Application of Concentrated Solar Radiation to Chemical Looping Combustion

Seyed Mehdi Jafarian

Thesis submitted for the degree of Doctor of Philosophy

School of Mechanical Engineering

Faculty of Engineering, Computer & Mathematical Sciences

The University of Adelaide, Australia

March 2014

Table of contents

Abstract

The novel concept of the application of the Oxygen Carrier (OC) particles in a Chemical Looping Combustion (CLC) system for diurnal storage of the concentrated solar thermal energy is presented here. Two innovative configurations of Hybrid Solar CLC (Hy-Sol-CLC) systems for continuous base-load power generation are proposed and assessed. The systems seek to take the key features of a CLC system that are desirable for a hybrid solar GTCCs; notably the production of an industrially pure stream of CO_2, inherent chemical and sensible heat storage, relatively low temperature of the fuel reactor relative to that of the air reactor and the potential to operate the fuel and air reactors at different pressures.

In the first proposed configuration, three reservoirs have been added to a conventional CLC system to allow storage of the OC particles, while a cavity solar receiver has been chosen for the fuel reactor. In this Hy-Sol-CLC system the flow rates of the fuel and OC particles were considered to be constant. The calculations demonstrated that the solar thermal energy can be stored using CLC components. However, this configuration is limited to a low solar share of about 6.5% when averaged over the whole day. Besides, the variations in fuel reactor temperature, owing to the diurnal variations of the input concentrated solar thermal energy, might result in damage to the OC particles.

The second Hy-Sol-CLC system addresses the limitations associated with the first configuration. In this system, as for the first one, a cavity solar reactor has been chosen for the fuel reactor while two reservoirs have been added to a conventional CLC for the storage of OC particles. A direct air-particle heat

exchanger has been also proposed to provide independent control of the temperature of the OC particles in the air reactor from those stored in the storage reservoirs. In this process the operating temperature of the solar fuel reactor is controlled through varying the flow rates of fuel and OC particles proportional to the variations in the input concentrated solar thermal energy. This hybrid cycle is estimated to achieve a solar share of up to 60% when averaged over the whole day. The performance of this hybrid system in a GTCC cycle was evaluated with and without the application of an after-burner. The after-burner was added to further increase the gas turbine inlet temperature. The calculations predict a first law efficiency of 50.0% for the cycle employing the after-burner, compared with 44.0% for that without the after-burner. However, this higher thermal efficiency is achieved at the cost of decreasing the solar share from 60.0%, without the after-burner, to 41.4% with it.

Applicability of the combinations of natural gas, CO and H_2, as fuel with the oxides of Co, Cu, Fe, Mn and Ni, as oxygen carriers in the proposed Hy-Sol-CLC system was also evaluated. The calculations demonstrated that, from all of the assessed metal-based oxygen carriers, only the pairs of CoO/Co, NiO/Ni and Fe_2O_3/Fe_3O_4 are potentially suitable for use in a Hy-Sol-CLC system working with natural gas. However, none of these materials allow any significant chemical storage of solar energy for the oxidation of CO and H_2.

An unsteady-state model of an OC particle exposed to high intensity solar heat flux was also developed to provide the fundamental knowledge required for the selection of an efficient solar cavity reactor for the Hy-Sol-CLC systems. The model was validated against the available data in the literature. The numerical analysis demonstrated that the application of direct heat transfer is desirable. However, it must be combined with a high convective cooling to avoid excessive heating rates, which would result in overheating of the particles.

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

I give consent to this copy of my thesis when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968.

The author acknowledges that copyright of published works contained within this thesis resides with the copyright holder(s) of those works.

I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library Search and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

Seyed Mehdi Jafarian   Date

Acknowledgment

I would not have been able to complete this journey without the aid, support and contribution of many people.

I would firstly like to acknowledge the support given to me by my supervisors Dr. Maziar Arjomandi and Professor Graham (Gus) Nathan who helped me in all time of my research and writing of this thesis. I thank Dr. Arjomandi for his patience, support and guide through up and down times of my PhD thesis. I thank Prof. Nathan for his motivation, enthusiasm, immense and comprehensive knowledge in the field of energy and combustion which were essential for my understanding and development of the proposed hybrid CLC system.

I would like to acknowledge Adelaide Scholarship International (ASI) for their financial support. I would also like to thank the current and former staffs of the School of Mechanical Engineering and Centre for energy Technology (CET).

I am deeply and forever indebted to my parents who are passed away. I am also extremely grateful to my brothers, Hadi and Mohammad and my lovely sister, Sara, and my Aunts specially, Homa Seraj, and my Uncles specially, Mahmood Jafarian, whose love and support led me to this point.

Finally, I would like to express my special gratitude and thank to Pegah for being the most loving, patient and understanding wife for over this long period.