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Research challenges in combustion and gasification arising from emerging technologies employing directly irradiated concentrating solar thermal radiation

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Abstract

We review the distinctive combustion-related research challenges that arise from new technologies under development to integrate combustion, gasification and pyrolysis technologies with concentrating solar thermal (CST) energy. Solar gasification and pyrolysis differ from autothermal gasification because the use of CST to drive the endothermic reactions results in different heating rates and gaseous atmosphere. We also review direct hybrid solar-combustion technologies, which integrate solar-receivers with combustors in the same device, to generate distinctive regimes of combustion. Reactions in these devices are subjected to fluxes of up to ~5 MW/m^2 (an order of magnitude higher than in most combustion systems) and wavelengths from the near-IR into the near-UV (whereas most practical systems are subject to predominantly IR irradiation). The broadband irradiation can excite a wide-range of gas-phase reactions in addition to influencing temperature through broad-band heating of soot or reacting particles. Such reactions are coupled non-linearly to the radiation and, in many cases, to the turbulent transport processes, which span a very wide range of temporal and spatial scales. The wavelength selectivity of lasers is also shown to offer the potential to isolate these phenomena, unlike broad-band irradiation, which drives them all simultaneously.

Keywords: Combustion; Solar thermal; Radiation-chemistry interactions

1. Introduction

Combustion and Concentrating Solar Thermal (CST) technologies are fundamentally complementary as two alternative sources of high temperature thermal energy. While CST has inherently low CO_2 emissions, but relies on an intermittent energy

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source, combustion harnesses stored chemical energy that allows it be used when it is required and encompasses the use of a wide range of fuels and technologies that offer a trade-off between the net cost and the net level of CO_2 mitigation. However, there are also a growing range of CST technologies under development that either employ combustion or gasification directly or which harness heat/mass transfer and/or reaction mechanisms to drive thermo-chemical processes that are highly synergistic with those employed in combustion, either for direct application in process heat or for energy storage. Furthermore, the role of CST is widely expected to increase in the future as the costs of solar concentrating technology are reduced through increased market penetration [1]. Hence there are many opportunities for further cost reductions through multi-disciplinary research that draws on expertise from both of these fields. The overall objective of the present review is to foster such developments.

Investment in the ongoing development of CST technologies continues despite the growing penetration and cost reductions in solar photovoltaic (PV) technologies because CST offers lower cost thermal energy storage, application in thermo-chemical processes and improved potential to hybridise [1]. However, despite their present rate of cost reductions, there remains a need to further lower the cost of these technologies. This, in turn, requires the development of more efficient technologies, which typically operate in more challenging regimes, together with the development of the new understanding and more reliable predictive capability that is needed to lower the cost of the scale-up of these technologies [1]. Among the most efficient devices are those that employ direct heat transfer to particles, since particles are efficient heat absorbers and direct irradiation avoids the exergetic losses of transferring heat through a wall [2–5]. However, new understanding is needed of interactions between Concentrated Solar Radiation (CSR) and chemical reactions, in both laminar and turbulent environments, to underpin the development of technologies that employ direct irradiation of combustion and gasification processes. The higher intensity and shorter wavelength of CSR relative to the radiation in conventional combustion systems means that these processes operate in regimes outside of the range where mechanisms have been explored previously. This, in turn, leads to both a lack of understanding and a high degree of uncertainty in the validity of presently available models. Hence the present paper seeks to review the types of technology in which these processes occur, assess the current status of understanding of the mechanisms present within them and identify useful methods that can be used to investigate these mechanisms further.

Concentrating solar thermal technologies employ mirrors to concentrate the direct solar radiation onto a central Solar Receiver, which is mounted on a tower. Of the range of solar thermal concentrating technologies have been developed [6], those of greatest interest owing to their greatest long term potential to lower cost is the central tower system [1,7]. These employ an array of “heliostats”, each of which supports one or more mirrors on a frame and is controlled with an automated tracking system, to reflect the radiation to the central receiver mounted on top of a tower. These systems can readily achieve fluxes of $\sim 1\ \mathrm{MW/m^2}$ and temperatures of ~1000 °C in demonstration-scale facilities, although commercial-scale systems are typically limited to about 600 °C, commensurate with the upper temperature of molten salts that are presently used to provide thermal storage [6]. An alternative technology is the parabolic dish concentrator, which has a higher optical efficiency that enables temperatures of ~1600 °C to be reached, albeit at a smaller scale than is possible with towers [6]. For both types of concentrator, the maximum ranges of temperature and flux at both the pilot and commercial scales is continuing to increase with ongoing development of solar concentrating systems. Hence solar concentrating systems are able to drive a wide range of thermo-chemical processes in addition to their application in power generation. Thermo-chemical process that have been demonstrated in the lab include gasification, [2], the thermal production of metals and minerals such as aluminium [8], lead [9], lime [10] and zinc [11]. In addition to offering low net CO_2 emissions, CST technologies offer potential to improve product quality by avoiding contamination of the chemical product with combustion products within the reactor and to increase the heating rate, which in turn can increase the rate of a reaction. However, chemical processes must also operate continuously and at steady state. This is difficult to achieve from thermal storage alone, not only because the storage requirements are 4 to 10 ten times larger than is currently achievable, but also because the heliostat field must be oversized by an order of magnitude to allow operation in periods of extended cloud [12]. This provides a driver for hybrid reactors that can operate with solar and/or combustion processes, in which case some periods of operation are likely to operate with both energy sources. The anticipated emergence of such hybrid reactors generates a need to understand the influence of high-flux radiation on combustion processes.

The significant interest in solar gasification raises the need to investigate the influence of solar radiation on soot. This is because, although the role of soot in solar gasification has received little attention directly, it is well established that soot is present under gasification conditions [13]. For example, the pyrolysis of biomass at high temperatures leads to secondary and tertiary reactions in the gas phase that converts tars into