SVU-International Journal of Engineering Sciences and Applications (2025) 6 (1): 69 to 79
Print ISSN 2785-9967 | Online ISSN 2735-4571
DOI 10.21608/svusrc.2024.324863.1241

A review on utilizing nanofluid in solar collectors: modeling, materials, challenges, and applications

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Abstract Solar energy is a clean, sustainable, and renewable alternative energy source that offers a promising solution to global energy challenges. Solar collectors are one of the most effective technologies for harnessing solar energy, particularly for heating applications. Among the various types, flat plate solar collectors stand out due to their simple design, affordability, and widespread use. However, despite their advantages, these collectors suffer from efficiency limitations that need to be addressed to maximize their potential. In recent years, nanofluids—suspensions of nanoparticles in base fluids—have shown considerable promise in enhancing the thermal performance of flat plate solar collectors. This review explores the latest developments in flat plate solar collector technology, focusing on design innovations, mathematical modeling, and the role of nanofluids in improving heat transfer efficiency. Additionally, the review addresses the key challenges of using nanofluids, such as stability, cost, and potential environmental impacts, and discusses their applications across various industries. The findings conclude that while nanofluids significantly enhance collector efficiency, more research is needed to ensure long-term stability and cost-effectiveness, paving the way for future advancements in solar energy technology.

Keywords: Solar energy, Flat plate solar collector, Nanofluids.

1 Introduction

The world's population encountered a growth of one billion between the years 1998 and 2010 and between the years 2010 and 2022. By 2050, it is estimated that the world population will reach 9.7 billion [1]. The rapid increase in the world's population escalates energy demand since energy is needed to power humankind's life in many sectors such as trade [2], industry [3], air conditioning[4], irrigation, transportation [5], …etc. Fossil fuels can meet the energy demand effectively as they have the advantages of higher specific energy (energy per unit mass) and relatively reduced price; however, they suffer from several disadvantages. These disadvantages include the environmental impact [6], the expected runout shortly, and escalating prices with time[7]. Fossil fuel environmental impact can be seen in the incomplete combustion inside the heat engines. Pollutants such as C, CO, NOx, and SOx are released during the incomplete combustion process causing a hazardous impact on the ecosystem [8], [9]. Air pollution, water pollution, acidic rain, and marine life threatening are examples of fossil fuel damage to the environment [10]. Besides the aforementioned gases, CO2 is released causing global warming potential (GWP) which threatens the existence of humankind. The second issue of the future runout is related to the limited amount of fossil fuels as the proven reserves for oil, natural gas, and coal are sufficient for 41, 67, and 230 years[11]. Rising fossil fuel consumption presents a significant economic challenge. As reserves dwindle, prices tend to rise at an accelerated pace. Considering the issues related to fossil fuels, it is necessary to find an alternative that is capable of addressing the fossil fuels issues.

Received: 29 September 2024/ Accepted: 29 November 2024
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Solar energy is a good candidate for addressing these issues as it is a clean source of energy with zero pollution, and it is a renewable source that lasts forever [12]. Solar energy can be utilized in many applications such as power generation [13], water heating [14], space heating [15], food drying [16], desalination [17], and atmospheric water harvesting [18]. For instance, using solar energy in water heating can be achieved via solar collectors [19]. The heated water can be used in many applications such as space heating, cement industry,

residential hot water demand (showering, laundry, and dishwashing), and pools [20], [21]. The most common working fluids, which are utilized in solar collectors, are water, an antifreeze- mixture [22], and oil [23]. Every working fluid has advantages and disadvantages. For example, water is abundant and readily available and has high heat capacity and low cost; however, it freezes at 0 oC and corrodes the tubes. In contrast, the anti-freeze mixture can operate in a wider temperature range than water and it does not cause tube corrosion. The demerits of the anti-freeze mixture are they require higher pumping power than water and it can be toxic if the mixture is inhaled. Water as a working fluid generally suffers from poor thermal conductivity. To mitigate the thermal conductivity, nanomaterials are added to water [24]. Thus, the amount of the transferred heat is increased which increases the efficiency of the solar collector. Materials such as carbon nanotubes [25], titanium oxide [26], zinc oxide [27], copper oxide [28], aluminum oxide [29], silver oxide [30], and iron oxide [31] are used as nanomaterials additive to base fluid, and they have proven efficient usage in solar collectors. This article conducts an overview of the nanofluid-based solar collectors. This article is structured as follows: the first section presents the solar collector design, the second section introduces the solar collector modeling, the third section reviews the materials used in nanofluids, the fourth section analyzes the nanofluids' challenges, and the last section reviews the current applications of the nanofluid-based solar collectors.

