DESIGN OPTIMIZATION AND OPTICAL CHARACTERIZATION OF A HIGH TEMPERATURE SOLAR RECEIVER

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Dedication

To my parents,
For teaching me the joy of learning,
The importance of education,
And preparing me for life after childhood

To my dear friend Mahamud for being supportive all the way

And

To all of my friends and family

For supporting and encouraging me through the past years

DESIGN OPTIMIZATION AND OPTICAL CHARACTERIZATION OF A HIGH TEMPERATURE SOLAR RECEIVER

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Abstract

Concentrated solar power (CSP) is a fast forwarding technology in power generation sector because of its' competitive price, abundance in nature and the most important fact is its' energy storage capability. Among the four types of available CSP technology, central receiver has more potential concerning with high temperature, power block efficiency and levelized cost of energy (LCOE). Other than conventional type of receiver design, the concept of this work is very particular in a sense of its design novelty.

National Renewable Energy Laboratory (NREL) come up with a new concept of high temperature solar receiver called near black body (NBB) receiver. This receiver design requires high specular reflective surface in its' front section at operating temperature 150ºC. High specular reflective surface refers to mirror finished surface. However, this specular reflective surface application is for high temperature solar receiver, the surface needs to be durable from thermal cycling, oxidation and environmental effect. This mirror finished specular surface helps to penetrate the sunlight inside the hollow tube and hence increase receiver's efficiency. But at such operating temperature and environmental condition, optical properties degradation rate is high. So to protect this mirror surface a thin layer of SiO_2 has been deposited by sol-gel method on top of electroplated silver coating. To obtain a rigid thin film structure, sol-gel procedure has been tested extensively by varying most dominant sol-gel parameters. Endurance test has been performed in the furnace at 150ºC for 1000 hours.

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Chapter 1: Introduction

1.1 CONCENTRATING SOLAR POWER

The limited supply of fossil fuel, the adverse impact of greenhouse emission on the global environment and the growing concern of climate change dictate the arising usage of renewable energy sources. Concentrated solar power (CSP) is the most potential renewable source of energy for solar to thermal or electric conversion because of its abundant resource. It satisfies most of the environmental issue as there is a small pollution compare to the coal power plant while generating electricity. Solar technology has a strong potential to meet our growing demand of energy and reduce dependence on fossil fuels. The amount of energy being consumed by us is only of energy being intercepted by earth [1].

Now-a-days CSP is a fast forwarding technology in power generation sector because of its concern to the climate change issues. 1 magawatt (MW) CSP plant is capable to abstain 688 tons of CO_2 emission compared to combined cycle system and 1360 tons of CO_2 emission if comparable with coal/steam cycle power plant [2]. 2014 CSP roadmap envisions that by 2050 global installed CSP capacity will reach to 1000 GW which would be capable to replace 2.1 gigatonnes (Gt) of CO_2 emissions annually [3].

The first commercial power plant, Solar One has been developed in 1982, California, USA [4]. This 10 MWe capacity plant was decommissioned in 1988 and retrofitted as a solar power tower utility-led project. This Solar Two CSP power plant was the first solar power tower commercially launched technology. It was in operation for only three years (1996-1998) but the objective was to demonstrate the economic possibility of commercial CSP tower technology [5]. Since then this trend is elevating and at the end of first decade of 21st century 1.3 GW of CSP plants are in operation worldwide. As of 2014, more than 4700 MW CSP plants are in operation

[6]. These plants are mainly owned by USA and Spain, however, North Africa, Middle East, India and China all are investing on CSP technology.

Four types of CSP technologies are accessible these days, i.e. parabolic trough, linier Fresnel, sterling dish and solar power tower. Among them solar power tower or central receiver CSP technology has more potential concerning with high temperature, power block efficiency and levelized cost of energy (LCOE) [7]. Here, incident sun rays hits the mirror surface called heliostats and reflected back towards a high temperature receiver where the concentrated rays transfer the heat energy to the heat transfer fluid (HTF). Concentrated solar flux impinging on the receiver allow the HTF to reach about 1000^{o}C temperature and then integrate this thermal energy into more efficient thermodynamic cycles for solar to electric power conversion.

In central receiver, the performance requirements of the plant are evaluated on three major subsystems: collector, receiver and power conversion subsystems [8]. The US department of Energy pursue for advanced receiver design under SunShot initiative to come across higher efficiency thermodynamic power cycles that can efficiently convert thermal-to-electric power with greater than 50% efficiency. The conventional design includes an array of tubes with multiple panels form a cylindrical shape. Working fluid passes through the tubes from inlet port and moving towards to outlet after receiving incident concentrated sunlight on the receiver's tube wall [9]. This typical design is known as external tubular receiver.

