Evaluation of Concentrated Solar Power Systems and the Impact of Different Heat Transfer Fluids on Performance

MOHAMED R. GOMAA*, RIAD AHMAD, M. A. NAWAFLEH
Mechanical Engineering Department,
Faculty of Engineering, Al-Hussein Bin Talal University,
Maan, 71110 Maan,
JORDAN

*Corresponding Author

Abstract: - Concentrated solar power (CSP) is one of the main technologies used. Thus, the object of research is the different concentrated solar power technologies. Moreover, this study aimed to compare the different concentrated solar power technologies in terms of their efficiency, cost, concentration ratio, and receiver temperature. Results showed that technologies were arranged according to high to low temperatures: the parabolic dish reflector, central receiver collector, linear Fresnel reflector, and parabolic trough collector. As well as, in this study, ranges of the heat transfer fluids are compared with each other by using exergy and energy analysis. The heat transfer fluids that are examined are liquid sodium, molten salt (60 % $NaNO_3$, 40 % KNO_3), supercritical carbon dioxide (sCO_2), water/steam, and air. Results showed that the liquid sodium at an elevated temperature range of (540–740 °C) is performed the best, with exergy efficiency of 61% of solar-to-fluid, the best liquid sodium case is at (d_o=10.3 mm, n_{banks} = 1, Δp_{rec}= 7.72 bar, η_{II} = 45.47 %) has been found. Finally, vas a positive and effective approach to solving the energy problems.

Key-Words: - Solar energy; Concentrated solar power; Heat transfer fluid, Concentration ratio, Receiver efficiency.

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1 Introduction

The world is currently moving towards using clean energy to obtain energy due to the near depletion of conventional energy sources and the issue of climate change. In recent years, solar energy has become one of the most widely used sources of renewable energy; its use has increased by 35 percent over the past decade. Among these technologies are CSP technologies, [1], [2]. It is an active solar system, meaning that it requires mechanical equipment, such as fans and pumps, to convert solar energy into electricity or heat, [3], [4]. A CSP system can provide high and medium heat for a variety of applications, including industrial processes, electricity generation, solar heating, and cooling, as well as water desalination, [5]. It is the primary characteristic of CSP systems that they deal directly with sunlight, as they use solar energy tracking systems to maximize the amount of sunlight that can be used to generate and supply power to the tracking system. Construction and maintenance of this system are expensive, despite its high efficiency and productivity, [6]. Globally, solar energy capacity is growing rapidly to meet the energy demand. The installed capacity of CSPs indeed increased from 1266 MW in 2010 to 6479 MW in 2020, [7]. Furthermore, the heat transfer fluid (HTF) in concentrated solar power is also an important objective, given the large quantity of HTF required for the operation of CSP plants. Hence, the HTF must be kept as cost-effective as possible while maximizing its performance.

The purpose of this study is to compare the efficiency, cost, concentration ratio, and receiver temperature of the various concentrated solar power technologies.

2 Materials and Methods

2.1 System Components

There are typically multiple components to a Concentrated Solar Power (CSP) system, including a receiver, an electrical generator, solar concentrators, and a steam turbine. Figure 1 illustrates the most important parts of this system, [8].

Fig. 1: Components of CSP plant, [8].

Mirrors or concentrators are used in solar fields to direct normal irradiance to an absorber referred to as the receiver, as well as a heat transfer system and thermal energy storage system that enhances energy efficiency and stores energy to allow the plant to be used at night, however not all CSP plants have storage capabilities, [9], [10], [11].

2.2 Working Principle of CSP

As part of the solar field, mirrors or concentrators are used to direct normal sunlight to an absorber, referred to as the receiver, as well as heat transfer and thermal energy storage systems that enhance energy efficiency and store energy for the use of the plant at night (as shown in Figure 2), though not all CSP plants can store energy, [12], [13], [14].

