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Heat transfer improvement using additive manufacturing technologies: a review

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ABSTRACT

Purpose: To provide a comprehensive review of additive manufacturing use in heat transfer improvement and to carry out the economic feasibility of additive manufacturing compared to conventional manufacturing. Heat transfer improvement is particularly interesting for different industrial sectors due to its economic, practical, and environmental benefits. Three heat transfer improvement techniques are used: active, passive, and compound.

Design/methodology/approach: According to numerous studies on heat transfer enhancement devices, most configurations with strong heat transfer performance are geometrically complex. Thus, those configurations cannot be easily manufactured using conventional manufacturing. With additive manufacturing, almost any configuration can be manufactured, with the added benefit that the produced parts' surface characteristics can enhance heat transfer. It can, however, lead to a significant pressure drop increase that will reduce the overall performance. In the given article, a comparison of the capital cost of a 100 MW parabolic trough power plant has been carried out, considering two types of solar receivers; the first is manufactured using conventional methods, and the second uses additive manufacturing. The heat transfer of the new receiver configuration is investigated using computational fluid dynamics through ANYS Fluent.

Findings: Although the cost of additive manufacturing machines and materials is high compared to conventional manufacturing, the outcome revealed that the gain in efficiency when using additive-manufactured receivers leads to a reduction in the number of receiver tubes and the number of solar collectors needed in the solar field It implies a considerable reduction of parabolic trough collector plant capital cost, which is 20.7%. It can, therefore, be concluded that, even if initial setup expenses are higher, additive manufacturing could be more cost-effective than traditional manufacturing.

Practical implications: With the reduction of the parabolic trough collector plant capital cost, the levelized cost of electricity will eventually be reduced, which will play a role in increasing the use of solar thermal energy.

Originality/value: No review studies discuss the manufacturing potential and cost-effectiveness potential of additive manufacturing when producing heat transfer improvement equipment, especially when producing long pieces. In addition, the paper uses a novel receiver configuration to investigate the economic aspect.

Keywords: Additive manufacturing, Heat transfer enhancement, Heat transfer coefficient, Finned tube, Parabolic trough collector

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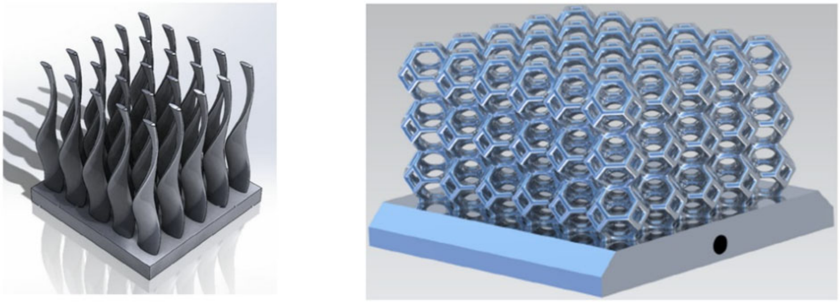
MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Global population growth, rise in living standards brought on by technological breakthroughs, and economic expansion have all contributed to the increased interest in energy efficiency improvement strategies. Heat transfer enhancement is important in electronic equipment, power and energy industries, and aerospace technologies. Energy demand is expected to increase by 76.9% between 2021 and 2050 [1]. Nuclear energy, fossil fuels, and renewable energy are currently the three main energy sources. Because they have abundant reserves and produce enough energy, fossil fuels are typically preferred [2]. However, the harm that fossil fuels cause to the environment has boosted interest in using alternative energy sources. Solar energy, wind energy, geothermal energy, hydraulic energy, biomass energy, and hydrogen energy are a few examples of renewable energy sources [1]. One of the most common ways to produce electricity from renewable energy is concentrated solar power (CSP) technology. As of 2021, 6.8 GW of functioning CSP plants were worldwide [1]. By 2030 and 2050, the projected total capacities are 83 GW and 342 GW, respectively [3]. Solar collectors in a PTC focus the solar radiation that enters their aperture at a receiver, which then gathers the concentrated flux striking its surface. As a result, heat is transferred from the incident radiations to a heat transfer fluid. The steam generator uses the heated fluid to exchange heat with it, changing water into steam that is expanded in a turbine to generate power. A receiver tube is a crucial component of the PTC system and the key factor affecting the system's thermal performance.