2 Solar collector design (flat plate)

Fig.1 depicts the simplest type of solar collector: flat plate collector. It encompasses glass cover, absorber plate, absorber tubes, and insulation. The solar radiation is transmitted through the glass cover and then received by the absorber plate to convert the solar radiation into thermal energy. The thermal energy is then transferred from the solar plate to the in-contact absorber tubes which in turns heats the working fluid passes through the tubes. The heated working fluid is provided to a certain application directly, to another fluid loop, or to an energy storage unit. Insulation material is attached to the flat plate solar collector in its back and sides for the sake of heat loss reduction through convection and radiation. As the heat loss is reduced, the solar collector efficiency increases. The materials of the absorber plate and the absorber tubes should have higher thermal conductivity to maximize the heat transfer, and hence the efficiency of the collector increases. Also, coating with selective material should be applied on the absorber plate to maximize the amount of absorbed solar radiation and reduce the reflected portion from it. Herein, the glass cover serves in transmitting the solar radiation and acts as a barrier for longwave radiation which traps heat inside the collector and increases its efficiency. Flat plate collectors have several advantages. They are simple in their designs, as depicted in Fig. 1. Flat plate collectors are easy to construct, and they require low maintenance costs, such as periodic cleaning to remove dirt and debris. They are reliable, durable, and affordable. They are offered by many suppliers and can be used in a variety of applications, such as water heating, space heating, and pool heating .

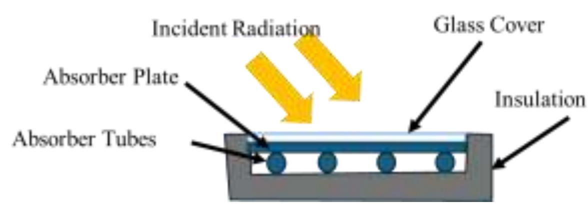

Fig. 1 Flat plate solar collector

3 Flat plate solar collector modeling

This section aims to present the mathematical modeling of the simple flat plate collector, as shown in Fig.1. Before introducing the equations of the model, the assumption should be stated. Herein, the assumptions regarding this collector are [11]:

- Heat transfer is considered as 1-D in all components
- The glass cover has a negligible temperature gradient

- Sky is treated as a black body
- The collector's headers are small
- Steady flow condition inside the collector
- The collector is clean (no dust) and there is no shade on it.

Fig. 1 depicts the flat plate solar collector energy balance. Absorber plates receive solar radiation from the sun which converts into thermal energy. The working medium inside the absorber tubes absorbs the majority of the thermal energy and the remaining thermal energy is dissipated to the ambiance and the surroundings via convection and radiation, respectively. The equivalent radiation I_{eq}, which is the amount of the received radiation by the absorber plate can be estimated from

$$I_{eq} = I\,\alpha\,\tau \qquad (1)$$

where I is the sun irradiance, α is the absorber absorptivity, and τ is the transmissivity of the glass cover. The term $\alpha\,\tau$ is known as the collector optical efficiency.

The amount of useful heat (Q_u) gained to the working fluid can be calculated from

$$Q_u = \dot{m}\,C_p\,(T_{out} - T_{in}) \qquad (2)$$

Where $\dot{m}$, C_p, T_{in}, and T_{out} are the mass flow rate inside the tubes, the specific heat of the working fluid, the inlet fluid temperature, and the outlet fluid temperature, respectively.

The efficiency of the collector (η) is defined as the amount of useful heat energy divided by the solar incident energy and it be estimated as[32]:

$$\eta = \frac{\dot{m}\,C_p\,(T_{out} - T_{in})}{IA} \qquad (3)$$

Where A is the surface area of the absorber plate.

Eq (3) referenced the efficiency of the collector to the incident radiation energy of the sun without highlighting the different energy losses that in turn reduce the efficiency. energy losses can occur due to the low optical efficiency or the heat losses in the collector via convection and radiation. To design a highly efficient collector, optical properties should be enhanced by using glass with high transmissivity and an absorber with high absorptivity. In addition, convection and radiation heat transfer with the ambiance and surroundings should be minimized. To calculate these losses, an analysis based on Fig. 1 is given below to every component in bullets.