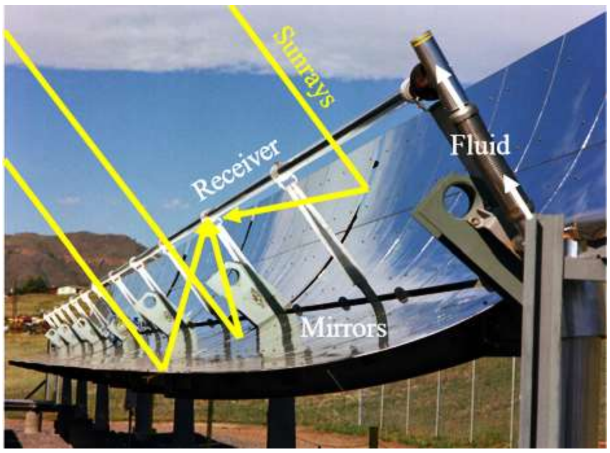

Fig. 2: Power generation in the parabolic trough, [14].

In the first instance, direct solar rays fall onto the reflecting mirrors, which act as concentrators for solar rays. After the mirrors are constructed, the solar rays are reflected toward the receiver, which can either be a tower or a tube, depending on the type of station. It is the receiver that receives the solar radiation coming from the mirrors, and then the receiver stores the energy of the radiation by converting it into heat through the use of a working fluid, which retains the heat in the form of steam for later use, [13].

2.3 Thermal Energy Storage In CSP

The limited availability of renewable energies such as wind and solar poses a problem for renewable energies. Therefore, to resolve these problems, energy storage is a critical solution, as thermal energy storage is more cost-effective than electrical energy storage, Figure 3 shows a parabolic trough station integrated with a thermal energy storage unit, [15].

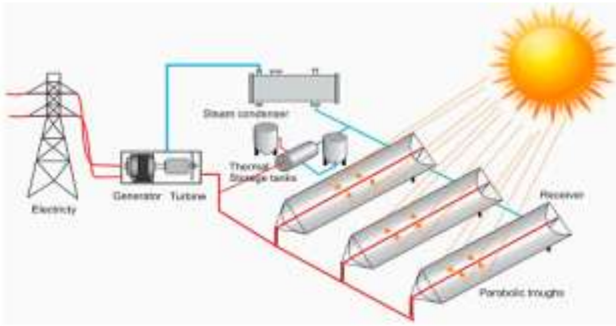

Fig. 3: A parabolic trough station integrated with a thermal energy storage unit, [15].

Energy industry professionals view the combination of CSPs and energy storage as an efficient and effective way of addressing the energy crisis, [16]. CSPs are considered a vital source of power generation, as they can provide deployable electricity in addition to the capability to store thermal energy. the largest widely used technique in thermal energy storage (TES) in commercial CSPs is Molten salt TES, but the industry is searching for cheaper and more efficient TES systems; and phase change materials (PCM) are marked as low-cost, high-energy TES systems, [17]. Because PCMs offer high-density energy storage, isothermal in nature, and operation in a variety of temperature conditions is available, [15]. The use of the PCM has several advantages including, [17];

1-Improved exergy efficiency.
2- Faster charging and discharging rate.
3- Raised heat transfer rate at the time of charging and discharging, specifically during phase change.

Among the phase change processes involved in PCM energy storage are evaporation, crystallization, and melting. When the material's temperature reaches a transition temperature, phase transition occurs, and the material is transferred from one state to another, such as from a liquid to a gas, solid to a liquid, and solid to a gas. In the phase transition process, solid-to-liquid PCMs are commonly utilized due to their high density and low volume change, [18].

2.4 Types of CSP

A concentrating solar collector consists of a tracking reflector that tracks the sun and concentrates radiation onto a line or point receiver. A thermal fluid circulates in the receiver and its temperature can rise to about 400 °C (for linear focus) or up to 800 °C (for point focus), [19]. In terms of economic and technical criteria, CSP technology can be divided into four different types. They are referred to as parabolic trough concentrators (PTCs), [4], linear Fresnel reflectors (LFR), [11], [19], [20], central receiver\solar towers (ST), and solar dishes, [21]. Today, CSP technologies are making tremendous progress around the globe, where the total installed at the end of 2015 was 4.8 GW, and it is predicted that by the end of 2030, it will reach 261 GW, [22].