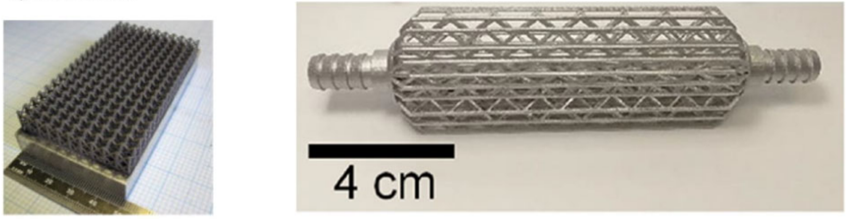
Several academics have been working on ways to improve heat transfer. The primary idea behind the investigated methods for improving thermal performance is to accelerate the heat transfer rate between the receiver and fluid. As said above, heat transfer enhancement is not only desired in PTC. For instance, heat exchangers are needed in power electronics because they produce too much heat due to internal losses. Therefore, they need proper thermal management to increase dependability and stop overheating-related failures. The simplest and most popular cooling method in power electronics is the heatsink. Their active convection surface area (fins) can be increased to significantly improve their thermal performance by extending fins to cause turbulence in airflow [4]. Heat transfer enhancement is needed in automotive industries for radiators for air-cooled machines. Due to the increase in heat generated in the windings, thermal management is the biggest challenge in electrical machines [5].

The balance between improving heat transfer and reducing flow resistance must be considered when developing and using heat transfer enhancement devices. For instance, boosting the heat transfer by improving the wall structure of the tube enables the reduction of the tube diameter, which will then increase the pressure drop. A pressure decrease compensates for any improvement in heat transfer because of the Colburn analogy, which fundamentally ties heat and momentum transmission [6]. Most heat transfer enhancement methods aim to alter the flow or expand the contact area, which raises skin friction. More expensive pumps are then required to drive the flow as pressure drop increases. A careful balance must be struck to ensure that savings from the heat transfer enhancement technology exceed the costs of a higher pressure drop. It led to the study of several innovative configurations with improved heat transfer and moderate pressure drop. Some, for instance, focused on improving the basic twisted tape design through perforated holes [7], edge cutting [8], extended surfaces [9], heat exchangers used in electronic equipment, etc. Such structures are too complex to be produced using traditional manufacturing techniques due to limited machining possibilities to fabricate 3D structures within channels. Such manufacturing limitation can be lifted through AM and has thus been investigated for heat transfer configuration design and manufacture to meet these objectives. AM, known as 3D printing, is a new technology that is developing quickly and gaining researchers' focus [10,11]. Due to the ability to produce dense metallic parts without requiring extensive post-processing, powder bed fusion (PBF) and directed energy deposition (DED) are the two most popular AM process types for creating metallic parts. PBF is further classified into direct metal laser sintering, electron beam melting, selective laser sintering, and selective laser melting. DED is classified into electron



a) Twisted fins

b) Truncated octahedron-shaped structure



c) lattice structure pin fin

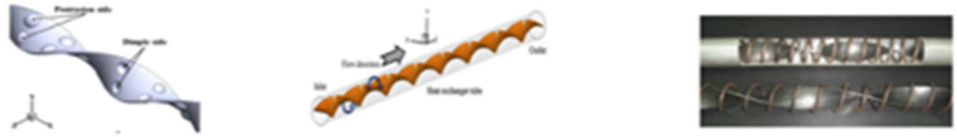
d) Complex fin structure

Fig. 1. Example of innovative fins structure [4, 13-15]