- The air gap between the absorber plate and the glass cover encounters convection heat transfer inside it and radiation heat transfer between the absorber plate and the glass cover.
- The glass cover encounters a radiation heat transfer and convection heat transfer with surroundings and the ambiance.
- The insulation in the bottom and the edges of the collectors encounters conduction heat transfer.
- The insulation exchanges the radiation heat transfer and convection heat transfer with surroundings and ambiance

These heat transfer mechanisms can be represented using the thermal resistance network, as shown in Fig. 2.

Where R_{p-c}, R_{c-a}, R_{e-a}, and R_{b-a} are the convection thermal resistance on the absorber plate, cover glass, collector edge, and collector bottom, respectively. Also, the radiation thermal resistances in the same locations are $R_{r,p-c}$, $R_{r,c-a}$, $R_{r,e-a}$, and $R_{r,b-a}$, respectively. The conduction resistances on the bottom and the edge of the solar collector are estimated to be $\frac{x_b}{k}$ and $\frac{x_e}{k}$, respectively. Every convection resistance is calculated from[11]

$$R_{i-j} = \frac{1}{h_{i-j}} \qquad (4)$$

Where h_{i-j} is the convection heat transfer coefficient between i and j. The radiation thermal resistance can be estimated from

$$R_{r,i-j} = \frac{1}{h_{r,i-j}} \qquad (5)$$

Where $h_{r,i-j}$ is the radiation heat transfer coefficient and can be estimated from

$$h_{r,i-j} = F_{ij}\varepsilon_i\sigma\left(T_i^2 + T_j^2\right)\left(T_i + T_j\right) \qquad (6)$$

Where F_{ij} ε, σ, T_i, and T_j are the radiation view factor, the emissivity, Stefan-Boltzmann constant, the temperature of i and the temperature of j. The thermal losses in the flat plate heat collectors are distributed into three directions: top, bottom, and edges. The combined thermal losses can be represented as [32]

$$Q_{Tl} = UA\left(T_p - T_a\right) \qquad (7)$$

Where U is the overall heat transfer coefficient, A is the absorber surface area, T_p is the absorber temperature, and T_a is the ambient air temperature. The overall heat transfer coefficient can be calculated from[33]

$$U = U_t + U_b + U_e \qquad (8)$$

Where U_t, U_b, and U_e are the overall heat transfer coefficients for the top, bottom, and edges of the collector, respectively. To calculate the top overall heat transfer coefficient the following set of equations is used[34]

$$U_t = \left(\frac{N}{\frac{C}{T_p}\left(\frac{T_p - T_a}{N + f}\right)^{e}} + \frac{1}{h_w} \right)^{-1} + \left(\frac{\sigma(T_p^2 + T_a^2)(T_p + T_a)}{(\varepsilon_p + 0.00591 N h_w)^{-1} + \frac{(2N + f - 1 + 0.133\varepsilon_p)}{\varepsilon_g} - N} \right) \qquad (9)$$

$$C = 520\,(1 - 0.000051\,\beta^2) \qquad (10)$$

$$f = (1 + 0.089\,h_w - 0.1166\,h_w\,\varepsilon_p)(1 + 0.07866\,N) \qquad (11)$$

$$e = 0.43\left(1 + \frac{100}{T_p}\right) \qquad (12)$$

$$h_w = 5.7 + 3.8V_w \qquad (13)$$

Where T_a, T_p, ε_p, ε_g, N, and V_w are the ambient temperature, absorber plate temperature, absorber emissivity, glass emissivity, the number of glass covers, and wind speed, respectively. Neglecting the radiation and the convection on the collector edges, the edges' overall heat transfer coefficient U_e can be calculated as[33]

$$U_e = \frac{\frac{K_{in}}{t_{e,in}} P t_c}{A} \qquad (14)$$

Where K_{in}, P, t_c, $t_{e,in}$ and A are the thermal conductivity of the insulation, the perimeter of the collector, the thickness of the collector, the thickness of the insulation at the edge, and the surface area of the absorber, respectively. In the same manner, the bottom overall heat transfer coefficient U_b can be calculated as[11]

$$U_b = \frac{K_{in}}{t_{b,in}} \qquad (15)$$

Then useful heat can be calculated as follows

$$Q_u = I\,\alpha\,\tau - UA(T_p - T_a) \qquad (16)$$

Eq (16) considers both the optical losses and thermal losses from the total radiation energy IA. Although Eq (16) is physically and mathematically correct, it is not practical to obtain T_p; Therefore, Eq (16) is modified to[35]

$$Q_u = F_R\,I\,\alpha\,\tau - F_R UA(T_{in} - T_a) \qquad (17)$$

Where T_{in} and F_R are the inlet fluid temperature and the heat removal factor, respectively.

