

Effect of Different Heat Transfer Fluids on the Performance of Solar Tower CSP

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Abstract: - Solar tower concentrating solar power (CSP) system focusing the solar radiation in the tubular receiver in which the radiation is absorbed and then transferred by convection and conduction into a heat transfer fluid. In this study, a range of the heat transfer fluids are compared with each other by using exergy and energy analysis, and by varying the tube wall thickness, the tube diameter, and the tube-bank flow configuration. The exergy efficiency is optimized with pumping work in the applied model, uniform flux is assumed, effects of the thermal stresses are neglected. For each fluid appropriate pressure and temperature conditions are chosen, depending on the applicable thermal energy storage (TES) and the power block (PB) configurations. The heat transfer fluids that are examined are liquid sodium, molten salt (60% NaNO₃, 40% KNO₃), supercritical carbon dioxide (sCO₂), 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. At the low range of temperature (290–565 °C), the liquid sodium remains superior to the molten salt, although allowing some exergy destruction in the sodium-to-salt heat exchanger. Water/steam performs relatively well in a receiver, Water/steam is a challenging heat transfer fluid for the integrated system due to the difficulty of integrating it with the storage of large-scale. Using the sCO₂ as the heat transfer fluid is infeasible because of the excessively-high pressure stress on tubes. Air also appears unsuitable for the tubular receivers, due to its poor internal heat transfer which result in the high losses because the external surfaces are much hotter.

Keywords: Solar tower, concentrating solar power (CSP), Heat transfer fluid, Exergy analysis and Receiver design.

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1. Introduction

Recently, the world's dependence on fossil fuels to produce energy has decreased because the consumption of it has caused the global reserve to decline [1]. In addition to the environmental pollution, global warming and climate change that has been caused by Burning the fossil fuels [2]. Therefore, the world turned to use the renewable energy sources such as the solar energy which is available clean energy, environmentally friendly and can be used in various applications [1].

There are a range of solar technologies that used in the world to benefit the solar energy such as the solar tower CSP which is an attractive renewable technology for large-scale use of solar energy that converts the solar

thermal energy into the electrical power in a complex process of heat transfer [3]. The main advantages of this system that it can produce energy when the Sun sits so it produces electricity for 24-hours a day, high efficiency, large scale, low operation costs and very low emissions [4]. It does not need any fuel, only requiring abundant and free sunlight, it does not produce any waste or harmful emissions, the sunlight concentration onto the one single receiver yields a higher temperature, the mirrors in this system tracking the sun at two axes to receive sunlight, so it can receive sunshine during winter even though the sun is in the low of the sky as a result the sunshine is utilized effectively and it is environmentally sound system [4]. Despite these positives there some

negatives that represents in requiring a vast area of land for construction, it is so expensive system, and the efficiency of this system is affected by the wind and causing problems in mirrors [5].

1.1 Working principle of the solar tower CSP

In the solar tower CSP, the thermal energy of the sun is converted to electrical energy [4]. As shown in Fig. 1, the main components of the solar tower CSP are a field of heliostat that contains thousands of sun-tracking mirrors, a central receiver on the top of a tower that contains the heat transfer fluid (HTF), a subsystem of steam generation that consists of heat exchangers, thermal energy storage (TES) system and a block of power [6].

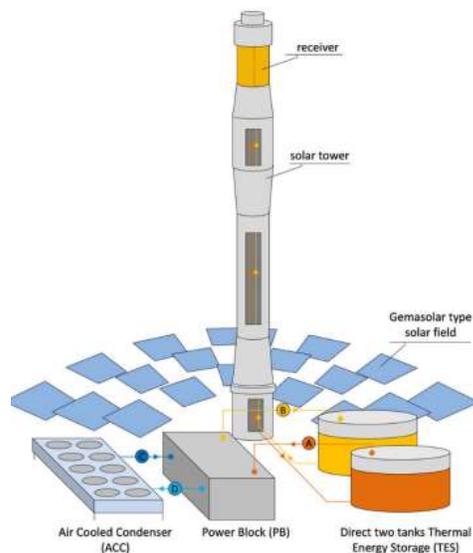


Fig. 1 Schematic diagram of solar power tower [30].

In the solar tower CSP, the rays of the sun fall on the surface of the mirrors, then the solar beam is reflected to the receiver after concentrating it by the heliostat field [6]. After that the solar energy is transferred through the receiver tube walls to a heat transfer fluid (HTF) by conduction and convection. The collected heat can exceed 900°C, this heated HTF transfers the thermal energy to the water by passing through the subsystem of steam

generation [7]. Water is heated to become superheated steam and then it is supplied to the steam turbine to generate electricity [4]. The first generation of solar tower CSP consists of the Direct Steam Generation without storage while the second generation uses the molten salt as the HTF and as storage medium [2]. The current effort is to develop a third generation of the solar tower CSP with targets of higher temperatures that exceeds 700 °C and has a higher-efficiency of the power block, more effective cost and more reliable technologies in each component of it [7]. The performance and efficiency of the solar power CST depends on several parameters such as the type of used receiver, heliostat field, varying the tube diameter of the receiver, tube wall thickness, and tube-bank flow configuration in the receiver, the power block type and the type of heat transfer fluid used in the receiver [5]. The most important component of solar tower CSP is the receiver with its flowing HTF, the types of receivers that used in the solar tower CSP are External cylindrical, flat, rectangular, cavity and tubular receivers [7]. But the tubular receivers are the most used types in the CSP receivers because of their simple manufacturing in which the absorbed energy is transferred to the heat transfer fluids (HTF) within the tubes [7]. The selection of the type of the receiver is based on the location of the plant site, HTF type, the heliostat field, receiver concentration ratio, the operating temperature range and the power cycle that is employed in the system [4].