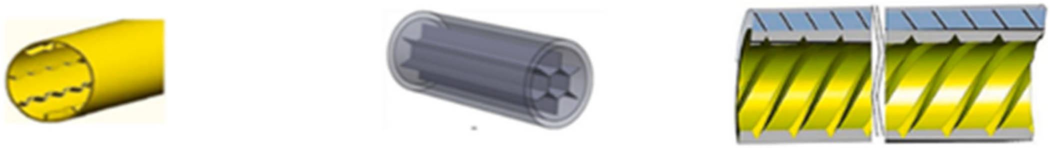
beam freeform fabrication, laser engineering net shaping, laser consolidation, direct light fabrication, and wire arc AM [12]. AM offers a variety of creative ways to improve an electrical machine's thermal performance. The developments brought about by AM technology offer various creative ways that impact heat transfer enhancement, particularly in creating extremely effective, compact, and lightweight heat exchanger systems by creating some innovative fin structures, as illustrated in Figure 1. The review paper aims to highlight opportunities for AM in designing and producing structures that enhance the heat transfer process. Also, the paper aims to evaluate AM cost-effectiveness by carrying out the economic feasibility of additive manufacturing compared to conventional manufacturing. The review first gives an overview of passive heat transfer techniques, followed by the possible uses of AM to improve heat transfer. It is concluded by the economic feasibility of using heat transfer parts produced by additive manufacturing.

2. Techniques of heat transfer enhancement

Three strategies are employed to improve heat transfer in internal channels and tubes: active, passive, and compound [16]. Active techniques require external power sources to improve heat transfer, thus limiting their suitability to specific uses. Active methods are typically more expensive, difficult, and less employed than passive methods. On the contrary, passive methods do not depend on outside input like mechanical or electrical actuation as they rely on adding inserts or changing the tubing's walls, thus modifying the tube structure. Passive methods have a minimal integration penalty with existing heat transfer technologies, making them the most popular kind of heat transfer improvement [16]. Compound techniques involve a combination of both active and passive methods. There is an emphasis on passive methods used in literature to improve heat transfer. They include pin-fins, finned inserts, wavy channels, tubes with internal ribs, protrusions, dimples, wire coils, and channels with twisted tape inserts. Zheng et al. [17], investigated numerically the effects of dimple twisted tape insert (Fig. 2a) on heat transfer. Their findings demonstrated an increase of 25.5% in the heat transfer coefficient. Several works have investigated the effectiveness of modifications made to twisted tapes to improve heat transfer. In the study done by Nakhchi et al. [18], it was shown that the heat transfer improves by 117% when using V-cut twisted tape (Fig. 2b), resulting in a heat transfer improved by 117%. The wire coil is another important technique where heat transfer area and flow turbulence are increased, resulting in an increased heat transfer rate. Bahabadi et al. [19] carried out an experimental study to determine how wire coil inserts affected pressure drop and heat transfer. Results showed that the pressure drop increased 4.75 times compared to the tube without inserts, while heat transfer increased by 85% compared to the tube



a) Dimple twisted tape b) V-cut twisted tape c) Wire coil and twisted tape insert



d) Internal longitudinal fins e) Star fins insert f) Internal helical V-grooved fins