4. Modeling the nanofluid

Many models are developed to estimate the thermophysical properties of nanofluid. The scholars agree mostly in the calculation of the density and the specific heat of the nanofluid and differs in the calculation of the dynamic viscosity and the thermal conductivity of the nanofluids. Here are the most used correlations for calculating the density, specific heat, dynamic viscosity, and thermal conductivity are as follows [35], [36], [37], [38].

$$\rho_{nf} = \rho_n \varphi_n + \rho_{bf}(1 - \varphi_n) \qquad (18)$$

$$\rho_{nf} C_{p,nf} = C_{p,n} \rho_n \varphi_n + C_{p,bf}\,\rho_{bf}(1 - \varphi_n) \qquad (19)$$

$$\mu_{nf} = \mu_{bf}\, g(\mu_{bf}, \varphi_n) \qquad (20)$$

$$k_{nf} = k_{bf}\, f(k_{bf}, k_n, \varphi_n) \qquad (21)$$

Where φ_n is the concentration of the nanoparticle in the nanofluid. Eqs (20) and (21) state that the nanofluid dynamic viscosity and thermal conductivity are multiple of the base fluid dynamic viscosity or thermal conductivity and a function that depends on the base fluid property and the nanofluid concentration. For example, to calculate the dynamic viscosity and thermal conductivity of the Al_2O_3 /water nanofluid the following correlation is used[39], [40]:

$$\mu_{nf} = \mu_{bf}(1 - \varphi_n)^{-2.5} \qquad (22)$$

$$k_{nf} = k_{bf}\left[1 + 1.0112\,\varphi_n + 2.4375\,\varphi_n \frac{23.5}{d_n} - \frac{0.0248\varphi_n}{0.613 k_n}\right] \qquad (23)$$

5. Survey on working nanofluid for flat plate solar collector

Different materials were used to enhance the thermophysical properties of the working fluid to extract the maximum amount of solar energy in the form of heat inside the flat plate solar collectors. Nanoparticles of Cu, CuO, Al_2O_3, TiO_2, SiO_2, Fe_2O_3, C, ZnO, MgO, and carbon nanotube (CNT) are added with different concentrations to different base-fluids such as water, ethylene glycol, and oil to enhance their thermophysical properties. This method aims to maximize the useful heat gain to achieve the highest amount of heat transfer, thereby the solar collector efficiency is increased. In the below, a thorough review of the previous work on using different nanofluids for flat plate solar collectors is presented highlighting the impact of the nanofluid on the performance of the collector.

5.1. Aluminum Oxid (Al_2O_3)

Ge et al[41] proposed a system for power generation consisting of a flat plate power collector and parabolic trough collector combined with an organic Rankin cycle. The study was conducted using ANSYS software and different nanoparticles are added to oil. The maximum collector efficiency for Al_2O_3 reached to be 73.73% when the nanoparticle concentration was 5% while the other materials such as TiO_2, Cu, and CuO reached close values of 73.74%, 74.02%, and 73.96% respectively. Farhana et al [42] conducted an experimental work to study the stability of the thermophysical properties of two nanofluids at a concentration of 0.5%. The study revealed that the efficiency enhancement of the Al_2O_3 and Crystal nano-cellulose (CNC) nanofluids are 2.48% and 8.46%, respectively. Although the efficiency enhancement of the Al_2O_3 nanoparticle is very low, the stability of the thermophysical properties is higher than CNC. In addition to using Al_2O_3 as a single nanoparticle type in the base fluid, other works tend to use hybrid nanoparticles to enhance and augment the solar collector performance. Salawu et al[39] used the hybrid Cu–Al_2O_3 and Cu with ethylene glycol for the flat plate solar collector. The result indicated a superior performance of the hybrid Cu–Al_2O_3 over Cu nanofluid.