2.4.1 Parabolic Trough Collector (PTC)

In electrical power plants, parabolic trough collectors are one of the most advanced and mature technologies that are employed to produce steam or process heat by absorbing direct solar radiation using mechanical or hydraulic tracking systems associated with sensors, [4], [23]. PTC consists of [24];

a) Collector: polished aluminum, steel, or glass.
b) Receiver: made up of a glass covering and metal pipe.
c) Reflector: reflector sheet or glass mirrors.
d) Tracking system.

Figure 4 Clarify this component, [24]. Many types of working fluid can be used as heat carriers inside the receiver, like; pressurized water, thermal oil, and Nanofluids which can increase the efficiency of the process; when using it the temperature of the PTC receiver tube can reach 350–400 °C, [25], [26], the installation cost of it about 4500–5800 $/kW, [24]. In addition, the efficiency is about 13-14 %, while the concentration ratio ranges between 15 and 70.

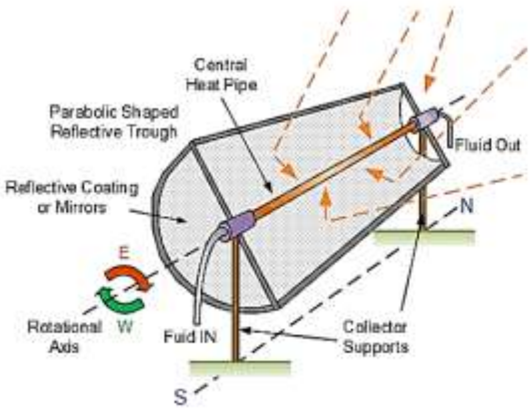

Fig. 4: Parabolic trough component, [14].

2.4.2 Linear Fresnel Reflector (LFR)

The linear Fresnel reflector (LFR) is a technology in constant development and has proven to be a cost-effective means of generating heat over the years. However, LFR undergoes high optical losses, resulting in lower thermal efficiency, which is estimated between 11%-19 %. LFR consists of separate linear primary mirrors placed near the ground at a height of about 3-5m above the ground, this construction is a prosperous future option due to its low cost and few mechanical issues due to wind loads compared to PTC. On the other hand, the optical efficiency of LFRs is limited due to the space between the main mirrors in addition to the shadowing and blocking effects of the main mirrors, [27]. A linear focusing technique requires a single-axis tracking mechanism to accurately track the position of the sun Figure 5 shows an LFR station. In addition, it's one of the most important concentrating solar systems for producing usable heat in the medium and high-temperature range (< 500°C). The concentration ratio ranges from 10 to 50 and the cost of it is very low. LFR receivers typically have an evacuated tube collector coupled to a secondary concentrator that is commonly a compound parabolic concentrator (CPC). Water/steam is frequently chosen to produce a high-pressure Super heater saturated steam, which can be used in Rankine cycle turbines or industrial processes, Thermal oil Therminol VP-1, and others are used for various thermal applications up to 400°C.

Fig. 5: LFR power plant, [28].

In addition to that, molten salts can be further utilized in power generation and used for storage goals. It is also emphasized that molten salt application is found to be more thermally efficient compared to hot oil operation and that molten salt offers the possibility of operation at higher temperatures up to 600°C, [28]. Its advantages are summed by: firstly, the support structure is simple and has an acceptable price. Furthermore, the fixed receiver reduces the risk of heat transfer fluid (HTF) leakage; in addition, it allows for comfortable extension of the automatic cleaning appliance. Finally, its production and spare parts are readily available on the market, [20].

2.4.3 Parabolic Dish Reflector

An effective solar dish is a point-focus device that uses a parabolic concentrator to focus direct solar radiation into a cavity. It can generate a large amount of clean energy with higher efficiency and quietness compared to conventional engines, but the cost of maintenance and installation will be higher. The system consists of a parabolic concentrator coupled to a power conversion unit that consists of a Stirling engine, an alternator, and a spiral cavity receiver. A parabolic concentrator collects incident solar irradiation and concentrates it at a stable focal point on a receiver, Figure 6 shows the system photograph.