Fig. 2. Example of complex structures of fins and inserts used in PTC [9,17,18,20,24,25]

without coil inserts. Combining the advantages of twisted tape and wire coil can improve heat transfer performance. Such a combination (Fig. 2c) was used in the study of Promvonge [20], leading to a maximum enhancement factor of about 1.5 in heat transfer. Fins efficiently improve heat transfer as they increase the contact surface area. In a study by Hosseinzadeh et al. [21], heat transfer was enhanced when using fins in a star structure (Fig. 2e). Torii et al. [22] investigated the introduction of vortex generators within finned tube heat exchangers, where they found that heat transfer is enhanced. At the same time, the pressure drop is decreased compared to a finned tube without a vortex generator Borhani et al. [23] numerically studied spiral fins and observed a 56% increase in heat transfer. A channel containing internally helical V-grooved fins (Fig. 2f) was studied by Baswakarma et al. [25] and showed to increase the heat transfer coefficient by 41.3%, with better overall performance. As Sahel et al. showed, baffles also enhance heat transfer by directing the flow, yielding enhanced overall performances compared to a plain tube [26]. In a numerical study on segmental baffles, Abbasi et al. [27] showed that the heat transfer coefficient could be increased by 11.5%, while Luo et al. [28] have demonstrated experimentally that trapezoidal shape baffles can improve the heat transfer coefficient by 10.2%. In numerical simulations, an increase in heat transfer of 8.5% was obtained by Liu et al. [29] with baffles containing fold helix. In another study, Liu et al. [30] investigated the effect of ribbed channels on thermal performance. Such enhanced thermal efficiency, with a ~2.85 performance evaluation criterion (PEC).

Numerical studies of a PTC receiver with rods inserted by Chang et al. [31] have shown increased heat transfer, yielding better thermal performances even though the pressure drop also increases. Shahzad et al. [32] suggested a configuration where a rod is inserted in a ribbed channel. Numerical studies showed that such a combination improved both heat transfer and hydrothermal performances. Several configurations of receivers have been developed by various researchers [28, 32-35] to further increase heat transfer. However, some configurations result in a higher pressure drop increase than the heat transfer increase, leading to poor overall performances. For instance, in a study by Kursum [24], the thermal performances of a tube containing longitudinal fins (Fig. 2d) were investigated. Results showed that the Nusselt number increased by 1.66 while a pressure drop of 5.75 was observed, resulting in a very low overall performance with a PEC of 0.93. Figure 3 shows the summary of heat transfer enhancement of some studies [17,31,32, 36-39], in terms of PEC. This accounts for both the Nusselt number and pressure drop, as it is crucial to consider the balance between heat transfer augmentation and flow resistance reduction because heat transfer enhancement is always accompanied by pressure drop. It is shown in Figure 3 that all studied configurations have good efficiency since the PEC is greater than zero, which means their performance is good compared to smooth channels. The configuration with the best PEC is the rod inserted in the ribbed tube [32]. It is attributed to the double impact of combining the rod insert and ribbed structure, which affects the heat transfer surface and pressure drop. The configuration with low PEC is the wall-detached twisted tape [38]. It is due to a high-pressure drop caused by increased flow resistance by a swirl flow. Nevertheless, most of these studies were done numerically and without experimental studies. As seen in the previous section, this can be attributed to the fact that these configurations are complex and cannot be fabricated using conventional manufacturing.