5.2 Iron Oxide (Fe_3O_4)

Bezaatpour and Rostamzadeh [43] conducted numerical work to enhance the performance of the flat plate solar collector by using rotary absorber tubes and Fe_3O_4/ water nanofluid. The study revealed that energy losses of 1.65% and 10.44% are restored when using a 2% concentration Fe_3O_4/ water nanofluid and the rotary mechanism. Akram et al [44]conducted experimental and numerical work on Fe_3O_4/ poly ethyne glycol nanofluid to evaluate the thermophysical properties enhancement and performance augmentation. Values of 13.35%, 0.06%, 0.37%, and 20.9% of enhancement at 0.1% nanoparticles concentration and 35 ºC, were obtained for thermal conductivity, density, specific heat, and viscosity, respectively. Also, the maximum improvement in the collector thermal efficiency is about 13.8%. Choudhary et al [45]conducted experimental work to test the performance stability of the Fe_3O_4/ (ethylene glycol/ distilled water = 50:50). Results indicated that at 1 % concentration of the nanoparticles, the performance was instantaneous, and it dropped drastically. In addition, when the concentration is between 0.2% and 1%. The performance stability lasts for 15 days. Also, the study reported that when the nanoparticles concentration is 1% and the volume flow rate is 30 L/h, the efficiency enhancement of the collector is 15.27% on the first day and 1.81% after 15 days of operation.

5.3 Copper Oxide (CuO)

Ashour et al [46] conducted numerical work using the ANSYS software package to study the performance of the flat plate solar collector. In their work, the utilized nanofluids are zinc oxide (ZnO) nanofluid and copper oxide (CuO) nanofluid water based at volume fractions of 0.05, 0.10, and 0.15% when the mass flow rate range is 0.0125–0.025 kg s^{-1}. The study revealed that the CuO/ water nanofluid has the best performance with an average efficiency value of 81.64% when the volume fraction is 0.1% and the mass flow rate is 0.0125 kg s^{-1} compared with 60.21% for the base water. The outstanding of the CuO nanoparticle encourages scholars to do further enhancement using innovative design. Nabie et al [47]utilized different absorber tube cross-section designs to augment the turbulence inside the tube to increase the heat transfer. Three different designs are studied. A hybrid nanoparticle of CuO-CNT was used with the best cross-section area performance (Case 3) at different volume fractions that range between 1-5%. The study revealed that the thermal performance of the hybrid single-walled carbon nanotube/CuO with a volume fraction of 1% performs best with an enhancement of 5.16%.

5.4 Carbon Nano Tube (CNT)

Most of the research on CNT is divided into single walled and multi walled carbon nano tube. The key difference between them is in the structure. As depicted in Fig.3, the multi walled CNT has different cylindrical layers with longer outer diameter compared with the single walled CNT. The two CNT types are utilized in much research for using them as nanofluid for the flat plate solar collector. Tong et al [48] utilized the multi walled type (MWCNT), CuO, Al_2O_3, Fe_3O_4, WO_3, and CeO_2 in the solar collector and studied their performance experimentally. The study revealed that the efficiency of solar collectors reaches 87% compared with 62% for the base fluid. In addition, the sensitivity of the efficiency, when using MWCNT, to the weather condition is the highest. Eltaweel et al [49]studied experimentally the performance enhancement of adding SWCNT in both the parabolic trough and flat plate solar collector. The efficiency of the collectors, when the nano concentration is 0.05%, are 55% and 59% for the parabolic trough and flat plate solar collectors, respectively. An eco-friendly material (clove) for preparing the CNT is used by Alfellag et al [50], as depicted in Figs .4 and 5. in their experiment they used clove-treated carbon nanotubes/titanium dioxide (CT-MWCNTs/TiO_2) nanocomposites that have ratio of (60:40). Different operating conditions are studied such as nano concentrations, volume flow rates, solar radiation and inlet temperature for evaluating the thermal performance of the collector. The ranges are (0.025, 0.05, 0.075, and 0.1wt %) for the concentrations, (0.3, 0.6, 0.9, and 1.2L/min) for the flow rate, (400, 600, 800, and 1000 W/m^2) for the solar radiation and inlet (30, 35, 40, 45◦C) for the inlet temperature. The study reveals that the maximum efficiency enhancement was 20.6% when the concentration is 0.1% and the volume flow rate is 1.2L/min. Elshazly et al [51] studied the performance of the flat plate solar collector when adding MWCNTs, Al_2O_3, and hybrid MWCNT/Al_2O_3 50:50% to the water. Different nanoparticles concentration ratios are used (0.5%, 0.025%, 0.01% and 0.005%). The study revealed that the efficiency enhancement is 26%, 29%, and 18% for the volume flow rates 1.5 L/m, 2.5 L/m, and 3.3 L/m, respectively. Table 1 illustrates the Comparative Analysis of Nanofluids for Flat Plate Solar Collectors.