The temperature of the receiver will be very high because it receives a large supply of concentrated solar energy, this heat, which is absorbed by the receiver, will work on heating the working fluids, which can be hydrogen gas or helium gas. As the temperature of these gases will reach 650 °C – 750 °C. In addition, for a 25MW plant, the cost of investment is about 2000 $/kW and 8000 $/kW and the efficiency may reach 35% when a concentration ratio equals 1300, and the temperature of the receiver is 850 K, [28].

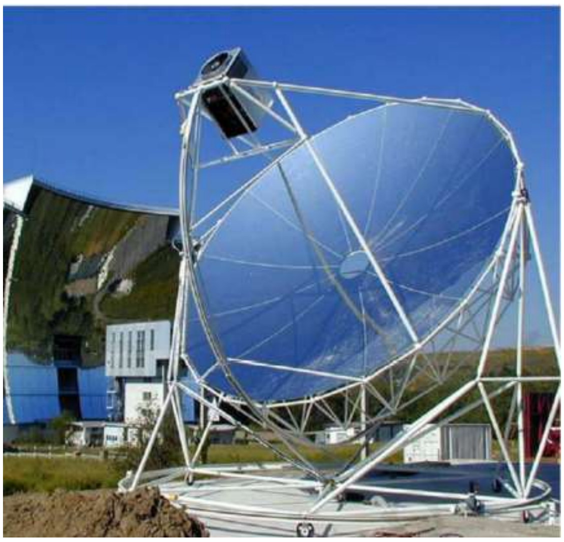

Fig. 6: Construction of parabolic dish collector system, [29[.

Since it possesses high thermal energy and efficiency, it is generally suitable to supply prime movers such as Bryton cycles, Rankine cycles, organic Rankine cycles, and micro gas turbines, [30]. In addition, one of its properties is that it doesn't require water for its cooling or operating processes, making it more suitable for power plant construction in water-shortage areas, [31]. The Solar Dish Stirling System has several uses, the most important of which is shown in Figure 7, [32].

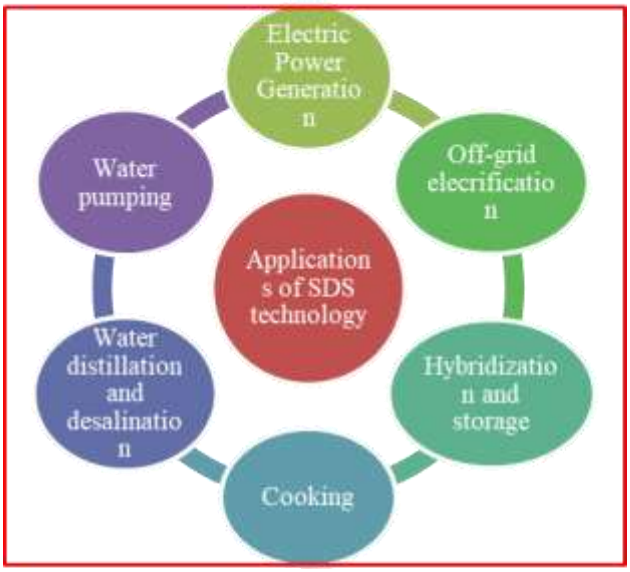

Fig. 7: Solar dish Stirling application, [33].

2.4.4 Central Receiver Collector/Heliostat Field Collector

Through a two-axis tracking mechanism, the mirrored collectors, called heliostats, reflect the incident solar radiation to the absorbing surface which is located at the top of the tower so that the sunlight is concentrated at the focal point. This heat can then be absorbed into the HTF by convection and radiation. This technique helps in raising the temperature of HTF and increases the efficiency in addition to reducing thermal losses, [34], [35].