1.2 Power Cycle

In the solar thermal power tower There are three major thermo-mechanical cycles that can be used, which include the Brayton cycle, the Rankine cycle, the combination of Rankine cycle and brayton cycle and the Stirling engine systems [8]. By operating the Power cycle at higher operating temperatures the efficiency of the power block will be increased and this is promised to be with the third generation of high-temperature receivers, which will increase the overall plant efficiency and savings of cost [6].

1.3 Thermal energy storage (TES)

Thermal energy storage system is a main component in the solar tower CSP as it presents the ability of dispatch at large scale [3]. To determine the temperature ranges that are applicable in receiver for different HTFs, the type of TES must be taken into account, with the other components of the system, such as the power block [9]. Thermal energy storage used in the solar tower could be Sensible thermal energy storage (STES) units or latent thermal energy storage (LTES) units [10]. STES units store the thermal energy directly by transferring the heat to a medium of storage, such as molten salt, oil, water, rocks and particles [9]. STES is commonly incorporated in the solar tower CSP systems because of its low cost and simplicity. It is the most direct and simple way to store the heat [11]. Molten salt TES is the most frequently used technology in the current operational solar tower CSP [10]. The alternative technologies and materials for storage are under development, which aim to improve the efficiency of power cycle by operating the turbine at a higher temperature range [9]. Jülich Solar Power Tower demonstrating the ability of storing the heat by flowing the hot air through ceramic elements [4]. Latent thermal energy storage (LTES) units in solar tower CSP are immature and promising technologies to store heat. Phase-change materials (PCMs) represent a kind of materials that can capture and absorb the energy during the solidification or melting process without rising a temperature. The Smaller LTES could be achieved by using PCMs, when it compared to STES of the same capacity. [10]. High-temperature PCM storage is challenging to commercialize due to several reasons including, high temperature corrosion [9]. Molten soda-lime silica glass could be used as the storage medium in a high temperature TES unit to store heat between a semi-liquid phase (molten state) at about 1000 °C and the solid phase at 500 °C

[11]. Metallic and Metalloid PCMs such as molten aluminum or molten silicon [10].

1.4 Heat transfer fluids (HTFs)

Heat transfer fluids that used in the receivers affect significantly on the efficiency of the receiver and the overall efficiency of the solar tower CSP system [13]. The temperature ranges of the HTF are used to determine the suitable TES and the possible power block [15]. the advantages and limitations of the thermophysical properties of the used HTF influence the thermal power absorbed by that fluid. This is a very important factor for the receiver efficiency [14]. Today, central receivers use water and molten salts (solar salt or nitrate salt) that allow easily thermal storage while Liquid metals have the strong potential for using in the third-generation tower systems according to their ability of remaining liquid at temperatures as high as (700–850) °C [16]. Because of the large amount of HTF that should be used to run solar tower CSP, so it's important to maintain the cost of the (HTF) as low as possible while remain maximizing the performance.

2. Types of Heat Transfer Fluids

Current studies show that, in addition to the conventional fluids, there are various innovative types of fluids can be used in central receivers to achieve the maximum possible efficiency [13]. In this section the HTF used in a solar tower CSP are discussed.

2.1 Molten salt

Molten salt of (40% KNO₃, 60% NaNO₃, aka 'Solar salt') is the most used HTF in the receivers of the central tower and in the TES system due to its reliability, efficiency, and low cost [19]. One of the important limitations of using molten salt is the operating temperature constraints. Since the nitrate salt should be operated within a range of temperature between 290–565 °C, with the upper limit because of the effect of chemical degradation and the effect

of corrosion and with a lower limit of temperature to avoid the freezing of salt [17]. Gemma solar was the first commercial CSP tower plant has utilized this technology, using the molten salt with capacity of thermal storage of 15 h, a 120 MW power of receiver, and a 19.9 MW power of turbine solar receiver [16]. The Noor III project of (150 MW) which use the molten salt as the HTF. This plant with capacity of thermal storage up to 7.5 h [18]. The Shouhang Dunhuang of “100 MW Phase II” solar power tower plant which has a capacity of the thermal storage of 11 h, using the molten salt as a storage fluid. Fig. 2, shows the molten salt and its working temperature ranges, power block throughout tower receivers with a fixed size of 100 m² and the thermal energy storage. The temperature ranges of molten salt are used to determine the suitable and possible thermal energy storage and the power block [29]. The temperature difference between heat exchanger inlet and outlet is assumed to be 20 °C.