Table 1: Comparative Analysis of Nanofluids for Flat Plate Solar Collectors

Nanofluid	Efficiency Improvement (%)	Stability Duration	Cost Implications
Al_2O_3	15-20%	Moderate (weeks)	Moderate
Fe_3O_4	18-22%	High (months)	Moderate-High
CuO	20-25%	Moderate (weeks)	High
CNT	25-30%	Low (days)	Very High

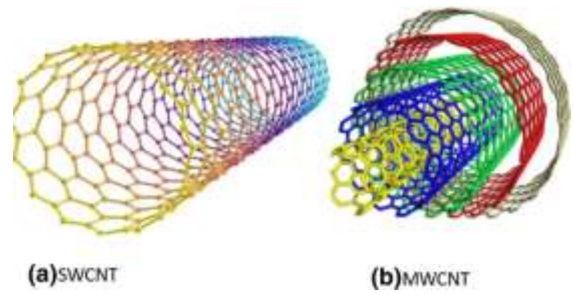

Fig. 3. The structure of the single walled and double walled carbon nano tube[52]

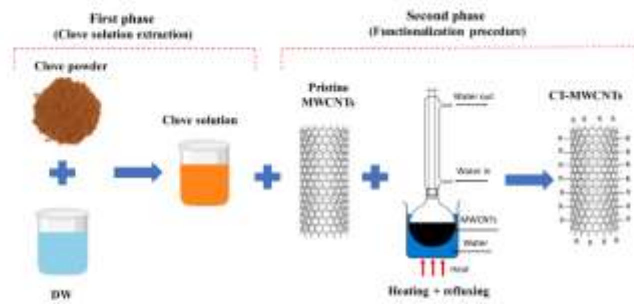

Fig. 4. Preparing MWCNT from Clove[50]

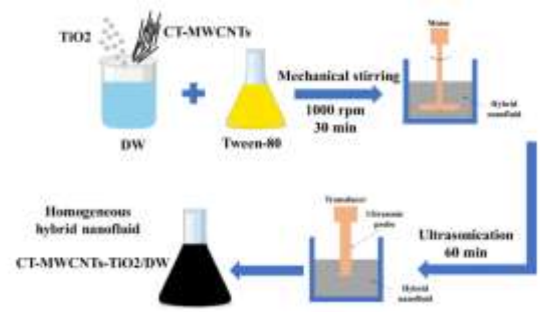

Fig. 5. Preparing CT-MWCNTs/TiO_2 nanofluid [50]

6. Nanofluids challenges

Although Nanofluids improves the thermal performance of the flat plate solar collector, they suffer from many issues. The critical issues for the nanofluid can be summarized as follows:

- **Diverse thermo-physical properties:** the thermophysical properties depends on the base fluid, nanoparticle type, nanoparticle shape, nanoparticle concentration and the preparation method. This creates discrepancies between different studies results. Therefore, the evaluation of the thermophysical properties of the nanofluid should be carried out with new approaches such as statistical methods in the microscopic view[53].

- **Formulation methodology:** preparation of the nanofluids can vary from one researcher to another. The most widely used preparation methods are (i) one-step[54], (ii) two-step [55], (iii) direct dispersion [56] , and (iv) in-suit [57]. The thermophysical properties differ in the one-step and the in-suit methods while it is stable in the two-step method. The by-product, which causes the inclusion of some chemical residuals in the nanofluid, is the main reason for the discrepancy in the thermophysical properties. The two-step method is preferable because it eliminates the by-product, but it demands a high energy stirring and sonication[53].
- **Particle morphology and aggregation:** When dispersing the nano particle in the fluid, some nano particles undergo sedimentation and some of them undergo agglomeration as depicted in Fig. 6. The aggregated nanoparticles create different shapes, aspect ratio, and nano surface topologies that affect the thermophysical properties of the nanofluid[53]. To address nanoparticle aggregation, we propose several strategies, including the use of surfactants and optimization of dispersion techniques. Surfactants play a key role in stabilizing nanoparticles within the base fluid by reducing agglomeration and preventing particle settling. Based on temperature ranges, we suggest specific surfactant recommendations:
  a. At lower temperatures (<60°C): Surfactants such as polyethylene glycol (PEG) and polyvinylpyrrolidone (PVP) are recommended due to their ability to maintain nanoparticle dispersion effectively at these conditions. These surfactants are known to have low degradation rates and can provide stable dispersion over extended periods.
  b. At moderate temperatures (60-100°C): Oleic acid and sodium dodecyl sulfate (SDS) can be more suitable for enhancing stability. These surfactants provide better protection against aggregation due to their strong adsorption on nanoparticle surfaces.
  c. At higher temperatures (>100°C): For high-temperature applications, surfactants such as Arabic gum and polymethacrylic acid are effective. These surfactants maintain stability in elevated temperatures while minimizing degradation, ensuring that the nanofluid can operate efficiently over extended periods. In addition to surfactant use, we emphasize the importance of careful selection of nanoparticle concentration and the adoption of advanced dispersion methods such as high-energy ball milling and ultrasonication. These techniques ensure a uniform distribution of nanoparticles, further improving the long-term stability of nanofluids.
- **Difference in measurement methodologies:** nanofluid is a two-phase fluid that encompasses fluid and dispersed solid particles inside it. In modeling, it is treated as single phase fluid and some phenomena such as the Brownian diffusion, thermophoresis are not considered. Conducting measurements in the nanofluid suffer from the deposition of the particle on the instrument probs, therefore, the recorded values of the instrument are not precise. Consequently, the final efficiency is not achieved[53].

