Innovative Uses of Solar Thermal Technology

Rajiv Shekhar

Abstract Solar thermal technology (STT) is versatile as it can be used to simultaneously generate electricity, process heat, and cooling. Initially, the emphasis of STT was on, and rightly so, large-scale electric power generation. A significant proportion of worldwide energy consumption ($\sim$60%) is in the form of heat for domestic and industrial use, for which STT can play a very important role (De Decker in The bright future of solar thermal powered factories, 2011) [1]. Substantial progress has been made in supplying solar thermal heat for domestic uses through flat plate collectors and concentrators. Use of solar thermal heat for vapour absorption cooling has also made reasonable progress. Some examples do exist where solar process heat (80–650 °C) and solar steam is being used in industries ranging from dairy to automobiles to textiles to pharmaceuticals (De Decker in The bright future of solar thermal powered factories, 2011) [1]. However, industrial applications of high-temperature solar thermal process heat are still in a state of infancy. In this paper, we will focus on some of the innovative applications of STT.

1 Metals Processing Operations

Metals processing operations are perfect candidates for STT as they use enormous amounts of fossil fuel directly or indirectly as electricity. There are several examples of the use of STT as a source of heat for the production of metals, such as zinc, by the carbothermic reduction of their oxides [2]. Here solar absorption furnaces (SAF) have been used. In SAF, concentrated solar radiation from heliostats is directed on to the reactants through a cavity in the reactor. The operating temperature could be as high as 1300–1500 °C. Details of SAF can be found in [2]. SAFs are still at an experimental stage.

R. Shekhar (✉)
Department of Materials Science and Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India
e-mail: vidtan@iitk.ac.in

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One area where STT could be integrated with metals processing operations is metallurgical furnaces. One such example is an aluminium soaking furnace (ASF) where aluminium slabs are preheated to 600 °C for hot rolling. A schematic diagram of a 10 slab industrial ASF is shown in Fig. 1.

An ASF operates in a batch mode. The slabs are loaded on to a grid in the mid-section of the furnace. Electrically heated air is circulated to heat the slabs. The strategy for integrating the ASF with STT is shown in Fig. 2.

Hot air from an open volumetric air receiver (OVAR) based solar tower technology is used to supply hot air to the retrofitted ASF through a thermal energy storage system [2]. An existing ASF can be easily retrofitted by providing entry ports for hot air in the side sections and exit port(s) in the mid-section. The cooler exit air is sent back to the OVAR. Details of the OVAR design are given in [3]. During the day, the air temperature from the OVAR will vary in consonance with solar irradiance. Hence, a thermal energy storage system is used as a means to ensure that air at a constant temperature is continuously supplied to the ASF. A stand-by thermal energy storage system is also shown in Fig. 2. It would be best to operate the retrofitted ASF in a hybrid mode: solar heating would be the pre-dominant source during the day, while electrical heating gradually taking over with a decrease in solar irradiance. Some details of the retrofitted ASF design are given in [2].

Use of STT in aluminium smelting is another possibility. Aluminium smelters are electricity guzzlers. In India, most of the smelters have captive coal-based thermal power plants. STT can be hybridized with the existing thermal power plants. The STT cost, a major impediment, would be reduced by nearly 40% as it will share the existing plant's generator.

Solar thermal heat has also been used in electrolytic refining of copper at the Gaby mine in Chile since June 2013 [4]. A 27.5 MW_{th} solar thermal plant supplies 83% of the heat required to maintain the electrolyte temperature at 48 °C, and in the process significantly reducing fossil fuel consumption.

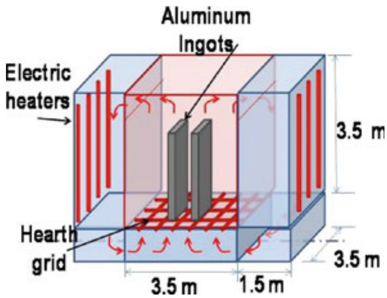

Fig. 1 A schematic diagram of a 10 slab industrial aluminium soaking furnace [2]. *Arrows* denote the flow of air in the furnace

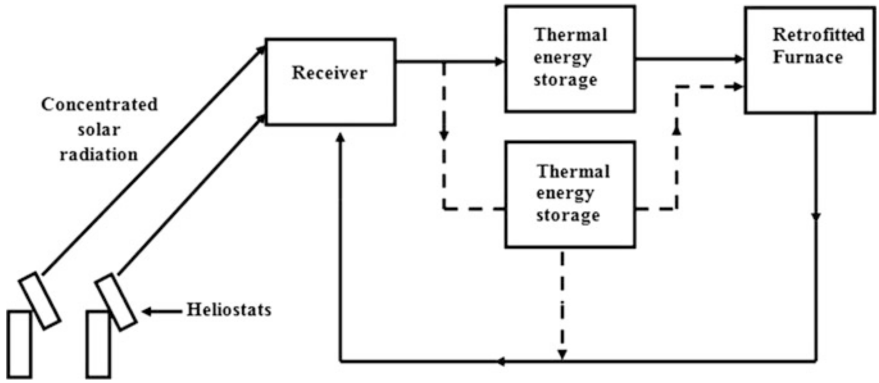

Fig. 2 Strategy for integrating solar thermal technology with a retrofitted ASF [2]