It's distinguished by its ability to produce a hundred megawatts or a thousand gigawatts universally in 2050 in inexpensive ways, [35]. Moreover, it does not need large spaces to create the solar tower station. In addition, the temperature of HTF can reach 1000°C or above, Figure 8 illustrates the Opillustratesa solar power plant with a central receiver, [36]. Its efficiency ranges from 17% - 21%, and its concentration ratio = 1000, [37], [38].


Fig. 8: Working principle of the solar tower, [39].

3 Results and Discussion

3.1 Comparison between CSP Systems

In the next table and charts, the main differences between the various CSP systems are summarized. In addition to efficiency, cost, and concentration ratio, CSPs differ in their receiver temperature as well. In terms of efficiency, the parabolic dish reflector occupies the highest rank, as it can reach up to 35 %, followed by the central receiver collector with an efficiency of about 21 %, then the Linear Fresnel reflector and the parabolic trough collector with an efficiency of about 19 % and 14 % respectively. On the other hand, in the field of price, the Linear Fresnel reflector is the most cost-effective with a very low price, followed by the parabolic trough collector, central receiver collector, and parabolic dish reflector respectively. The concentration ratio is categorized in ascending order as follows; firstly, the Linear Fresnel reflector with a ratio of 50, secondly, the Parabolic trough collector with a ratio of 70, thirdly, the central receiver collector with a ratio of 1000, the parabolic dish reflector with the highest ratio of concentration up to 1300. According to the receiver temperature for each concentrator, the parabolic trough collector receiver temperature can reach 400 °C. The Linear Fresnel reflector with a Receiver temperature of about 500 °C, as well as, the central receiver collector receiver temperature can be estimated at 1000 °C. The highest receiver temperature among each concentrator is for a parabolic dish reflector, which can reach 1500 °C.

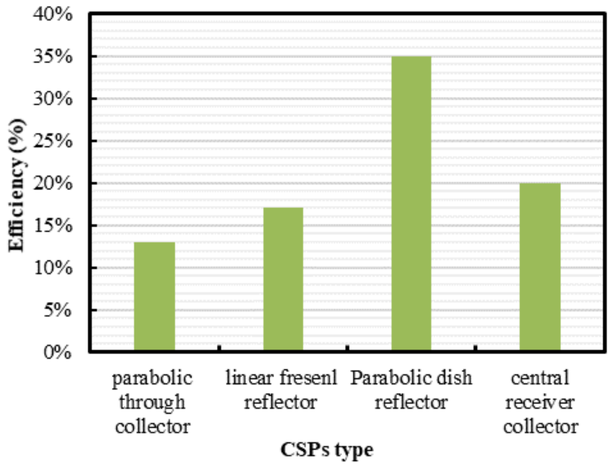

Fig. 9: Efficiencies difference for CSPs

Figure 9 refers to the difference between the efficiencies of each technique of CSPs. Indeed, the parabolic dish reflector has the highest efficiency among the others, and it can reach 35 %, also, it indicates that the efficiency of the central receiver collectors is around 21 %, while the efficiency of the Linear Fresnel reflector is 19 %, finally, the Parabolic trough collector has the lowest efficiency which estimated approx. 14 %.

In addition, the concentration ratio differences for CSPs are shown in Figure 10 clarifying that the point focuses concentrators (Parabolic dish reflector and Central receiver collector) own the highest concentration ratio as it can reach 1300 for the parabolic dish reflector and 1000 for the Central receiver collector. Compared with linear focus concentrators (Parabolic trough and linear Fresnel reflector) which are estimated to be the parabolic trough at 70 and the linear Fresnel reflector at 50.