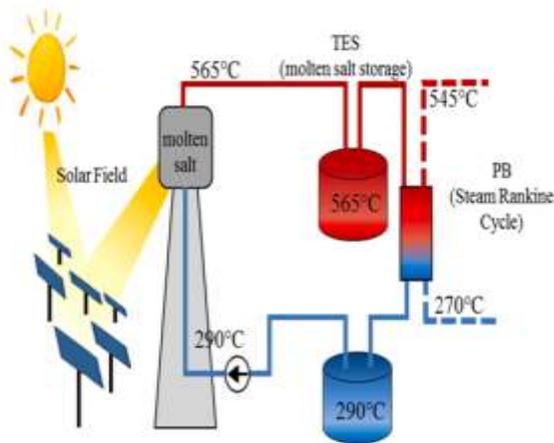


Fig. 2 molten salt –TES: molten salt [29].

2.2 Liquid sodium

Liquid sodium provides higher operation temperatures than the molten salt so it has the more efficient power cycle [21]. Because of the temperature range of it in the liquid phase (97.7–873 °C) and for its very high thermal conductivity sodium receivers is best suited to the high temperature and high-flux applications

especially in CSP [24]. Additionally, sodium is an exceptional HTF which enhance the performance of CSP due to its high thermal conductivity [15]. But in contrast to molten salt, it is expensive and unsuitable for the dual operation as the HTF and TES medium [24]. It is a highly combustible material when it is in contact with the air or water [13]. IEA-SPSS project is the first generation of sodium central receivers, which was researched in Spain and developed in the U.S [26].

Liquid sodium was compared with molten salt as the HTF in central receivers. Molten salt is cheaper and is capable of being used as the storage medium [19]. Fig. 3, shows the Liquid sodium and its working temperature ranges, power block throughout tower receivers with a fixed size of 100 m² and the thermal energy storage. The temperature ranges of Liquid sodium are used to determine the suitable and possible thermal energy storage and the power block. The temperature difference between heat exchanger inlet and outlet is assumed to be 20 °C.

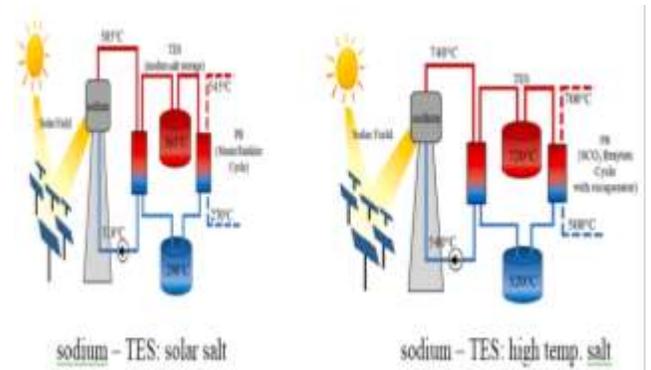


Fig. 3 Liquid sodium with two different TES [29].

2.3 Supercritical CO₂

Supercritical CO₂ (sCO₂), which is a compressed carbon dioxide at a pressure of 72.9 bar or more [14]. (sCO₂) is used in solar tower CSP plants as the heat transfer fluid in the in the Brayton cycle power block for CSP plants [23]. When sCO₂ is operated above its critical point (31.10 °C, 72.9 bar) the physical properties of it, provide performance advantages of the sCO₂ for

Brayton cycle over the other cycles type such as the steam Rankine [21]. However, the extremely high operating pressure required in the receiver which is over 200 bar makes many challenges especially when it's combined with the considerations of, thermal stress, radiation, thermal resistance and the corrosion of the CO₂ [22]. The advanced receiver of sCO₂ has a potential to be compatible with the sCO₂ Brayton cycle. The major interest in sCO₂ appears because sCO₂ is attractive in the Power Block. Fig. 4, shows sCO₂ and its working temperature ranges, power block throughout tower receivers with a fixed size of 100 m² and the thermal energy storage. The temperature ranges of molten salt are used to determine the suitable and possible thermal energy storage and the power block.

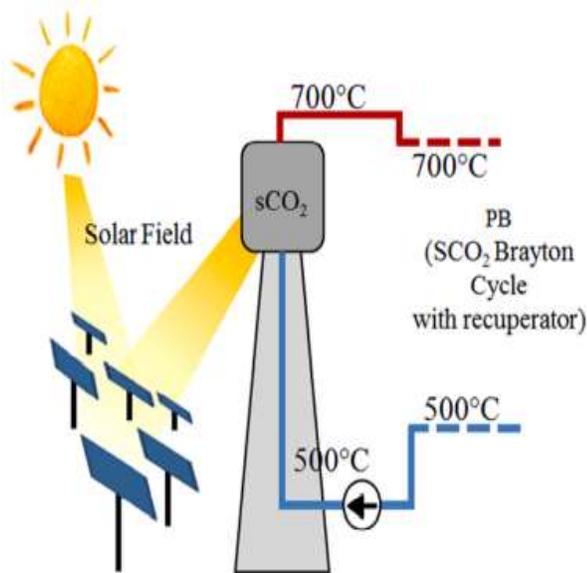


Fig. 4 sCO₂ – No storage [29].