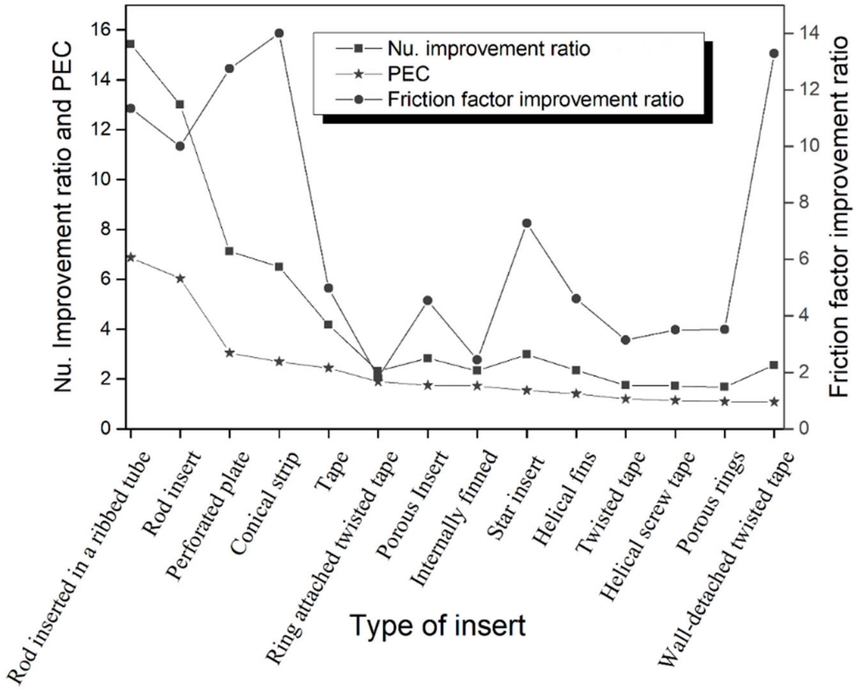


Fig. 3. Comparison of thermo-hydraulic performance of different configurations

3. Potential of additive manufacturing

3.1. AM and heat transfer

Additive manufacturing has the advantage of enabling the production of parts or devices with complex geometries. There have been studies on additive manufacturing-based products in the heat transfer improvement field, especially for small-size heat transfer devices. Wong et al. [40] produced circular, elliptical, and V-shaped fins using selective laser melting technology. After multiple experiments, results showed that heat transfer is enhanced compared to conventional fins. In their study, Kirsch and Thole [41]explored microchannel pin fin arrays produced by AM using laser powder bed fusion. They compared their heat transfer performance with pin fin arrays produced by conventional manufacturing. It was shown that the friction factor increased due to the high surface roughness of AM parts, leading to a higher pressure drop than the increase in heat transfer. The wavy channel, produced by direct metal laser sintering using Inconel 718 as material, was also investigated [42]. A 15% increase in heat transfer coefficient was achieved because of the rougher surface. Aris et al. [43] investigated experimentally the pressure loss and heat transfer variations caused by vortex generators produced using the SLM technique. Their findings revealed a nearly 90% improvement in heat transfer. With improvements in manufacturing technology, the idea of improving boiling heat transfer with SLM-fabricated surfaces and porous structures is now being discussed in the literature. Ho et al. [44] studied the boiling heat transfer enhancement of micro-fins structure fabricated using additive manufacturing SLM method. It was shown that the heat transfer coefficient was enhanced significantly compared to the plain surface. In the review by Byiringiro et al. [45], additive manufacturing was shown to have the potential to produce different receiver configurations that can play a role in reducing the capital cost of PTC plants. Wei et al. [46] made a comparison of configurations with straight fins that can be produced using conventional manufacturing (Fig. 4a) and with interrupted

a) Straight fins b) interrupted fins

Fig. 4. Example of fins [46]

fins produced using AM (Fig. 4b). It was found out that the interrupted fins have an excellent enhancement of heat transfer, 1.4 times that of straight fins and 2.6 times that of the smooth tube.

3.2. Effect of surface roughness

Parts produced by AM exhibit a distinct surface roughness resulting from the manufacturing process itself. This surface roughness allows boundary layer distortion and local flow mixing, increasing the heat transfer coefficient. AM parts generally have a noticeably higher roughness than parts produced by conventional methods, as shown in Table 1. Notably, roughness strongly depends on the employed technique, machine parameters, and build direction [47,48]. The hydraulic and thermal performances of the channels are strongly impacted by this roughness [47,49]. The relationship between the roughness and thermal performance of channels can be predicted by the correlation developed in [49], as shown in Equation 1.

$$\frac{1}{\sqrt{f}} = -2.0\log\left(\frac{k_s/D_h}{3.7} + \frac{2.51}{Re\sqrt{f}}\right) \tag{1}$$

with $\frac{k_s}{D_h} = 18\frac{R_a}{D_h} - 0.05,$ (2)

$$Nu = \frac{(Re^{0.5}-29)Pr\sqrt{f/8}}{0.6(1-Pr^{2/3})} \tag{3}$$

where: f is the friction factor, Re is the Reynolds number, k_s is the equivalent sand grain roughness, D_h is the hydraulic diameter, R_a is the arithmetic mean roughness, Nu is the Nusselt number, and Pr is the Prandtl number.

