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A Review on Thermal Transport and Fluid Flow in High-Temperature Porous Media Solar Thermochemical Reactor

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Abstract – At the present time, a high-temperature focused solar-driven thermochemical reacting system for hydrogen and syngas production has been an effective different to fossil fuels to tackle energy problems and climate change. The research and development of concentrated solar radiation utilization as a heat source to induce high-temperature raw materials conversion into fuels accessible has attracted tremendous interests worldwide. Integrating porous media in the solar reactor has become the concentration in current years for the thermal performance improvement of solar thermochemical reacting system. 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.

Keywords: Solar Thermochemical, Thermal Transport and Fluid Flow, Thermophysical Models, Porous Media, User-Defined Functions

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1. INTRODUCTION

Thermochemical processes, and specifically those processes that involve heterogeneous solid–gas thermochemical looping of metal oxides, are vital technologies with relevance to several analysis fields and industries. Thermochemical reactions are characterized by a significant change in enthalpy and high thermal effects accompanying the reaction. Chemical processing and commodity production industries feature many heterogeneous thermochemical reactions. Thermochemical looping or cycling refers to processes featuring multiple thermochemical reactions occurring sequentially and the cyclic production and reaction of intermediary compounds. The combination of reactions sequentially results in a desired overall reaction. Thermochemical looping systems have the potential to drive the overall reaction more energy efficiently and with less irreversibility than other industrial methods, leading to higher energy efficiencies and more economical processes. One developing field of thermochemical processing is focused solar thermochemistry, in which focused solar thermal energy is utilized to drive thermochemical processes. Calcium oxide-based thermochemical looping is a two-step thermochemical looping system being investigated for use with concentrated solar thermal energy for the applications of carbon dioxide (CO2) capture and high-temperature thermal energy storage (TES) (Bellouard, et. al., 2017).

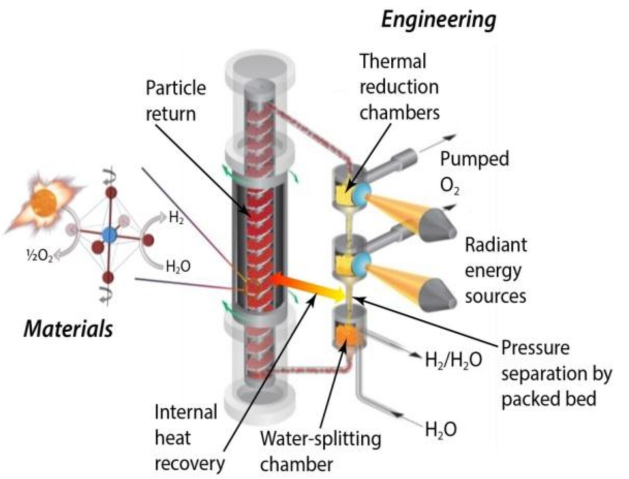

Figure1 Solar Thermochemical Reactor for Hydrogen Production

Solar radiation has immense potential to meet future energy needs. In addition to being abundant and unlimited, it has high energy content and can be collected with little risk to the environment. However, solar radiation arrives on earth with low energy flux, is intermittent, and is inconveniently distributed in locations of low population density. In one approach to address these challenges, solar radiation is concentrated to high fluxes and captured in solar receivers to provide high temperature process heat, addressing the challenge of low flux. Multiple, mature technologies exist for concentrating solar radiation to ratios from one-hundred to several thousand. The process heat is used to drive chemical reactions producing fuels which are stored for use as needed, addressing intermittency, and transported to desired locations, addressing the challenge of an inconvenient distribution. One potential fuel is syngas, a mixture of H2 and CO produced by splitting H2O and CO2. Syngas can be processed using gas-to-liquid technologies such as Fischer-Tropsch processes, to yield liquid hydrocarbons such as gasoline, diesel fuel, or kerosene. The only energy source of the overall process is concentrated solar radiation and the only feed stocks are H2O and CO2. The liquid fuels are compatible with existing infrastructure, enabling renewable solar energy to be used in place of fossil-derived fuels, even for the high demand of mobile applications (Steinfeld and Palumbo, 2001).