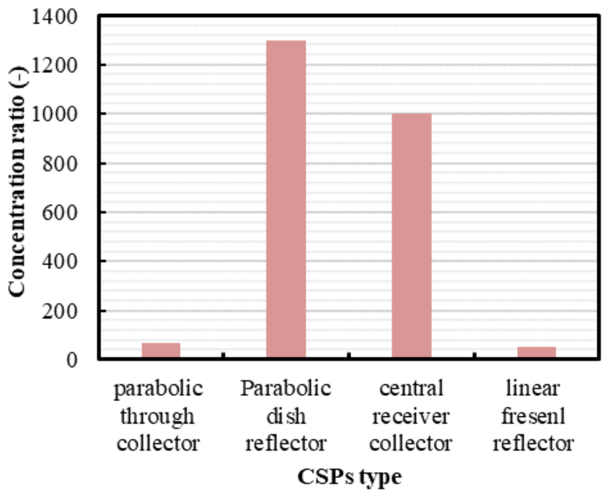

Fig. 10: Concentration ratio differences for CSPs.

Finally, Figure 11 illustrates the differences in receiver temperature for all CSPs, the highest temperature can be obtained from parabolic dish reflectors as it can reach Up to 1500 °C, then the central receiver collector with 1000 °C, followed by the Linear Fresnel reflector with 500 °C, and last is the parabolic through with around 400 °C.

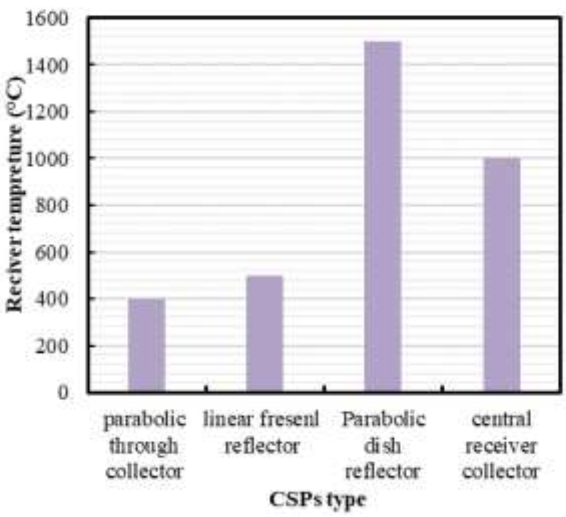

Fig. 11: Receiver temperature differences for CSPs.

According to the previous comparisons, we can see that the receiver of parabolic dish reflectors has a higher temperature than the other CSPs, in addition to the highest efficiency and concentration ratio of the others. However, the cost of construction is more expensive than the others. So, it is used to supply prime movers such as the Bryton cycle, Rankine cycle, organic Rankine cycle, and micro gas turbines, which require high operating temperatures. On the other hand, the Linear Fresnel reflector is the cheapest price among the CSPs. So, it is used for producing usable heat in the medium and high-temperature range.

3.2 Heat Transfer Fluid (HTF)

Heat transfer fluids (HTF) play a critical role in collecting energy from the solar field and transporting it to the power plant. As shown in Figure 12 the different HTF uses with the solar application, [38].

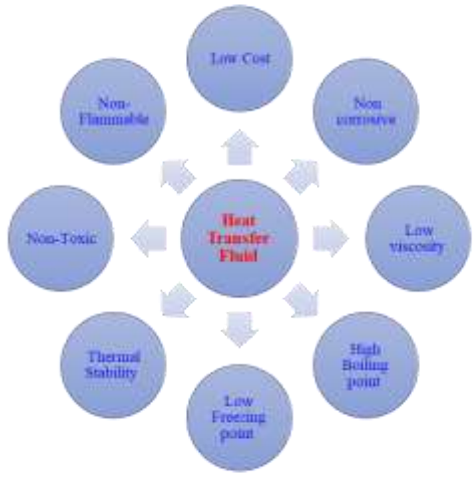

Fig. 12: Characteristics of the ideal HTFs

A detailed accounting of exergy is presented in Figure 13; the liquid Sodium has the best performance within the selected HTFs, especially in the higher range of temperatures. In contrast to the molten salt, liquid sodium can supply heat to the high-temperature sCO_2 Brayton cycle, which has a higher efficiency of thermal-to-electrical and will cost less than that of a steam Rankine cycle. As a result of the lower external wall temperature of liquid sodium, the receiver performance at lower temperatures is marginally better than that of molten salt, even taking into account the exergy losses in the heat exchanger. Despite its low cost and dual role as an HTF and TES, molten salt continues to be a competitive working fluid in central tower CSP systems, [39]. Water/steam can connect with the steam turbine directly, which saves the cost of equipment such as the heat exchanger, but it has difficulty integrating with the storage system, [40], [41], [42].