2.4 Air

Air is used as an HTF in the solar tower CSP because of its ability to operate at temperatures as high as 1000°C which is higher than that of oil and the molten salt, which could increase the thermal-to-electric efficiency for the power block [20]. In addition, it can be used as the working fluid in open or closed air Brayton cycles, which make the power block less complex by eliminating the heat exchanger

[13]. Air is non-corrosive, costless, nonpolluting and has resistant to boiling and freezing [15]. Furthermore, air is basically free, costless and nonpolluting [20]. In addition to that air doesn't need previous preheating. However, the low conductivity and low heat capacity of air make receivers with air as HTF less efficient than the others[30].since air increases the difference of temperature between the wall of the tube and the fluid, and results in the high of exergy destruction in internal convection, and drives up the external losses according to elevated external temperatures[15].the way to overcome this problem is to strive to increase the heat transfer coefficient by using internally-finned tubes or rough tubes [29]. Air at elevated temperature of 800–1000 °C has better heat-transfer properties, specifically the internal heat transfer coefficients, but the material of receiver tubes should be considered carefully [20]. Fig. 5 , shows the air and its working temperature ranges, power block throughout tower receivers with a fixed size of 100 m² and the thermal energy storage. The temperature range of air is used to determine the suitable and possible thermal energy storage and the power block.

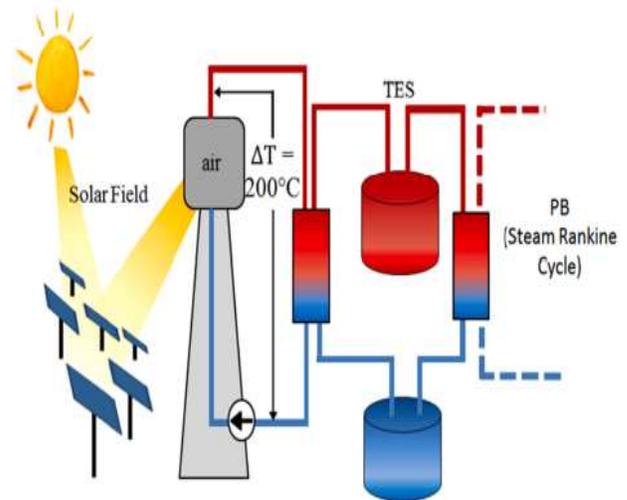


Fig. 5 air – TES: packed-bed [29].

2.5 Water/steam

The use of a steam simplifies the cycle of power by eliminating the heat exchanger

because the steam is directly used in the turbine [16]. Water is available, has good physical properties represents in high specific heat of (4185J/kg·K), non- toxic, low viscosity and low cost [13]. The disadvantages of using water as HTF represents in that the flow of two phase of water/steam is difficult to handle in the receiver, the steam is corrosive to the tubes and it can't be used when the sun goes down which result in less usage of it in the solar power tower [29]. The Phase change material (PCM) storage could be employed with DSG to increase the efficiency of the storage but this may increase the cost and the complexity[20].in addition to the challenges the fact that the integration of energy storage with the water/steam system [12].The PS10 (11 MW) and PS20 (20 MW) projects in Spain were the first commercial solar power towers in the) world [16].That utilized water as the heat transfer fluid to produce saturated steam at about 250–300 °C. Ivanpah, the largest solar thermal power plant in the world (377 MW), used a solar receiver of the steam generator [15]. Until now the highest solar tower power plant which is called “Ashalim Plot B of (121 MW)”, consisting of a steam receiver and steam turbine, was built in Ashalim, in 2017 [16]. Fig. 6, shows the Water/steam and its working temperature ranges, power block throughout tower receivers with a fixed size of 100 m² and the thermal energy storage. The temperature ranges of Water/steam are used to determine the suitable and possible thermal energy storage and the power block.

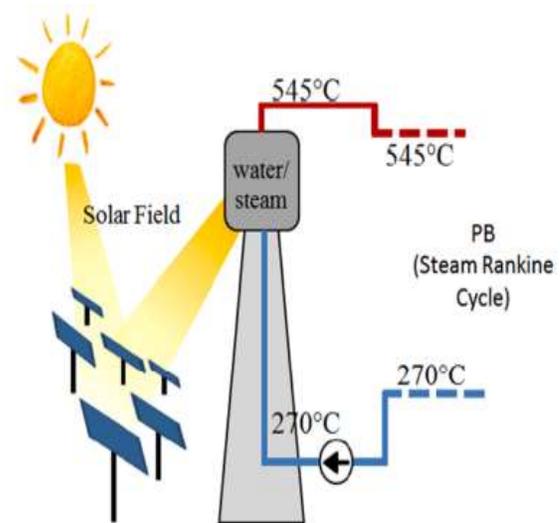


Fig. 6 water/steam – No storage [29].

2.6 Intensive thermophysical properties of the HTFs

The receiver efficiency is strongly depending on the properties of the heat transfer fluid HTF. Fig. 7, shows the major thermophysical properties of the selected HTFs. Fig. 7 (a) showing that water/steam has the highest specific heat capacity, which means that it needs more energy for heating up or cooling down the fluid through a given range of temperature water (0–324.68 °C liquid, and 324.69–1000 °C vapor) as it is compared to other HTF fluids. Fig. 7 (b) shows the variation of viscosity of the selected HTFs. Viscosity effects on the energy losses which is related to the fluid's movement inside the tubes as it generates pressure drop and heat losses [29].