2. LITERATURE SURVEY

(Zhang et al., 2018) [1] thermal transport and fluid flow in high-temperature porous media solar thermochemical reactor were investigated by considering totally different thermophysical models. The numerical simulation was performed using FLUENT software system with user-defined functions. Moreover, totally different cases, as well as LTNE model, radiation model, momentum supply term model, heat transfer model, and also the impact 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. The results from this study might give valuable references for the analysis on high temperature porous media solar thermochemical reactors. The conclusions are drawn as follows:

(1) The typical temperature deviation between LTE and LTNE will increase by nearly 10 times with the increase within the rate from 0.005 to 0.5 m/s. LTNE model might guarantee the accuracy of simulation under traditional speed and high-temperature conditions.

(2) Radiative heat transfer plays a major role within the method requiring high-temperature operational conditions.

(3) The porous media has positive effects on providing massive specific surface areas and increasing the uniformity of temperature and velocity distribution within the reacting medium.

(4) Judgment from the pressure drop, Wu model is nearer to the real under the present conditions.

(5) Wu model and Vafai model exhibited similar trends of temperature distribution. A significant increase within the fluid part temperature was observed with Wu model and Vafai model compared to Hwang model for higher values of the cell sizes of porous media.

(Bellouard et al., 2017) [2] A combined drop tube/packed bed solar reactor was with success operated for the gasification of wood biomass at high temperature. The influence of various parameters like temperature (1000-14000C), sort of biomass (unprocessed, dried, torrefied) and oxidizing agent (H2O, CO2) on the syngas production and composition was evidenced. The gas yields, especially for H2, were improved by increasing the temperature in the reactor. The CH4 concentration was reduced as well as the amount of secondary hydrocarbons (C2H2) when increasing the temperature, while the amount of H2 was enhanced. The advantage of using steam as gasifying cause and hydrogen supporter on the produce of syngas was highlighted. The possibility of using this solar reactor for continuous gasification was successfully demonstrated with wood biomass. High carbon conversion rates, up to 93.5%, were reached during such continuous solar runs. Material mass balances proved that the syngas mass is superior to the initial feedstock mass due to the addition of water. Finally, cold gas efficiency (solar upgrade factor) up to 1.21 was achieved, and most solar-to-fuel energy conversion efficiency of 28% was reached with wood biomass at 14000C. The results obtained throughout this experimental solar campaign are used to style a unique high-temperature solar reactor conception for continuous biomass gasification throughout extended on-sun operation.

(Diver et al., 2017) [3] Solar hydrogen production from water by the utilization of solar driven two-step thermochemical cycles is probably an alternate to fossil fuels. Recognizing that thermochemical cycles are heat engines that convert thermal energy into energy and are, therefore, analogous to mechanical work producing machines, we have planned a new kind of heat engine. As in Stirling and Ericsson cycle mechanical work producing counterparts, counter-current recovery of sensible heat within the cycle is essential to high efficiency within the CR5. Investigations of the efficiency potential of the CR5 conception recommend solid-to-solid counter-current recuperation will be effective which the cycle will probably be efficient. Moreover, recuperation mitigates the necessity for complete reaction extent and permits the utilization of a support for the ferrite operating material. These investigations additionally suggest that the underlying thermodynamically properties of the iron oxide redox materials are marginal at the temperatures dictated by materials which variety of schemes can probably be needed to compensate. These include adjusting the redox thermodynamics by work different metals for iron within the spinel; taking advantage of solid-gas reactions by continuous removal of the product gases; and effectively lowering the product gas partial pressure by counter-current sweeping. Like different engines, the CR5 involves various style problems and tradeoffs. It places extraordinary demands on materials and involves high-temperature moving components. Additionally, the CR5 should be designed and operated to avoid crossover through the recuperator. Within the method of evaluating materials for the CR5 heat engine, we have developed a new kind of reactant material during which ferrite particles are spread during a monolithic zirconia structure. These materials seem to enhance and maintain reactivity and kinetics, yet as offer the structural support required within the CR5 heat engine. To determine the practicality of the CR5 conception, we tend to are through an experiment evaluating materials, exploring the thermodynamic style area, and evaluating fluid flow at intervals the device. Given the potential, uncertainties, and results so far, we've got decided to style, build, and test a prototype device. If suitable materials will be developed and also the design challenges will be met, the CR5 heat engine conception appears to supply an integrated approach for probably efficient and low-priced solar hydrogen.