2 Solar Fuel Production

Solar fuel is a higher energy fuel which is produced from a lower energy resource such as natural gas or petroleum coke (PC) using solar energy. The additional energy comes from the "entrapment" of solar energy to form synthetic gas (syngas), which is a mixture of hydrogen and carbon monoxide. Both natural gas and petroleum coke undergo steam gasification reactions: (i) $CH_4 + H_2O = 3H_2 + CO$ and (ii) $C + H_2O = CO + H_2$.

Figure 3 shows an experimental petroleum coke reactor. It is in the form of a cylindrical cavity, 201 mm long, with an inside diameter of 120 mm [5]. The front opening of the reactor is covered by a quartz window to insulate the reactor from the surroundings. The reaction takes place in the region beyond the aperture. 142 μm PC particles and steam, both at 150 °C, were injected circumferentially at mass flow rates between 31–76 and 61–150 mg/s respectively. Heat for the endothermic reaction between PC and steam is provided by concentrated solar radiation, passing through the 50 mm aperture. The intensity of solar radiation varied from 1680 to 3360 kW/m^2 of aperture area. PC particles and steam formed a vortex with a residence time varying between 0.69 and 1.55 s. The reactor temperature varied from 1023 to 1545 °C. Syngas, along with the unreacted PC particles and steam, exited through a pipe at the back end of the reactor. In a single pass, 87% of the PC was converted into syngas. It may be pointed out that the low temperature steam required for gasification can also be produced by STT. Further details of the reactor are given in [5].

High temperature (750–850 °C) steam reforming of natural gas is a well-known industrial process to produce syngas. However, high temperatures and the non-continuous nature of solar irradiance had stalled the use of STT, which with the present technology can only give temperatures up to 550 °C. In addition to the steam-natural gas reforming (SNGR) reaction, the second reaction is the water-shift (WS) reaction, $CO + H_2O = CO_2 + H_2$, which takes place in the temperature range

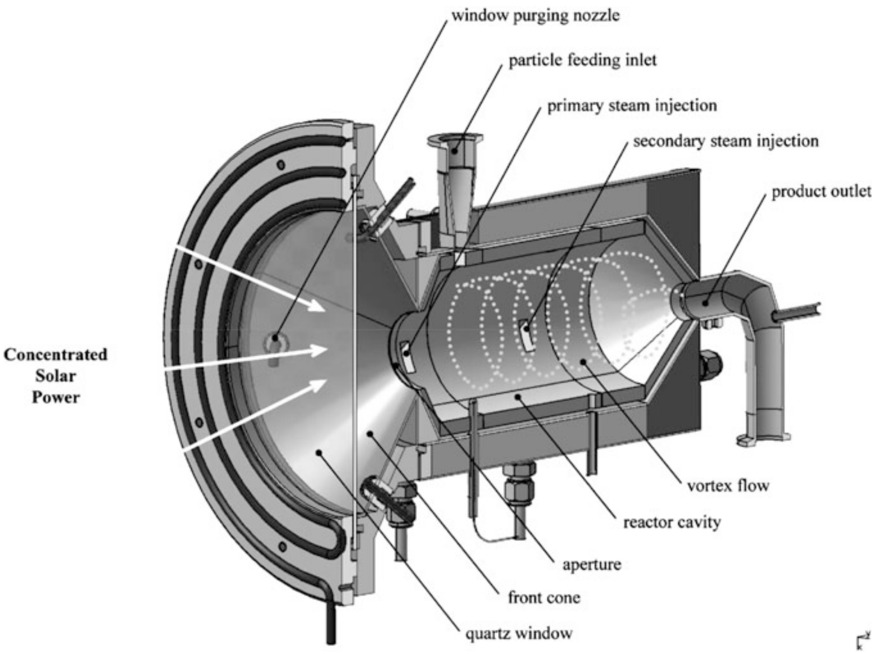

Fig. 3 Schematic diagram of a reactor used for the steam gasification of petroleum coke [5]

of 350–400 °C. Both reactions require catalysts for fast kinetics. Hence the trick was to somehow have appreciable natural gas reforming kinetics at a temperature less than 550 °C. Scientists at CSIRO used a membrane reactor [6], which in essence is a cylinder filled with catalysts, surrounded by a supported Pd membrane. Natural gas and steam are injected from one end of the reactor, which is heated through a counter-current hot air heat exchanger. The H_2 produced by the two reactions is absorbed by the Pd membrane, thereby driving both the SNGR and WS reactions to the right, and in the process significantly increasing their kinetics. CSIRO also developed two bimetallic CeO_2–La_2O_3-supported Cu–Cu-based catalysts, which showed greater activity than the Ni-based catalyst (for natural gas reforming) and Fe–Cr based catalyst (for water-shift reaction) 550 °C and 1 atm. Laboratory tests achieved a CH_4 conversion of 95%. Details of prototype reformer testing and integration with solar thermal energy are given in [6].