The SunShot initiative program set a subsidy-fee levelized cost of energy (LCOE) goal for CSP which will provide electricity at a cost of \$0.06/kWh or less by the end of the decade. Figure 1.0.1 is a graphical presentation which shows the transformation of cost reduction of four prime subsystems of solar tower. Price is moving downward since 2010 (\$0/21/kWh) because of significant technical advances in performance and efficiency. In general, this target requires higher operating temperature for longer lifetime which drives higher efficiency and lower cost.

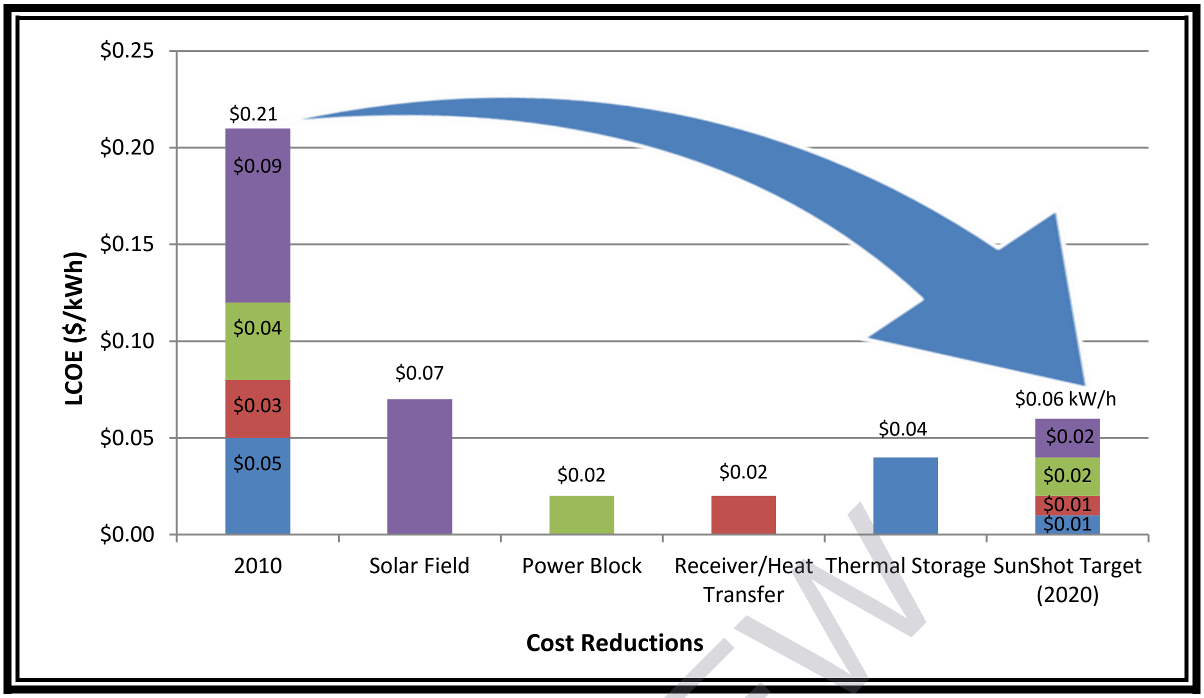

Figure1.1: Department of Energy SunShot goal 2020 [10]

1.2 High Temperature Solar Tower Receiver

Power generation from renewable sources has limitations; like, intermittency, remoteness of good resource regions, and scale potential. Central receiver technology has promising approaches to address these issues. This is why this technique is considered as one of the big shot in power generation sector. Todays' central solar receiver technologies can reach up to 1000ºC which satisfy receiver's efficiency target (≥50%) by mitigating high temperature stability challenge (>650ºC).

Todays' central solar receiver technologies can reach up to 600ºC using either steam or molten nitrate salt as the heat transfer fluid (HTF). Above 600ºC, molten nitrate salt becomes unstable while operating with Rankine power cycle and can reach ~35% efficiency [11]. As because of this limitation, power tower technology can't reach <1000ºC even though it has the capability. To solve this issue, new type of HTF is proposed accompanying with different type of receiver and thermodynamic cycle. The concept of closed Brayton cycle with supercritical CO_2 as

the working fluid first proposed in 1968, by Feher [12]. This concept is widely used on nuclear power generation in gas reactors and then also explored in solar power plants [8, 13-16].

In parallel with supercritical CO_2 extensive research is going on solid particle receiver (SPR). This is a direct absorption tower receiver idea first came out in 1980 [17]. Benefits of this receiver is the HTF can also be used as thermal energy storage (TES) medium which is a very economical way to meet the SunShot goal of \$0.06/kWh. The two pioneer national laboratories; Sandia National Laboratories in Albuquerque, NM and National Renewable Energy Laboratory in Golden, CO, are working together to test their own prototype receiver in a solar field [18, 19].