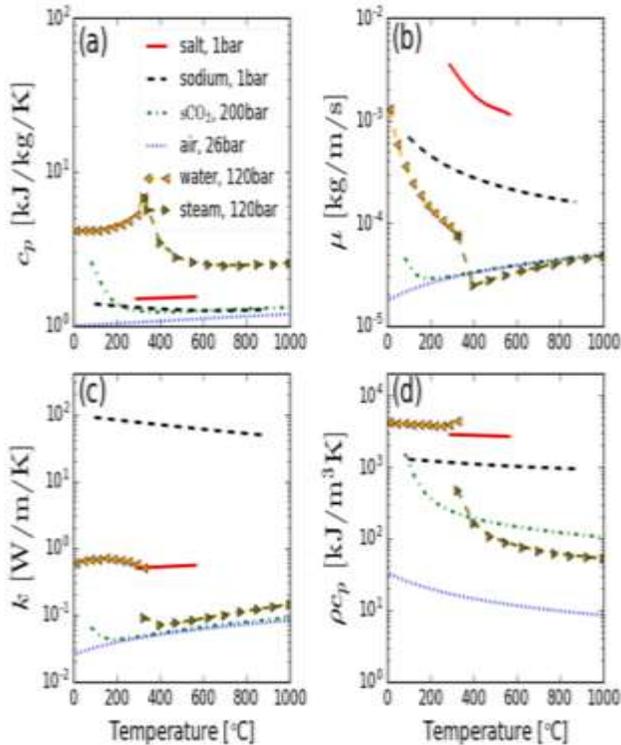


Fig. 7 Thermophysical properties of five selected HTFs as functions of temperature [29].

In addition to influencing the turbulence of the flow. Fig. 7 (c) shows that the liquid sodium (97.7–873 °C) has the most value of thermal conductivity, and it is in the two orders of magnitude higher than liquid water and molten salt [24]. Fig. 7 (d) shows that molten salt is accounted to be a good thermal energy storage medium in the high temperature range (290–565 °C), because it has high density (ρ , kg/m³) and high specific heat capacity (c_p , kJ/kg/K), which result in a high volumetric heat capacity (ρc_p , in kJ/m³/K), and consequently low volume of storage to store the same amount of energy, at the same range of operating temperature [21].

The improvement of heat transfer is come at the cost of the increased pressure drop [27]. So, it is important to control the pressure drop while enhancing the efficiency of heat transfer [28]. The performance of the fluid as an HTF is determined by the combination of the thermophysical properties of it.

2.7 Figures of merit (FOM)

It is a single way of comparing the intensive properties of specific heat transfer fluid, FOMs are the most convenient way to determine the performance of the HTFs [29]. By the substitution of the thermophysical properties of each HTF into the FOM, the selected HTFs are ranked as shown in Fig. 8(a), (c) and (d) show similar trends that sodium performing the best, followed by the water. Molten salt represents a reasonable choice in the operational temperature range. While the sCO₂ can be considered at high temperature (> 600 °C). Fig. 5 (b) shows that the water is the best without any consideration of the heat transfer across the wall [29].

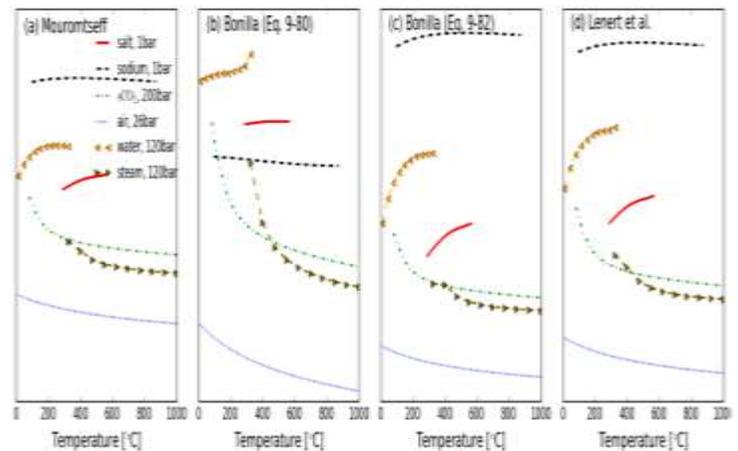


Fig. 8 FOM for different HTFs [29].

However, the best heat transfer fluid for the tubular receiver cannot be determined based on a limited analysis rely only on the thermophysical properties of the selected fluid alone. The FOMs shown above are valid within specific assumptions. However, as an example, different heat transfer fluids have a different operating temperature range. The performance of heat transfer fluid is not best determined if the comparison is constrained under a certain range. In addition, the FOMs present only rankings without a quantified difference of performance [28]. Other factors such as the mechanical stress on the tube, the exergy destruction, external losses, and tube wall conduction should also be taken in account. So,

a good evaluation of operating fluids needs a more detailed model that takes all of these factors in account.

3. Results and discussion

3.1 Molten salt, liquid sodium and water/steam receivers

Fig. 9, shows the effect of the varying tube diameter, flow configurations and the wall thickness for a receiver of molten salt. Fig. 9 (a) shows the exergy efficiency of a molten salt receiver only, while Fig. 11 (b) shows the exergy efficiency of molten salt system (molten salt receiver plus pump and Rankine cycle), including the effect of the receiver losses, PB losses and pumping losses.