(Torabi et al., 2017) [4] In recent years, the interest in second law analyses of porous thermal and thermochemical systems has increased. a good deal of attention has been paid to the LTNE model of porous media, as this model will a lot of accurately present the energetic and exergetic performances of the system. Although an oversized range of investigations on entropy generation in porous media under LTNE condition exist, several systems didn't receive adequate attention. These often include those systems that feature extra physicochemical effects. For example, so far, the effects of magnetic field and radiation heat transfer have not been considered in conjunction of LTNE model. Moreover, there's presently just one study that accounts for the impact of temperature jump and its direct impact on the entire entropy generation in small porous channels. There has been additionally very limited work on entropy generation investigation in with chemicals reactive porous media. As mentioned in Section three of this review, though many published studies have thought-about LTNE condition to simulate entropy generation in chemically reactive porous systems, only one of them has considered LTNE model together with chemical kinetics.

(Wheeler et al., 2017) [5]. reviews the progress, challenges and opportunities in numerical modelling of thermal trans- port, thermochemical reactions and thermomechanics in high-temperature solar thermochemical systems. Continuum-scale models are presented in mathematical detail whereas highlights the literature that uses them. The discussion is increased by selected samples of numerical studies of solar thermo- chemical systems for solar fuels and commodity material production. Property predictions necessary for the modelling of solar thermochemical reaction systems are covered.

(Li et al., 2016) [6]. A transient heat transfer model is developed for high temperature solar thermochemical reactors by coupling the Monte-Carlo ray tracing primarily based} radiation model with the thermal lattice Boltzmann technique based convection-diffusion model. Detailed simulation results are conferred for the heating method and therefore the first reduction step during a novel 10 kilowatt solar reactor style that consists of a horizontal cavity-receiver, a windowless aperture, an array of 14 tubular absorbers, and three layers of insulation. The solar-to-fuel efficiencies are predicted, and also the values on the order of 5¡0% are realizable with the current reactor design. The specified temperatures and O2 partial pressures are moderately realizable. The present model is a basis that may be extended to model the oxidation step and therefore the redox cycling. Supported the current reactor style, a nominal 10 kw solar reactor has been fabricated and is presently below experimental testing at the University of Florida. Comparisons of the modeling results with experimental tests will be reported in future add terms of the temperature evolution and O2 and CO/H2 production.

(Wang Fuqiang et al. 2014) [7]. Heat transfer performance analyses of porous media solar receiver are investigated by combining the MCRT methodology and Fluent software system with UDFs. The MCRT methodology is employed to get the heat flux distribution on the fluid entrance surface of porous media solar receiver. The irradiative heat transfer between the porous media strut is solved by each the P1 approximation and Rossel and approximation via UDFs within the Fluent software system. The subsequent conclusions are drawn:

(1) The maximum temperature difference between the modified P1 approximation and Rosseland approximation is 4.97%, the variation of irradiative heat transfer models has very little impact on the temperature distribution of porous media solar thermochemical receiver.

(2) The maximum solid phase and fluid part temperature for the changed P1 approximation condition is above that for the Rossel and approximation condition.

(3) The solid phase and fluid part temperature variations between changed P1 approximation and Rosseland approximation conditions disappear at high optical thickness with higher fluid velocities.

(4) The consistent temperature distribution development between completely different irradiative heat transfer models at high optical thickness began to disappear with the increasing of solar irradiance and mean cell size.

(5) The lower fluid inlet speed induces higher relative temperature distinction at the fluid outlet surface between the changed P1 approximation and Rosseland approximation conditions.

(Tan Jianyu et al. 2014) [8]. The heat transfer performance of porous medium receiver with quartz window is numerically studied. With the aim to be a lot of according to application, the temperature distribution of porous medium receiver model with fluid inlet set at the aspect wall is compared with the condition of fluid inlet set at the front surface. The planoconvex quartz window is introduced with the aim to attenuate the thermal stress of porous medium receiver. The subsequent conclusions are drawn.

(1) With the introducing of Plano-convex quartz window, the height heat flux magnitude on the front surface of porous medium receiver decreases and also the image radius will increase to stay energy balance.