Numerous research studies have examined the impact of the AM surfaces' roughness on heat transfer and pressure drops. In a study by Stimpson et al. [47], small channels produced using direct metal laser sintering were investigated experimentally to understand the impact of roughness on heat transfer performance. A significant increase was seen in the Nusselt number and friction factor compared to a smooth tube. Generally, the thermal performance of the tube was enhanced because the Nusselt number increased four times higher than the pressure drop. Another attempt to enhance heat transfer using rough surfaces was made by Ventola et al. [50], in which they used an AM laser-based technology to produce heat sinks for cooling electronic devices. Due to surface roughness, the forced convection heat transfer was improved by 73% compared to smooth surfaces. Saltzman et al. [51], analysed the impact of surface roughness on the heat transfer performance of a crossflow heat exchanger produced using a laser based PBF method. Overall, heat transfer was shown to have increased by 10% while pressure drop increased by up to two times. However, higher surface roughness can also present some drawbacks to heat transfer, as in some cases, the increase in pressure drop is larger than the heat transfer. It was the case in a study by Kirsch [42], where the high surface roughness of wavy channels increased the heat transfer coefficient. Still, thermal performances were affected by the increased pressure drop. In addition to roughness, the higher porosity found in AM-produced parts can lead to low thermal performance. This is because porosity affects the material's thermal conductivity, fatigue, and tensile strength [52]. In their research, Hosseinzadeh et al. [53] observed that the Nusselt number becomes low when porosity is increased. Using laser sintering, Collins et al. [54] evaluated the heat transfer of a tube produced from aluminium alloy. In addition to porosity, there were tiny cavities in the material bulk, which reduced thermal conductivity. Their results showed that thermal performances were 20% lower than that of smooth channels. Due to a lack of research on thermal control applications in AM products, many industries are still reluctant to fabricate and integrate heat transfer devices using AM.

Table 1.
Typical surface roughness [55]

Manufacturing process	Surface roughness range, µm
Conventional manufacturing	
Forging	2.2-15
Die casting	1.3-5
Grinding	0.5-2.5
Additive manufacturing	
Binder jetting	3-13
Selective laser sintering	5-35
Fused deposition modelling	9-40
Laser powder bed fusion	5-18
Electron beam powder bed fusion	10-30
Powder DED	10-60
Wire DED	45-200

Further studies on mitigating the surface roughness and porosity to increase thermal conductivity and optimise pressure drop are still needed. Additionally, the majority of cases studied involve small-sized electronic applications. In many larger-scale applications, including thermal energy storage, energy recovery, automotive, aerospace, etc., it is necessary to investigate other AM methods, such as Directed Energy Deposition (DED), that can be adapted to achieve larger-sized objects compared to powder-based processes.

4. Economic feasibility analysis

It is being questioned if AM can be as cost-effective as conventional manufacturing processes. Cost comparisons between AM and conventional manufacturing have been done using different models. Dickens and Hopkinson [56] developed a model to compare AM parts produced using Selective laser sintering (SLS) and Injection moulding. This model indicates that AM is cost-effective below a specific manufacturing volume. Nevertheless, injection moulding becomes more cost-effective than AM as the production volume increases. Another model by Berger [57] indicates that the complexity of the design does not affect the cost of AM, contrary to traditional manufacturing, where the level of complexity could lead to increased cost of manufacturing. In this section, a parabolic trough collector (PTC) will be considered to evaluate the economic feasibility of AM against conventional manufacturing, where a new receiver configuration to be used in this PTC solar field is analysed.