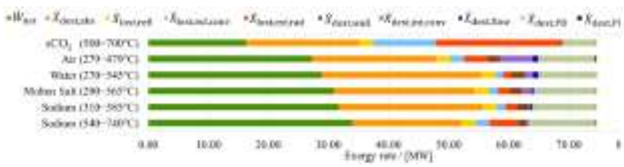

Fig. 13: Detailed exergy of the best-case configurations found for each working fluid, [20], [40].

Exergy destruction in absorption was large during the boiling process because of the low external wall temperature, while exergy losses in external radiation are low, [43]. SCO_2 seems that it is not a promising HTF selection for the receiver. Dealing with high working temperatures and pressure in the tubes of the receiver causes higher exergy losses than the anticipated savings resulting from the direct connection to a sCO_2 Brayton cycle.

Air seems that it is not a strong HTF due to its poor thermophysical properties, which cause extremely high external wall temperatures. It has the largest exergy destruction in internal convection and in pumping work, across all the fluids. It has to operate at a lower temperature with low flux to avoid high external wall temperature, even though it can work at a high-temperature range (e.g., 800–1000 °C). Air receivers, if it is feasible, will be required to make use of channels with enhanced heat transfer, [20], [38], [44].

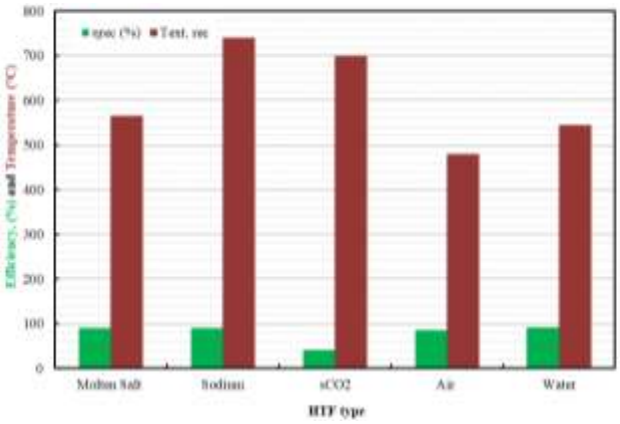

Fig. 14: Comparison between receiver efficiency and T_{max} for the selected HTFs

Figure 14 shows a comparison between receiver efficiency and T_{max} for the selected (HTFs), which shows that the liquid sodium has the highest performance, then molten salt follows it.

4 Conclusion

As a result of differing tracking strategies and methods for focusing light, concentrated solar power generates different receiver temperatures and varying efficiencies. The Parabolic dish reflector has the highest receiver temperature which can reach Up to 1500 °C the highest efficiency value of about 35 %, and the highest concentration ratio in a range of 1300. Despite this, it is the most expensive technique among CSPs it can reach 8000 USD/kW. while the central receiver collector can record the temperature of 1000 °C with an efficiency of 21 % and a concentration ratio of approximately 1000 with a high cost of investment. As an alternative, the Linear Fresnel reflector is the most efficient and economical, as it is the least expensive investment, but it has a limited concentration ratio, estimated at 50, and its receiver temperature can reach 500°C with a 19% efficiency. The parabolic trough collector receiver temperature can reach 400 °C with an efficiency of 14 % and a concentration ratio of about 70 with a low cost of investment. Finally, the performance of a range of heat transfer fluids in the tubular receivers. Among the study of HTF, it is shown that a strong performance benefit of using the liquid sodium at a high-temperature range with a system efficiency of 45.47 %, it also remains better than the molten salts that have n efficiency of 41.42 % even though at low-temperature range.

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