1600K. The outlet walls are maintained at constant temperature 600K. After the analysis process 27 different cases were simulated and values were obtained further for optimization these values were used in tagauchi optimization method for finding the S/N Ratio shown in table below.

Table 1. Values obtained after the CFD analysis

Cases	Porosity	Radiation	Velocity	Total Heat Transfer	S/N Ratio
Case 1	0.6	1400	0.003	28916.33	89.22286
Case 2	0.6	1400	0.004	31057.98	89.84346
Case 3	0.6	1400	0.005	27493.87	88.78472
Case 4	0.6	1500	0.003	36373.45	91.21569
Case 5	0.6	1500	0.004	35167.88	90.92292
Case 6	0.6	1500	0.006	35396.1	90.97911
Case 7	0.6	1700	0.003	70885.86	97.01119
Case 8	0.6	1700	0.004	67227.43	96.55093
Case 9	0.6	1700	0.006	60006.48	95.56396

Cases	Porosity	Radiation	Velocity	Total Heat Transfer	S/N Ratio
Case 10	0.7	1400	0.003	31003.54	89.82823
Case 11	0.7	1400	0.004	29582.7	89.42076
Case 12	0.7	1400	0.006	26915.8	88.60015
Case 13	0.7	1500	0.003	41578.54	92.37738
Case 14	0.7	1500	0.004	39531	91.93876
Case 15	0.7	1500	0.006	35316.64	90.95959
Case 16	0.7	1700	0.003	70890.29	97.01174
Case 17	0.7	1700	0.004	67209.11	96.54856
Case 18	0.7	1700	0.006	60373.05	95.61686
Case 19	0.9	1400	0.003	31567.21	89.98472
Case 20	0.9	1400	0.004	29565.5	89.4157
Case 21	0.9	1400	0.006	26524.43	88.47292
Case 22	0.9	1500	0.003	41389.05	92.33771
Case 23	0.9	1500	0.004	39529.74	91.93848
Case 24	0.9	1500	0.006	35354.06	90.96879
Case 25	0.9	1700	0.003	72239.19	97.17546
Case 26	0.9	1700	0.004	70927.65	97.01631
Case 27	0.9	1700	0.006	60261.08	95.60074

RESULTS



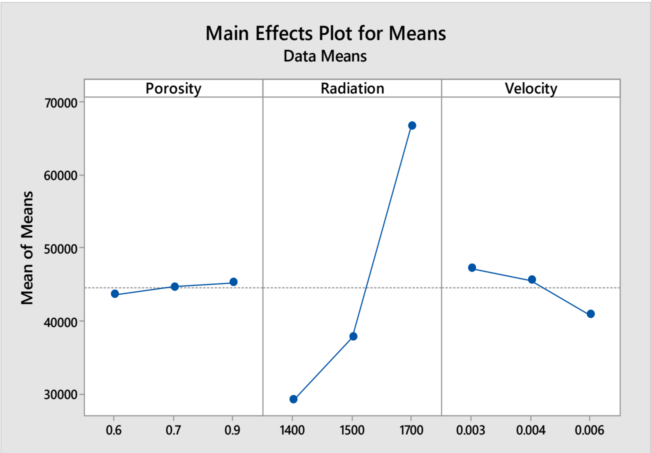


Fig. (a)S/N Ratio Graph (b)Mean Ratio Graph

Level	Porosity	Radiation	Velocity
1	92.23	89.29	92.91
2	92.48	91.52	92.62
3	92.55	96.46	91.73
Delta	0.31	7.17	1.18
Rank	3	1	2

Prediction

When porosity is 0.9 radiation is 1700 K and velocity is 0.003 m/s

Predicted value

Porosity	Radiation	Velocity
0.9	1700	0.003

Predicted value S/N Ratio

S/N Ratio
97.17546

Analysis of variance (ANOVA) is a statistical technique that is used to check if the means of two or more groups are significantly different from each other. ANOVA checks the impact of one or more factors by comparing the means of different samples.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Porosity	2	0.488	0.19%	0.488	0.244	2.42	0.115
Radiation	2	242.303	96.29%	242.303	121.151	1200.50	0.000
Velocity	2	6.820	2.71%	6.820	3.410	33.79	0.000
Error	20	2.018	0.80%	2.018	0.101		
Total	26	251.629	100.00%				

DF - degrees of freedom, SS - sum of squares, MS - mean squares (Variance), F-ratio of variance of a source to variance of error, $P < 0.05$ - determines significance of a factor at 95% confidence level.

CONCLUSION

In the present study CFD analysis along with tagauchi optimization is performed. Firstly 27 different cases with varying values of porosity, Solar intensity and inlet velocity were considered. Further CFD analysis was performed to find the output in different cases depending on these cases further the parameters were optimized using tagauchi optimization technique. From the complete analysis procedure it is observed that the best result is seen for total heat transfer ratewhich is seen in the case if the porosity is 0.9, solar intensity is 1700 K and inlet velocity is 0.003m/s. after performing taguchi method the model is further validated with new input parameter in ANSYS for cfd analysis and total heat transfer rate is calculated. The maximum heat transfer rate obtained is 72239.19 W when porosity is 0.9, solar intensity is 1700 K and inlet velocity is 0.003m/s. Thus from the this study optimized parameter for thermochemical reactor can be further used for the future industrial purposes to obtain the highest level of efficiency.

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