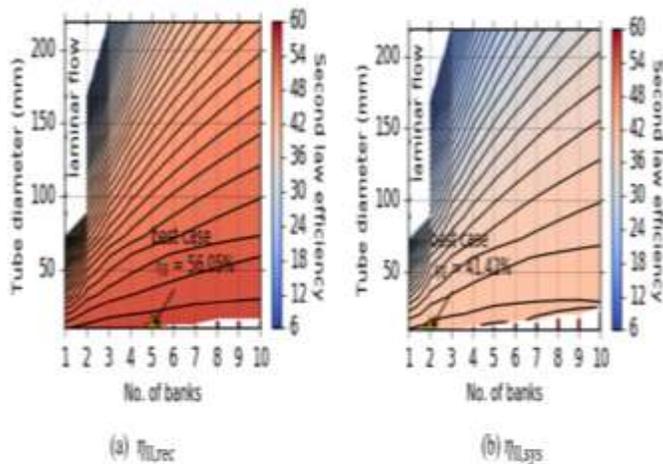


Fig. 9 (a) The exergy efficiency for molten salt receiver only, (b) for the whole system [29].

The operating temperature of the receiver is from 290– 565 °C. The Red dots on the right bottom of each figure indicate infeasible points at which the pressure drop is over 100 bars [29]. The efficiency lines show the trend of the relationship between number of banks and tube diameter, the tubes of large-diameter should configure with the more banks in series to increase internal heat transfer when it compared to the small-diameter tubes if the same second law efficiency is desired to achieve. While reducing the tube diameter improves the internal heat transfer, which results in reducing exergy

destruction in external losses and internal convection, due to the low inner and outer wall temperatures. A larger number of banks increase the tube friction due to increasing fluid velocity, which result in improving heat transfer enhancement and so higher efficiency of the receiver. However, the tubes of small-diameter and more banks increase the pressure drop within the receiver, which is require increase the pumping work [27]. trade-off between the receiver efficiency and the pumping losses leads to the optimum in the efficiency of system, which is the molten salt receiver at fewer tube banks, by dropping from five banks (i.e., the best case for the receiver only) to two banks (i.e., the best case for the whole system) [28]. Without accounting the costs, the best molten salt case is at ($d_o = 10.3$ mm, $n_{banks} = 2$, $\Delta p_{prec} = 16.93$ bar, $\eta_{II} = 41.42\%$) has been found, the Pump isentropic efficiency and the power block exergy efficiency were assumed to be 80% and 75%, respectively [29]. However, the welding of small tubes is costly, and the receiver must employ a pump with high capacity which increases the cost[28]. Hence, from a cost point of view, it is better to have a larger tubes with a fewer welds and simpler manufacturing. As an example, for a specified configuration with larger tubes ($d_o = 48.3$ mm, $\Delta p_{prec} = 4.32$ bar, $n_{banks} = 10$, $\eta_{II} = 40.73\%$), the 0.7% drop in efficiency could be paid off by a cheaper pump and a longer lifespan of tubes with less pressure stress [29]. The commercial salt receivers use tubes of approximate 14 mm [18].

3.2 Liquid sodium

Fig. 10, Shows the optimal Exergy efficiency $\eta_{II,sys}$, including the pumping and the power block losses, for the liquid sodium system as a function of varying tube size and flow configuration for the, at a range of operating temperature (310–585 °C) of the sodium receiver. The results show that the liquid sodium receiver is more efficient than that of molten salt. The liquid sodium receiver has low sensitivity to the variation of tube dimensions and the flow configurations due to

its high thermal conductivity [24]. Liquid sodium has better performance than the molten salt with fewer banks that is connected in series. The system efficiency could be improved by improving the thermal-to-electricity efficiency by the operation of the sCO₂ Brayton cycle at high temperatures (>700 °C). Which could be performed by the use of high temperature liquid sodium as the HTF in the receiver as shown in Fig. 10 (b).

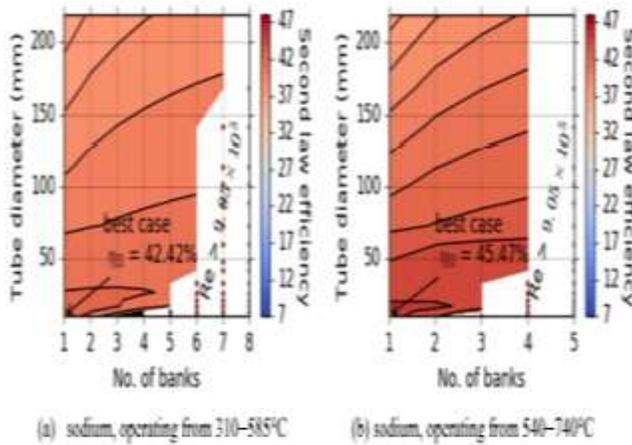


Fig. 10 Exergy efficiency (η_{II}) of system [29].

The efficiency of the receiver was increased due to the low exergy destruction in the absorption and in the wall [27]. To store the energy at high temperature; the conventional molten salt cannot be used. Hence, the other TES materials could be used, such as carbonate, chloride salts, PCM materials and molten glass [10].