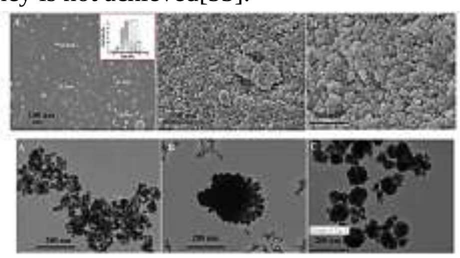

Fig. 6. Aggregated nanoparticles during the dispersion[58]

- **Dominance of heat transfer is crucial:** nanoparticles are responsible for increasing the heat transfer inside the nanofluid; however, pressure drop increases when the concentration of the nanoparticles increases. The augmentation of heat transfer can be seen in the laminar flow regime at the entrance region; therefore, optimization is needed[53].
- **Suitability in high temperature applications:** the high temperature of the nanofluid leads to the higher Browanian motion which increases the number of the collision of the nanoparticles that leads to agglomeration and nanoparticle settling. To reduce this effect, surfactants such as Arabic gum, polymethacrylic acid, sodium octanoate, polyethylene glycol, oleic acid, polyvinylpyrrolidone, and sodium dodecyl sulphate are needed. Surfactants' performance also depends on the temperature[53], [59]. The higher operation temperature leads to surfactant degradation.
- **Fouling and erosion:** Nanofluids are inherently susceptible to fouling and erosion, which are unavoidable byproducts of their applications. These processes can lead to erroneous research findings due

to particle scaling, loss, and the abrasive nature of nanofluids. Continuous operation can result in a decrease in nanofluid concentration and diminishing heat transfer performance. The abrasive nature of nanofluids can alter the surface characteristics and geometry of the flow path, potentially affecting measurement accuracy. Many studies overlook these factors, which can introduce significant uncertainties and compromise the reliability of research findings.

- **Cost effective:** nanofluids have higher initial costs due to the expense of nanoparticles (e.g., Al_2O_3, CuO, CNT), specialized preparation methods, and stabilizers like surfactants. Maintenance costs are also higher as nanofluids require periodic stabilizer addition and cleaning to prevent aggregation and sedimentation. However, nanofluids enhance thermal performance by 10–30%, reducing collector area requirements and improving efficiency in auxiliary systems, leading to higher annual savings. For example, while a conventional fluid system has a payback period of approximately 3 years with annual savings of $1,200, a nanofluid system demonstrates a longer payback period of 4.5 years but higher annual savings of $1,800. Nanofluids are particularly suitable for high-performance applications, such as industrial heating or concentrated solar power, where efficiency gains outweigh the additional costs.
- **Environmental Impact:** While nanofluids offer significant thermal performance benefits, their environmental implications require careful attention. Disposal of nanofluids can pose risks due to nanoparticle release, which may lead to soil and water contamination. For example, metal oxide nanoparticles like Al_2O_3 and CuO can accumulate in ecosystems, affecting aquatic life and soil microorganisms. To mitigate these risks, proper end-of-life management strategies are essential, such as recycling nanofluids using filtration and centrifugation techniques to recover nanoparticles for reuse. Additionally, biodegradable surfactants and environmentally benign base fluids should be prioritized to minimize ecological impact. Regulatory frameworks for nanofluid disposal and handling also need to be established to ensure safe practices in industrial-scale applications.