Dr. Zhiwen Ma, senior scientist from NREL received \$3.7M grant for his novel near-blackbody high temperature concept [19]. The overall purpose of this project is to implement a research project that can investigate, develop and test the near black-body high temperature solid particle receiver and examine different modes of heat transfer mechanism in gas-solid particle system at high temperature (1000+ ºC). Design objective is to overcome the issues associated with current molten salt CSP system i.e. heat transfer fluid (HTF) instability at <600ºC, high efficiency and cost barriers.

The novelty of this conceptual NBB receiver is, this design is divided into three different optical zones; front or flare section, middle section and end section. These three sections are distinguished by their optical properties and thermal stability at temperatures. That is, flare section is highly specular surface but operable only at 150ºC, middle section is high hemispherical but low specular reflective surface which can thermally stable up to 1000ºc and the end section is an oxidized metallic surface with 95% absorptivity at 1000ºc.

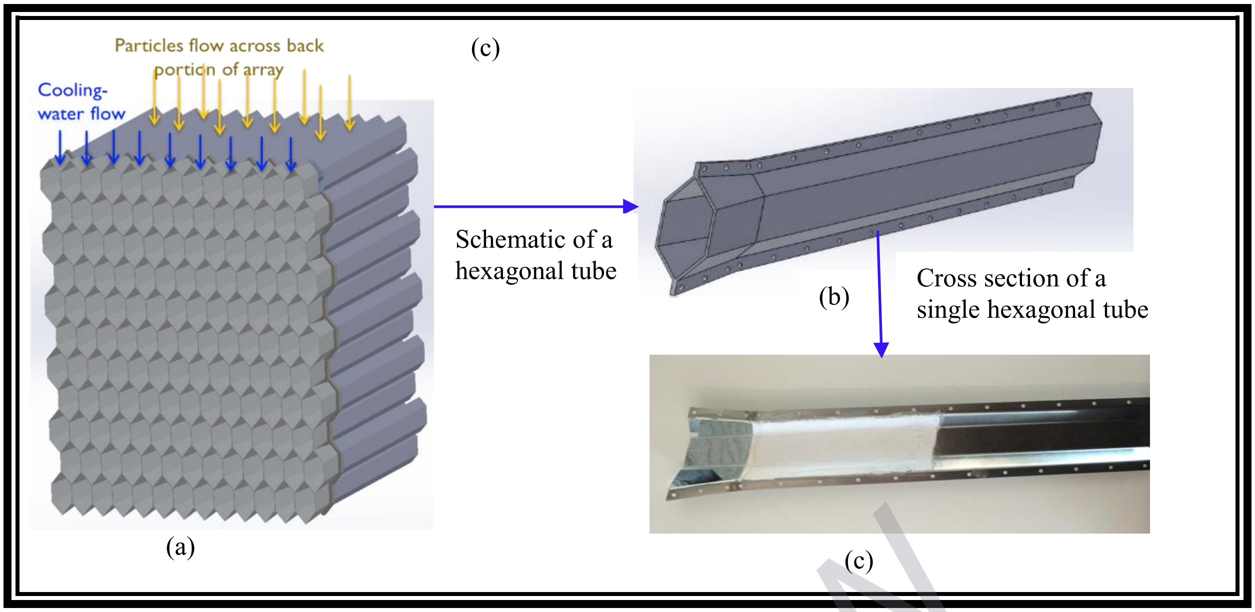

Figure 1.2: (a) Schematic of a NBB receiver (b) Schematic of a single hexagonal tube (c) Cross section of a hexagonal tube

Figure 1.2(a) is a schematic diagram of a small prototype NBB receiver and 1.2(b), (c) are a close shot of single hexagonal tube. 1.2(c) is cross sectional view of a fabricated tube with three different reflective surface. Fabrication procedure and on-sun testing of this single tube is discussed in details in chapter 4.

In this thesis I concentrate on optical characterization of NBB receiver. This receiver design requires high specular reflective surface in its' front section at operating temperature 150^{o}C. This mirror finished specular surface helps to penetrate the sunlight inside the hollow tube and hence increase receiver's efficiency. But at such operating temperature and environmental condition, optical properties degradation rate is high. Most commonly used mirror finished high specular reflective material is silver (Ag) or Aluminum (Al) [20]. But the degradation rate under ambient conditions without a protection layer is rapid for both materials. Unprotected silver surfaces tend to degrade in ambient air, especially at elevated temperatures. Al is not a very good option to use because of its ability to scratch while handling. Real solar field is located in a very