3.3 water/steam

Fig. 11, Shows the Exergy efficiency η_{II} , sys, including the receiver and pump losses, for the system of water/steam, as a function of a varying tube size and the flow configuration. The receiver is operating from 270–545 °C. The Red dots on the right bottom of the figure indicates that the pressure drops are over 80 bars. The speed of sound of steam, steam at 545 °C, 120 bar is 667.56 m/s [29]. as the molten salt, the most efficient water/steam receiver must have a small tube with a few tube banks in series.

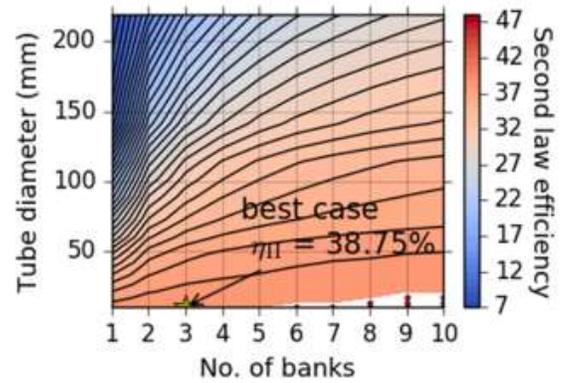


Fig. 11 Exergy efficiency (η_{II}) system [29].

3.4 sCO₂

The sCO₂ system must be handled and treated carefully, since it is designed to operate at a high range of temperature and high pressure. The ideal-case for sCO₂ is a receiver with a negligible pressure drop through the inlet and outlet ($p_i \approx p_o$) and a negligible temperature difference within the external wall and the fluid [22].

The feasible case is found with CR = 160, as shown in Fig. 12. The red dots in the figure indicates that is safety factor is smaller than 1.2. Further reducing of the CR resulting in lower net heat transfer in the receiver while the external losses remain relatively constant, therefore the overall system efficiency become lower [29]. The 17 mm tube is infeasible at its specified available thicknesses.

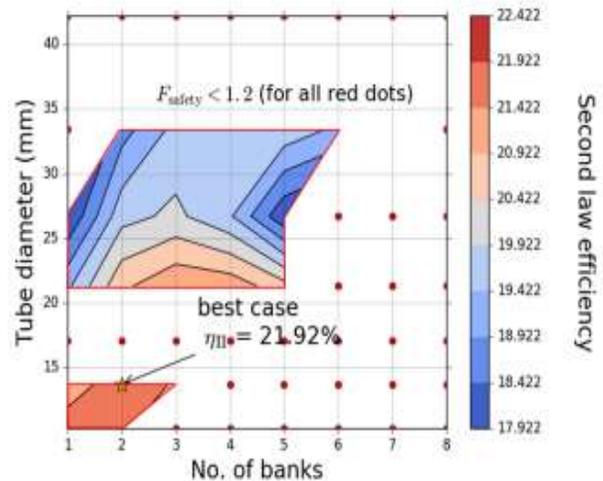


Fig. 12 Exergy efficiency η_{II} , sys [29].

3.5 Air receiver

The air system has uncompetitive performance because of its poor heat transfer that led to large exergy destruction in the wall conduction and in the internal convection. A sensitivity study as shown in (Table 1) is conducted to evaluate the Exergy efficiency ($\eta_{II, sys}$) of the air system of a varying concentration ratio and pump inlet pressure. For a given amount of Q_{sun} , the receiver aperture area was determined by the CR ($A_{aper} = Q_{sun} \cdot G \cdot CR$). The trade-offs between internal convection, external thermal radiation and pumping losses for the air receiver were reflected in the system second-law efficiency [20]. Fig. 13, Show that air operates in the low-pressure range is less efficient than that of the elevated pressure range. A large pumping work consumption which results in a large amount of heating generation due to compression, since temperature and pressure were directly proportional, which reduces efficiency of the system. Intercooling can be used to reduce the pumping work [26]. When pressure increased (e.g., 100 bar), the pressure drop within the receiver does not cause as much pumping work as occurring at the low pressure (e.g., 8 bar) [26]. As a result, with relatively larger n banks = 3, the better internal heat transfer is occurred, and consequently the efficiency of system is increased. The best-case $\eta_{II, sys}$ for the air receiver was identified as 36.43% [29].

Table 1. Exergy efficiency ($\eta_{II, sys}$) of the air system [29].

| Pressure (bar) | CR = 800 | CR = 640 | CR = 400 |
|----------------|---|---|----------|
| 8 | (infeasible, $\dot{W}_{PI} > \dot{W}_{dec}$) | (infeasible, $\dot{W}_{PI} > \dot{W}_{dec}$) | 23.94 |
| 13 | 14.49 | 24.79 | 30.22 |
| 27 | 33.45 | 34.49 | 32.24 |
| 50 | 33.41 | 34.63 | 32.64 |
| 100 | 35.41 | 36.43 | 36.32 |

3.6 Overall comparison

Detailed accounting of exergy is represented in Fig. 14, the liquid Sodium has the best performance within the selected HTFs, especially in the higher range of temperature. In contrast to the molten salt, liquid sodium is able to supply heat to the high-temperature sCO₂ Brayton cycle, that has the higher efficiency of thermal-to-electrical and will cost less than that of a steam Rankine cycle. The receiver performance of the liquid sodium at lower temperature range is only marginally better than the molten salt due to the lower external wall temperature, before considering the exergy losses in the heat exchanger. Molten salt is still a competitive as a working fluid in the receiver, and both with its dual role as HTF and TES, and its low price, it is the most used HTF in central tower CSP systems today [17]. Water/steam can connect with the steam turbine directly, that saves cost of equipment such as the heat exchanger, but it has a difficult in integrating with storage system [29].