(2) The pressure distribution similarly because the temperature distribution for the condition of fluid inlet set at the aspect wall is extremely completely different from that for the condition of fluid inlet set at the front surface.

(3) Because the flow mass rate is kept unchanged, the solid section temperature of the porous medium receiver will increase with porosity increasing within the same position.

(Fuqiang Wang et al. 2013) [9]. The thermal performance of porous media receiver was investigated by combining the MCRT technique and FLUENT software system with UDFs. The MCRT technique was used to get the heat flux distribution on the fluid inlet surface of porous media receiver. The LNTE model with Rosseland approximation was used to investigate the temperature distributions. The following conclusions are drawn:

1. Heat flux distribution features a robust impact on the temperature distribution. the most temperature for non-uniform heat flux distribution boundary condition is 1372 K, and also the most temperature for uniform heat flux distribution boundary condition is 1287 K.

2. The radiation heat loss on the fluid inlet surface cannot be neglected throughout the thermal performance analysis of porous media receiver.

3. The maximum temperature of solid section and thickness of thermal non-equilibrium region will increase with body increasing.

4. The most temperature of solid phase and equilibrium temperature decreases with the increasing of flow mass. The temperature variations between the solid phase and fluid phase will increase on the thermal non-equilibrium region with the increasing of flow mass.

5. The temperature of solid phase decreases with the emissivity increasing. The maximum temperature of the solid phase increases with the particle diameter increasing.

(Richard B. Diver et al. 2006) [10]. Solar H production from water by the utilization of solar driven two-step thermochemical cycles is probably an alternate to fossil fuels. Recognizing that thermochemical cycles are heat engines that convert thermal energy into energy and are, therefore, analogous to mechanical work manufacturing machines, we've got formed a new kind of heat engine. As in Stirling and Ericsson cycle mechanical work manufacturing counterparts, counter-current recuperation of sensible heat within the cycle is vital to high efficiency within the CR5. Investigations of the efficiency potential of the CR5 idea suggest solid-to-solid counter-current recuperation is effective which the cycle will probably be efficient. Moreover, recuperation mitigates the requirement for complete reaction extent and permits the utilization of a support for the ferrite working material. These investigations additionally suggest that the underlying thermodynamically properties of the iron compound redox materials are marginal at the temperatures determined by materials which variety of schemes can in all probability be needed to compensate. These include adjusting the redox physical science by substituting different metals for iron within the spinel; taking advantage of solid-gas reactions by continuous removal of the product gases; and effectively lowering the product gas partial pressure by counter-current sweeping.

3. REACTOR

To realize high fuel production rates in a single reactor for non-stoichiometric redox cycling, vastly differing conditions of temperature and atmosphere must exist for the reduction and oxidation steps. Prior prototype reactor designs have attempted to address this requirement in various ways. One prototype operated the steps sequentially in the same cavity receiver lined with reactive material, achieving efficiencies of 0.4% and 1.7% using different morphological structures of ceria]. This design, however, requires that the solar radiation not be used during the oxidation step. A similar approach is to operate multiple reactors sequentially but in alternating states, so that one is always using the solar resource. This approach requires the construction of at least two complete reactors and a system for moving the reactors or the focal point of the concentrated solar energy. An alternative solution is to place the metal oxide on a rotating structure which passes through zones of differing conditions, creating a single reactor to run both steps continuously. This method has been demonstrated in multiple reactors (Bellouard, et. al., 2017).

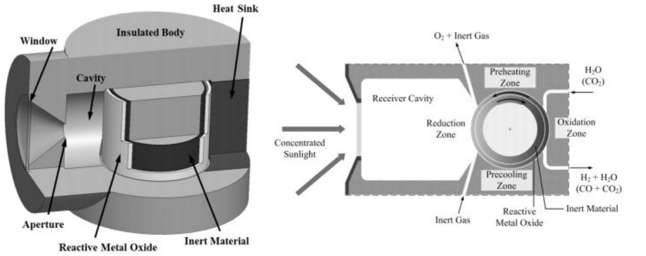

Figure 2 Reactor for solar-driven non-stoichiometric redox cycling of a metal oxide