4.1. Cost orientations of a PTC plant using AM receivers

PTC is one of the best and most well-known systems for using solar radiation to generate useful power or heat. It consists of a parabolic mirror that focuses sunlight rays on the receiver tube, where the absorbed heat is transmitted to a heat transfer fluid. The PTC capital cost, its performance, and the running and maintenance expenses affect how much the electricity produced will cost. A sizeable fraction of the capital cost is dedicated to the solar field. This solar field consists of several loops, with a few solar collectors in each loop, as shown in Figure 5. The designed power block's thermal energy requirement determines how many loops are needed. Important elements in a solar field are solar collectors, receivers, and piping systems, among others. We focus on the receiver and how improving its performance using an AM-made configuration may affect the solar field cost. To support the economic impact of employing AM-produced receivers, the example of a 100 MW PTC power plant can be used. This power plant relies on a solar field consisting of 1,168 solar collectors (Euro through ET 150) and 42,048 receivers (Scott PTR 70) [58]. This solar field costs 377.69 USD/m^2 [58]. The area of the solar collectors is 817.5 m^2, and the estimated cost of the commercial solar collector is 152 \$/m^2 [59]. Therefore, the total cost of solar collectors is equal to 145,135,680 \$. The cost of the Schott receiver is estimated at 100 \$/m [60]. The total cost of all receivers is 17,071,488 \$.

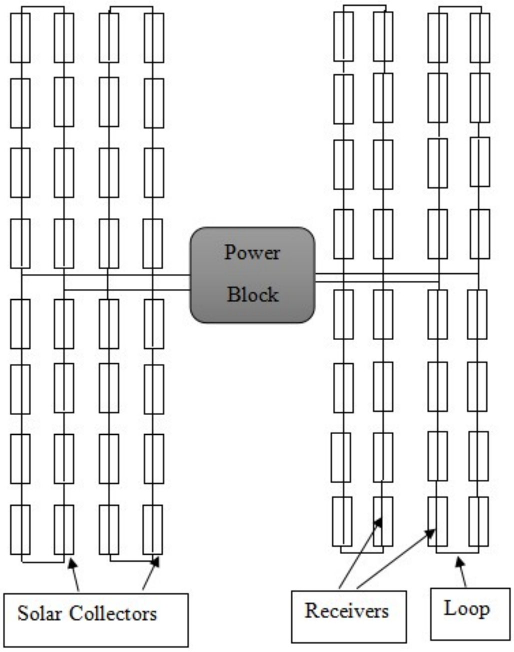
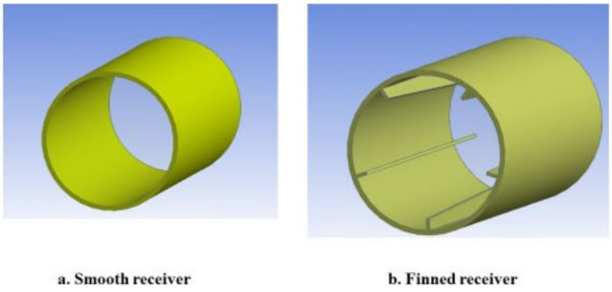


Fig. 5. Example of a solar field

The piping system includes heat transfer fluid, pipe networks, and their support. The cost is estimated at 37.77 \$/m^2 [59]. The total cost of the piping system is 36,064,306.8 \$. The land and the site landscaping cost depends on the solar field size and is estimated to be 15.11 \$/m^2 [59].

4.2. Heat transfer analysis of new receiver

The heat transfer enhancement analysis used a new receiver configuration containing fins with increasing height. The smooth and modified tubes with fins were modelled, as shown in Figure 6.



a. Smooth receiver

b. Finned receiver

Fig. 6. Receiver configurations

To investigate the heat transfer performance, the calculation of heat transfer in terms of the Nusselt number and the pressure drop in terms of friction factor was carried out using computational fluid dynamics (CFD) analysis through ANSYS Fluent. The governing equation used in this study is the Reynolds Averaged Navier-Stokes (RANS) equation using the realisable k-epsilon model.