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 [27]. sCO₂ seems that it is not a promising HTF selection for the receiver. Dealing with a high working temperatures and pressure in the tubes of receiver causes higher exergy losses than that of anticipating saving resulting from the direct connection to a sCO₂ Brayton cycle. Air seems that it is not a strong HTF due to its poor thermophysical properties that 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 the lower temperature with low flux to avoid high external wall temperature, even though it has the ability to work at a high temperature range (e.g., 800–1000 °C). Air receivers, if it feasible, will require to make use of channels with enhanced heat transfer [20].

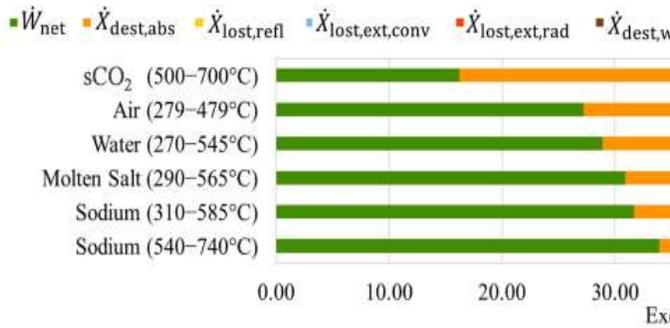


Fig. 14 Detailed exergy of the best-case configurations found for each working fluid [29].

The Overall results are shown in (Table 2), which summarizes the optimal configurations of the flow for each fluid. Which shows that the liquid sodium has the highest performance, then molten salt followed it.

Table 2. Summary of the best-case receiver configurations identified for each HTF [29].

| | Molten Salt (290–565 °C) | Sodium (310–585 °C) | Sodium (540–740) |
|------------------------|--------------------------|---------------------|------------------|
| Case | #1 | #2 | #3 |
| $T_{ext,ref}$ (°C) | 642.97 | 639.16 | 789.58 |
| $F_{abs,ext,un-avail}$ | 20.14 | 64.17 | 13.20 |
| CR | 800 | 800 | 800 |
| $T_{L,ref}$ (°C) | 290 | 310 | 540 |
| $T_{1,ref}$ (°C) | 290.74 | 310.52 | 540.93 |
| $T_{ext,ref}$ (°C) | 565 | 585 | 740 |
| $p_{1,ref}$ (bar) | 1 | 1 | 1 |
| $p_{1,ext}$ (bar) | 17.93 | 5.76 | 8.72 |
| $p_{2,ext}$ (bar) | 1 | 1 | 1 |
| V_{in} (m/s) | 5.59 | 7.08 | 9.69 |
| d_c (mm)/DN | 10.3/DN6 | 10.3/DN6 | 10.3/DN6 |
| t (mm)/Sch | 1.73/Sch40 | 1.73/Sch40 | 1.73/Sch40 |
| n_{stack} | 2 | 1 | 1 |
| Mach No. | – | – | – |
| $\eta_{t,ext}$ (%) | 89.65 | 90.00 | 83.81 |
| $\eta_{t,rec}$ (%) | 55.45 | 56.72 | 60.92 |
| $\eta_{t,ref}$ (%) | 47.73 | 49.24 | 63.52 |
| $\eta_{t,sys}$ (%) | 41.42 | 42.42 | 45.47 |
| W_{net} (MW) | 0.19 | 0.14 | 0.31 |
| W_{ext} (MW) | 30.90 | 31.79 | 33.92 |

4. Conclusions

This report studies 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 high temperature range, it is also remaining better than the molten salts even though at low temperature range. The

examination of the exergy destruction of the heat exchanger for liquid sodium at low temperature case show that it is very similar to the exergy destruction of the internal convection for the molten salt receiver. So, the gaining efficiency at this low temperature range is only so marginal for the liquid sodium because the temperature difference between the working fluid and internal wall are low, which result in low exergy destruction in the internal convection. sCO_2 , as a HTF is higher than the air depending on their thermophysical properties, while the study on external losses and pressure concluded that the air shows better performance than that of the sCO_2 receiver. Air and sCO_2 could be more beneficial in other CSP systems but show not to be applicable in simple tubular receivers of uniform flux. Water/steam is beneficial from the performance of receiver point of view, the relatively high exergy destruction in the absorption making it less efficient than liquid sodium or molten salt. It has challenges to the integration with storage. For the most efficient tower system, including a tubular receiver of uniform flux, a suitable TES and a simple PB of fixed exergy efficiency, should have a receiver with a small tube, mostly connected in parallel. While large tubes would reduce the fabrication and the material costs on the receiver, because of reducing the flow-path and this less complex.

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