The reactor consists of a horizontal cylindrical chamber (0.035 m i.d. and 0.044 m long) that contains the porous ceramic structure (Fig. 3). The front of the device is directly irradiated by concentrated solar power provided by a solar furnace consisting of a sun-tracking heliostat and a two m-diameter parabolic concentrator (85 cm focal length, 120° aperture, maximal power of 1.4 kW delivered at the focus, Gaussian flux density distribution). The lateral walls of the foam are surrounded by an insulator and a hemispherical glass window separates the system from the close air to produce a controlled atmosphere within the chamber. A flow of inert gas (nitrogen) enters by the front of the receiver, flows within the porous foam and sweeps the gaseous product species out of the chamber (Li, et. al., 2016).

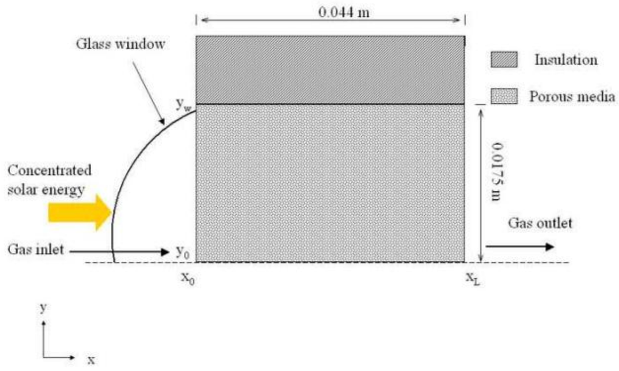

Figure 3 Cross-section sketch of the solar reactor

4. POROUS MEDIUM

A porous medium (or a porous material) could be a material containing pores (voids). The skeletal portion of the material is commonly referred to as the “matrix” or “frame.” The pores are usually filled with a fluid (liquid or gas). The skeletal material is sometimes a solid; however structures like foams are typically also usefully analyzed using idea of porous media. A porous medium is most frequently characterized by its porosity. different properties of the medium (e.g., permeability, tensile strength, electrical conductivity) will generally be derived from the various properties of its constituents (solid matrix and fluid) and therefore the media porosity and pores structure, however such a derivation is sometimes complex. Even the idea of porosity is simply easy for a pyroclastic medium (Wang, et. al., 2014). Several natural substances like rocks and soil (e.g., aquifers, petroleum reservoirs), zeolites, biological tissues (e.g., bones, wood, cork), and man-made materials like cements and ceramics will be thought-about as porous media. Several of their necessary properties will only be rationalized by considering them to be porous media. The idea of porous media is employed in several areas of applied science and engineering: filtration, mechanics (acoustics, geomechanics, soil mechanics, rock mechanics), engineering (petroleum engineering, bio-remediation, construction engineering), geosciences (hydrogeology, petroleum geology, geophysics), biology and biophysics, material science, etc. Fluid flow through porous media could be a subject of most typical interest and has emerged a separate field of study. The study of additional general behavior of porous media involving deformation of the solid frame is named poromechanics (Wang, et. al., 2013).

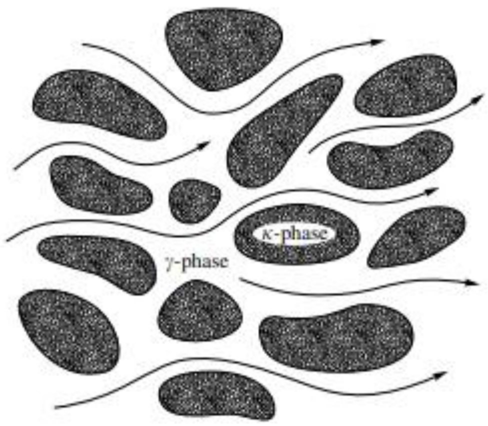

Figure 4 Transport in a rigid porous medium

5. CONCLUSION

Based on the review study has carried on the research breakthrough to the Analysis of thermal transport and fluid flow in high-temperature porous media solar thermochemical reactor, As a key technical indicator of porous media solar thermochemical reactor, thermal transport and fluid flow characteristics have vital impacts on hydrogen production efficiency. These problems could be achieved a lot of with efficiency and at a lower cost by applying computational fluid dynamics (CFD). It includes different research papers are surveyed related to the solar thermochemical reactor.

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