Simulation results showed that the Nusselt number for smooth and finned tubes are 269.2 and 716.3, respectively and that the friction coefficients for smooth and finned tubes are 0.02694 and 0.03629 respectively. The performance evaluation criterion (PEC) of the finned tube is equal to 2.4 In addition, the heat transfer of two receivers was compared using equation 1 to get an idea of the impact of the new receiver.

$$Q = h \times A \times (T_2 - T_1) \tag{4}$$

where: Q is the heat transfer, h is the heat transfer coefficient, A is the area of heat transfer, and T_2 and T_1 are the temperature at the outlet and inlet, respectively.

For smooth tube heat transfer is equal to:

$$Q = 2779.9 \times 0.1444 \times (527.2 - 320) = \\ = 83194.9\,W \tag{5}$$

For finned tube, heat transfer is equal to:

$$Q = 3031.8 \times 0.0177 \times (586.3 - 320) = \\ = 119497.3\,W \tag{6}$$

The above calculation shows that the ratio of the heat transfer of the finned tube to the smooth is 1.4. This means that 1.4 smooth receivers can be replaced by one finned receiver. Therefore, utilising the novel receiver in the same PTC plant reduces the number of receivers from 42,048 to 30,035. In the solar field, receivers are 36 per solar collector assembly [58]. Therefore, the number of solar collector assemblies will become 835. In other words, the number of receivers and solar collectors needed in the solar field will be reduced by 28.56% and 28.5%, respectively. Since the geometry of the new receiver is complex, it can be produced using AM. The cost of producing all receivers needed will be 53,573,057 \$ (this includes the manufacturing cost, materials cost, and labour cost), which means the receivers) manufacturing cost will be increased by 289%. Although the cost is higher compared to the commercial receiver, the efficiency of the new receiver configuration is higher than that of the commercial receiver, as discussed above. Therefore, indirect cost, which includes the solar collector cost, pipe system cost, and the receivers' land and site improvement cost will be reduced by 28.6% since the solar field size decreases. Thus, the total capital cost of the plant solar field will be reduced by 20.7%. Although the cost of AM machines and materials is high compared to conventional manufacturing, the gain in efficiency achieved from the additive-manufactured receivers can overcome the cost increase. Additive manufacturing can help reduce the capital cost of a PTC plant as AM, directly and indirectly, lowers the number of capital-intensive elements such as receivers and solar collectors. It, in turn, reduces the overall solar field costs.

5. Conclusions

The present review article focused on the possible use of AM to enhance heat transfer, with several receiver configurations developed to improve heat transfer. Based on the reviewed studies, it is shown that improvement in heat transfer is often accompanied by higher pressure drop. This increases operation costs due to the need for more pumping power. Most configurations with optimised heat transfer and pressure drop are complex and cannot be produced using conventional manufacturing. The major advantage of AM is that almost any configuration can be produced. The advancements made possible by AM technology provide numerous innovative means for improving heat transfer, particularly in creating extremely effective, compact, and lightweight heat exchanger systems, by creating some innovative fin structures crucial in many industries. The effect of using AM on costs was discussed by developing a new configuration of receiver-containing fins with increasing height. A solar field of a 100 MW PTC plant was taken as a case study for cost comparison. It was found out that even if the cost of the receiver produced by AM is higher than that of the commercial receiver, the efficiency gains will reduce the number of receivers needed for the solar field and thus reduce the number of solar collectors needed. This will, in turn, reduce mirror cost, HTF system cost, land and site improvement, and structure and control system. The total capital cost of the plant solar field will be reduced by 20.7%, which will reduce the total capital cost and yield a lower levelized cost of electricity (LCOE) for PTC.

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