3 Enhanced Oil Recovery (EOR)

Global recoverable reserves of heavy and viscous crude oil amount to nearly 430 billion barrels. High viscosity, between 0.1 and 10 Pa s, is a major impediment to the recovery of these oils by conventional methods. Increasing crude oil temperature significantly reduces its viscosity making it easier to pump. Steam injection is the most common method of heating crude oil. In EOR, steam is pumped down the well into the oil reservoir. Oil is heated and pressurized, forcing it out of the well. In addition, in oil-bearing strata, where steam cannot penetrate by capillarity, the temperature of oil increases due to the conductive heating of the strata [7]. Either a part of the recovered crude oil or natural gas is the most important heat source for the generation of steam. However, both processes release greenhouse gas emissions, while simultaneously consuming valuable resources. Fortunately, much of the recoverable heavy crude oil is located in areas with high solar irradiance. Thus STT generated steam becomes a viable option for EOR, more so in places where the cost of natural gas is high. A solar steam demonstration project based on solar tower technology has been set up at Chevron's Coalinga field in California. With the help of one $\sim$100 m tall tower and 3822 heliostats, 60% quality steam is generated at 260 °C and 48.3 bar [7].

4 Thermoelectric Co-generation

Researchers at MIT have adapted the conventional parabolic trough collector (PTC) to come up with a system that simultaneously produces "generatorless" electricity and heat [8]. In a conventional PTC, the inner steel tube, which contains the thermic fluid, is coated with a solar selective coating with high absorptivity and low emissivity. The metal tube, in turn, is surrounded by a glass tube; the annular space between them contains vacuum to minimize convection losses. The adapted, MIT system is depicted in Fig. 4. The collector, inclined at an angle θ, consists of three concentric tubes, with the innermost tube containing the thermic fluid.

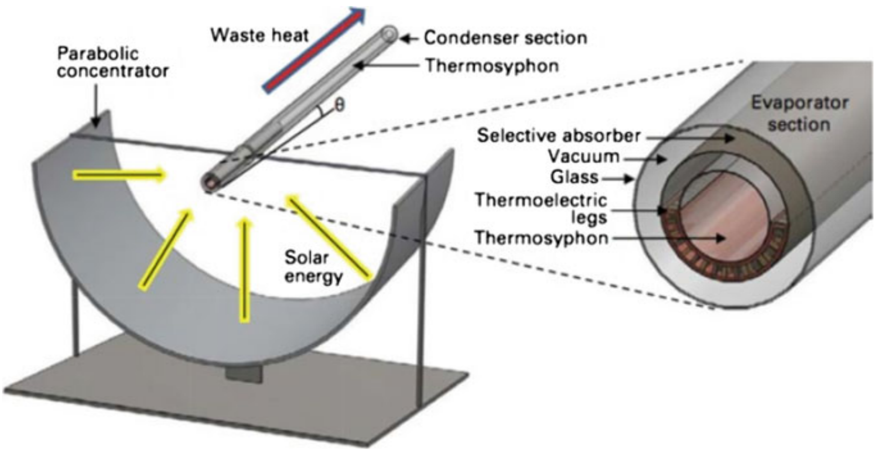

Fig. 4 A modified parabolic trough system for thermoelectric co-generation

The middle tube has a solar selective coating; its surface acquires the highest temperature on exposure to concentrated solar irradiance. A vacuum exists between the two outer tubes. Themoelectric (TE) devices fill the space between the two inner tubes with one leg in contact with the “hotter” central tube and the other in contact with the relatively “colder” innermost tube. The higher end of the collector extends beyond the width of the parabolic mirror; this end is relatively cooler as the solar radiation from the parabolic mirror does not fall on it. When concentrated solar radiation from the parabolic mirrors falls on the collector, the TE device generates electricity. Simultaneously, the thermic fluid is vapourized and the vapour flows towards the cooler, upper end, where it releases heat, condenses and flows down to the lower end by gravity. This process is continuously repeated, creating a thermosyphon. This system may be of great use for distributed co-generation.

5 Conclusions

STT is very versatile, which can simultaneously produce electricity, heating and cooling. In fact, the proportion of three outputs can, in principle, be changed depending on the requirements, like a three-way valve. There are other potential innovative uses of STT. Take the example of cold storages in India, which are largely located in semi-urban and rural areas where electricity supply is very erratic. Consequently, a significant proportion of India’s fruits and vegetables perish. A composite, self-compensating vapour absorption-compression system could be a possible solution. Despite the current high costs of STT, because of its versatility, I expect STT to form a significant proportion of the renewable portfolio in the near future. And if you add to it, doses of human ingenuity and innovation, sky would be the limit for STT.

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