THE UNIVERSITY of ADELAIDE

Simulating High Flux Solar Radiation and Assessing its Influence on a Sooty Flame

Xue Dong

BEng

Thesis submitted for the degree of Doctor of Philosophy

School of Chemical Engineering

Faculty of Engineering, Computer & Mathematical Sciences

The University of Adelaide, Australia

September 2015

Table of Contents

ABSTRACT

Integrating concentrated solar thermal energy into fossil-fuels for the production of power/clean fuels is receiving growing attention as the combination of the two energy sources can provide lower emissions of carbon and other pollutants, lower cost, and continuous supply. Various types of hybrid concepts have been proposed. However, all of these concepts employ stand-alone solar receivers and standalone combustors. The University of Adelaide has developed an alternative approach with which to fully integrate a combustor into a solar cavity receiver. This offers the potential for significant savings from reduced infrastructure investment and reduced start-up and shut-down losses. In addition, this hybrid also results in the direct interaction between concentrated solar radiation and a flame, which is theoretically known to be coupled. However, the influence of concentrated solar radiation (CSR) on the flame has not been experimentally investigated. Hence this thesis aims at filling this gap.

High flux solar simulators, comprising an array of high-intensity-discharge lamps coupled with elliptical reflectors, have been widely employed to study concentrated solar thermal energy systems. The use of electrical solar simulators holds the advantage over natural solar radiation in providing repeatable performance without the variability of the solar resource. Reliable models which predict the heat flux generated by a solar simulator are desirable because they enable efficient and systematic optimization of the system to meet the required trade-off between cost and performance. To this end, a concentric multilayer model of the light source is developed in this study to accurately predict the spatial distribution of the heat flux at the focus using a commercial Monte Carlo ray-tracing code. These simulations were validated with measurements of both the radiant intensity of the light source and the distribution of the concentrated heat flux. Further to that, on the experimentally validated ray tracing model, the geometry and surface reflectance of the additional concentrators were also assessed of two high flux solar simulators: one employs a single lamp, the other uses a seven-lamp array. In addition, the time-resolved spectra of solar simulators employing a metal halide and a xenon arc lamp are also measured, which provides the first

experimental results of this kind that acquired from the same spectrometer to allow for direct comparison.

This thesis also reports the first set of measurements of the influence of concentrated solar radiation on the soot volume fraction and temperature in a laminar sooty flame. Detailed laser diagnostics was performed on a laminar sooty flame with and without the irradiance of CSR, because laser diagnostics are demonstrated to hold the advantages of being non-intrusive, lower interferences and of being applicable to environments with high flux radiation. The current measurement using laser induced incandescence shows that the soot volume within the laminar flame was increased by 55% by CSR. In addition, the measurement of temperature using two-line atomic fluorescence shows that the flame temperature was increased by around 8% under CSR.

In addition to the detailed laser diagnostics, an assessment of the influence of soot volume fraction on the global performance of the flames was also performed through a systematic study of flames using fuels of different soot propensities, which is achieved by blending hydrogen into hydrocarbon fuels, with hydrogen volume fraction ranging from 0 to 100%. Results show that flames with higher soot volume fraction have higher radiant fraction and lower NOx emissions.

The principle contribution of the thesis is that the first measurement of the influence of concentrated solar radiation on the soot volume fraction and temperature of a flame was performed, which pushed forward the existing understanding of the interaction between broadband solar radiation and combustion. Its second major contribution is establishing an experimentally validated ray-tracing model that accurately predicts the concentrated heat flux from the solar simulator, and on this model, new design and optimization of solar simulators were performed. While this ray-tracing model is developed for metal halide lamps, the methodology is applicable more generally to solar simulators employing other types of discharge arc lamps.

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

16/01/2016

Xue Dong DATE

ACKNOWLEDGEMENT

The completion of this thesis would not be possible without many people and organizations' support.

First of all I want to acknowledge my supervisors, Professor Peter Ashman, Professor Graham (Gus) Nathan and Associate professor Zeyad Alwahabi. I thank Peter for his patience in assisting me to find the research topic I am interested in, and his very detailed instructions to me about what to do in every stage of the PhD program. I thank Gus for involving me into this exiting solar-combustion hybrid project, and for contributing and sharing his knowledge and insight in combustion and concentrated solar thermal engineering, which is critical to form my understanding of the fundamental mechanism of this study. I thank Zeyad for ensuring a safe laser lab for everyone to work in, and for many informative discussions about influence of solar radiation on combustion.