7. Survey on the application of flat plate solar collector

The flat plate solar collector is used in many applications for the sake of utilizing the sun's energy and converting it into useful heat. The heat is used for other purposes such as domestic hot water demand, power generation, and industrial processes. In the below, applications concerning the flat plate solar collector are discussed, highlighting its working principles

7.1. Flat plate solar collector for residential hot water demand

The basic usage of the flat plate solar collector is to heat water. For homes, water is needed for household usage such as baths, washing dishes, and washing clothes. A flat plate solar collector is installed usually on the house roof or in the yard. The collector harnesses the solar energy to heat the working fluid inside it. The heated fluid can go directly to the residential purpose or exchange the heat with another fluid loop, as depicted in Fig. 7. The heat exchange occurs in the storage tank in which the collector fluid heats the residential water in the daytime. In this system, control components, such as the flow control valve, bypass valve, and supply reservoir, are integrated to ensure proper flow operation in extreme conditions such as severe cold weather. Water from the tank is provided to the demand (bath) and domestic cold water enters the tank.

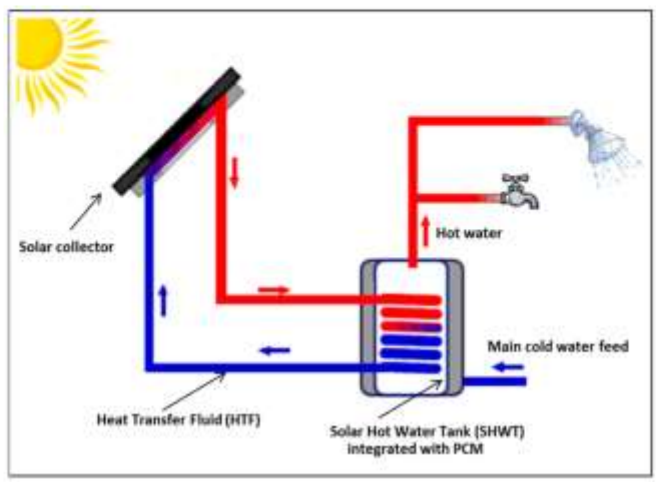

Fig. 7. Flat plate solar collector for residential hot water demand[60]

7.2. Flat plate solar collector integrated with PV

A photovoltaic thermal collector (PVTC) is a type of solar energy system that efficiently harnesses sunlight to produce both electricity and heat. It consists of a solar panel placed above a solar collector. The solar panel converts sunlight into electricity, while the collector captures the residual heat that's not used for electricity generation. A cooling fluid flows through the collector, absorbing this heat. This collected heat can then be used for various applications, such as heating homes, providing hot water, preheating industrial processes, drying crops, or powering other low-temperature heat requirements. By utilizing the heat that would otherwise be wasted, PVTCs offer a more comprehensive and sustainable solution for solar energy generation, maximizing the efficiency of the system.

7.3. Flat plate solar collector for power generation

A system utilizes a flat plate solar collector and a parabolic trough solar collector for oil heating used for power generation [41]. The heated oil is integrated with a heat engine for power generation. Herein, the heat engine is an organic Rankine cycle (ORC) that utilizes a fluid with low boiling point temperature to produce power. In a two-stage solar collector, a low-temperature heat transfer fluid starts by flowing through a preheating section (flat plate collector) Here, it gets heated up to a temperature below 80 ^oC. Then, it enters a second section (parabolic trough collector) where it's heated even further, reaching 200 ^oC. This hot fluid is stored in a tank to maintain a steady temperature for the system. The hot fluid transfers its heat to a working fluid in an evaporator. This working fluid is then cooled down and stored in another tank. Finally, the cooled fluid is pumped back to the preheating section to start the process again.

8. Conclusion

Solar energy is a clean and renewable energy source. One way to use solar energy for heating is with solar collectors. Flat plate solar collectors are a popular choice because they are simple, affordable, and widely available. However, their efficiency could be improved. Nanofluids, which are fluids containing tiny particles, have the potential to increase the efficiency of solar collectors. This article reviews flat plate solar collectors, focusing on their design, how they work, how nanofluids can improve them, the challenges of using nanofluids, and the different applications where they are used. The article concludes that nanofluids can improve the performance of solar collectors, but more research is needed to ensure that their performance remains stable over time. Also, some modifications can be made to the absorber tubes (different tube cross-section designs) to increase the turbulence which augments the heat transfer and the collector efficiency.

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