I would like to acknowledge the Australian Research Council for providing financial support to this project through Linkage funding. Partial of the work was also funded by the Australian Government through the Australian Renewable Energy Agency (ARENA), which is gratefully acknowledged. I also want to thank the China Scholarship Council and the University of Adelaide, which jointly provides the scholarship for my PhD program.

I would like to thank Dr Zhiwei Sun and Mr Dahe Gu for the great cooperation in the lab work and for many productive discussions during the course of this investigation. I would like to thank Professor Aldo Steinfeld from ETH Zurich and his research team for sharing the optical design procedure of their solar simulator. I would also like to thank the workshop staff Jason Peak and Garry Clarke for constructing the solar simulator employed in this work.

I would like to thank all my friends Qing fang, Peijun Guo, Houzhi Wang, Hanci Jiang and Shannon MacManus for their help, support and company. You are amazing friends, who stay with me through this challenging journey, which makes our friendship glamorous even in the darkest nights.

I would not be able to make this long journey without the support and understanding of my family: my Mum, despite of her initial opposition of me flying to the other end of the world to pursue the next stage of my life, has been supporting and cheering me up all the way since I started; my Dad, who is always encouraging me to fulfil my dreams, has on the other hand been worried about my well-being and keep reminding me to be safe and maintain a healthy lifestyle, which benefits me a lot during this work-intense period; and my sister, to whom I talk about everything, has been a wonderful listener and wise advisor and accompanied me all the way through from the other end of the world; and my nephew Hanbo, who has been a very considerate kid and patiently waiting for me to go back home and bring him snacks, even though I didn’t show up for a few years. Thank you for your amazing support!

PREFACE

This thesis is submitted as portfolio of publications according to the “Specifications for Thesis 2014” of the University of Adelaide. The journals of which the papers were published or submitted are highly ranked journals in the research field of Chemical Engineering. Data on the impact factors of the journals are listed below:

Journal Title	5-year Impact Factor
Combustion and Flame	3.557
Solar Energy	4.452
Journal of Solar Energy Engineering	1.934

The main body of work contained in this thesis consists of the following five journal papers:

1) **X. Dong;** G. J. Nathan; Z. W. Sun; D. H. Gu; P. J. Ashman, “Concentric multilayer model of the arc in high intensity discharge lamps for solar simulators with experimental validation”, Solar Energy, (2015), acceptted.

2) **X. Dong;** Z. W. Sun; G. J. Nathan; P. J. Ashman; D. H. Gu, “Time-resolved spectra of solar simulators employing metal halide and xenon arc lamps”, Solar Energy 115 (2015) 613-620.

3) **X. Dong;** G. J. Nathan; Z. Sun; D. Gu; P. J. Ashman; Z. Alwahabi; B. Dally, “The influence of high flux broadband irradiation on soot concentration and temperature of a sooty flame”, manusctript under prepartion for Combustion and Flame.

4) **X. Dong;** G. J. Nathan; S. Mahmoud; P. J. Ashman; D. Gu; B. B. Dally, “Global characteritics of non-premixed jet flames of hydrogen-hydrocarbon blended fuels”, Combustion and Flame 162 (4) (2015) 1326-1335.

5) **X. Dong;** G. J. Nathan; Z. W. Sun; P. J. Ashman; D. H. Gu, "Secondary concentrators to achieve high flux radiation with methal halide solar simulators", Journal of Solar Energy Engineering, (2015), submitted.

Some additional aspects of this work were published in peer-reviewed conference papers. These are included as appendices.

A) **X. Dong**, Ashman, P.J., Nathan. G.J. "A high-flux solar simulator system for investigating the influence of concentrated solar radiation on turbulent reacting flows", Proceedings of Solar 2012, Australian Solar Council, Melbourne, 2012.

B) **X. Dong**; G. J. Nathan; Z. Sun; D. Gu; P. J. Ashman; Z. Alwahabi; B. Dally, "Influence of simulated solar radiation on the soot volume fraction in laminar sooty flames ", Proceedings of the10th Asia-Pacific Conference on Combustion, Beijing, China, 2015.

C) **X. Dong**; P. Ashman; G. Nathan "Global characteristics of hydrogen-hydrocarbon blended fuels turbulent diffusion flames", Proceedings of the Australian Combustion Symposium, Novermber 6-8, 2013, Western Australia.